

# CNC 빅데이터 분석

Keywords : IoT EDA Classification Forecasting GNICT

## \* CNC 빅데이터 분석

- CNC가공 공정의 데이터를 통한 품질 문제 해결과 생산성 향상은 스마트팩토리 부분의 필수적인 요소
- CNC 설비와 네트워크 연결을 통해 생산데이터를 수집하고 가공조건에 따른 가공불량 예측과정을 학습사례

- 분석에 사용된 변수명 : X,Y,Z, 스핀등의 변수 총 48가지
- 데이터 개수 : 96,169개
- 데이터셋 총량 : 14.62 MB
- Deep Neural Network
- Random Forest
- 필요SW : Python
- 필요패키지 : Tensorflow, Keras, numpy, pandas, glob, sklearn, scipy

## 2) Data 정리

1. Train.csv: 25개의 Row로 구성되고 각번호(0~25)는 experimnt\_xx.csv로 연결되며,
2. Train.csv는 label values로 이를 다시 단순화한 class column을 추가하고 class에 label value를 부여함.
3. experiment 파일별 label값(#2) 추가하고
4. experiment 파일을 하나로 합치고(sum\_experiment)
5. 합친 sum\_experiment을

1) 탐색적 분석 </br> 2) train과 test data set으로 분류하고 </br> 3) Training (RandomForestClassifier)</br>

6. 새로운 가공값을 부여하여 불량, 양품 판단하는 ML

| 데이터 변수 종류     | 개 수 |
|---------------|-----|
| 샘플 관련 변수      | 6개  |
| 기계의 X축 관련 변수  | 11개 |
| 기계의 Y축 관련 변수  | 11개 |
| 기계의 Z축 관련 변수  | 11개 |
| 기계의 스핀들 관련 변수 | 12개 |
| 기타 변수         | 4개  |

| Input Data     | Description          |
|----------------|----------------------|
| No             | 작업 번호                |
| material       | 작업 소재                |
| feed rate      | Tool 이동 속도 (mm/s)    |
| clamp pressure | 소재 Clamping 압력 (bar) |

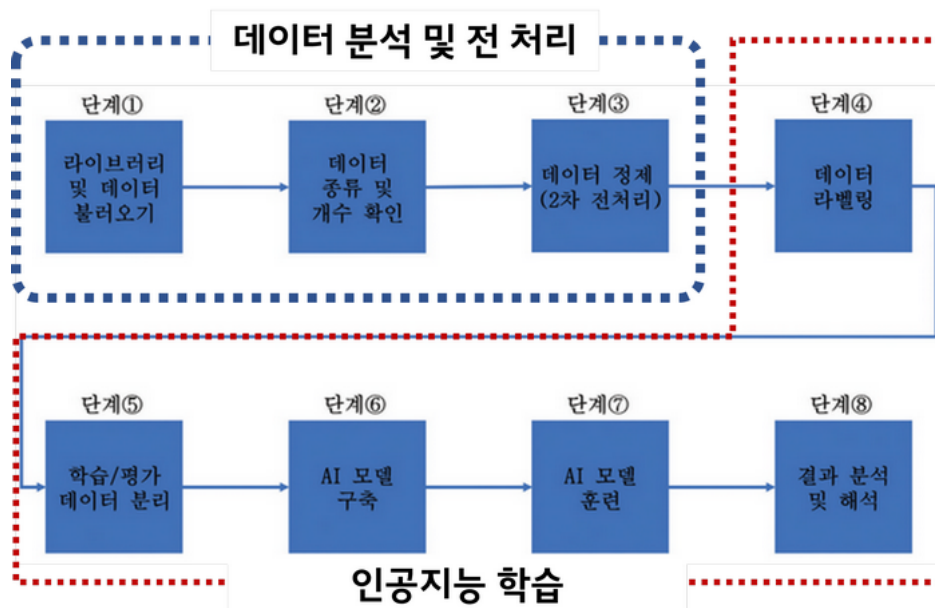
| Output Data              | Description             |
|--------------------------|-------------------------|
| tool condition           | 일정시간 사용한 Tool, 새로운 Tool |
| machine_completed        | 가공 완료 여부                |
| passed_visual_inspection | 육안 검사 결과                |

- 양품/불량품 기준 :

◦ 라벨은 양품, 불량품 2가지이며 분류 기준은 다음과 같다.

| 라벨  | 공정완료 유무<br>(machining_process) | 육안검사 통과 유무<br>(passed_visual_inspection) |
|-----|--------------------------------|------------------------------------------|
| 양품  | O                              | O                                        |
| 불량품 | X                              | X                                        |
|     | O                              | X                                        |

### 3) 분석단계 프로세스



## 2. Import libraries

```
In [1]: import numpy as np
import pandas as pd
import seaborn as sns
import holoviews as hv
from holoviews import opts
hv.extension('bokeh')
from matplotlib import pyplot as plt
from sklearn.model_selection import train_test_split
from sklearn.preprocessing import StandardScaler, LabelEncoder
from sklearn.metrics import accuracy_score, f1_score, roc_auc_score
import os
import glob
from scipy import signal
import lightgbm as lgb
import shap
DIR = "D:\\PKK_Programs\\09_AI_Education\\인공지능-기본과정\\13_KAMP\\CNC_dataset\\tool_wear\\"
```



## 3. Load the Dataset

- Datafiles(csv) list

```
In [2]: csv_path = DIR + "experiment"
print(csv_path)
all_files = glob.glob(csv_path + "\\*.csv")
all_files

Out[2]: D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment
['D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\01.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\02.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\03.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\04.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\05.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\06.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\07.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\08.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\09.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\10.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\11.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\12.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\13.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\14.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\15.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\16.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\17.csv',
'D:\PKK_Programs\09_AI_Education\인공지능-기본과정\13_KAMP\CNC_dataset\tool_wear\experiment\18.csv']
```

- Datafiles(csv) 갯수 확인

```
In [3]: csv_count = len([name for name in os.listdir(csv_path) if os.path.isfile(os.path.join(csv_path, name))])
print(f"experiment_xx.csv 화일갯수:{csv_count}")
```

experiment\_xx.csv 화일갯수 : 18

```
In [4]: csv_count = len([name for name in os.listdir(csv_path) if os.path.isfile(os.path.join(csv_path, name))])
for i in range(1, csv_count + 1):
    #load files
    exp_num = '0' + str(i) if i < 10 else str(i)
    exp_df = pd.read_csv(f"experiment_{exp_num}.csv")

    #print(f"experiment_{exp_num}.csv")
print(f"experiment_xx.csv 화일갯수:{csv_count}")
```

experiment\_xx.csv 화일갯수 : 18

- Train csv(label data) load

```
1) tool_condition: worn(마모), unworn(미마모) </br> 2) machining_finalized: yes(공정완료), no(공정 미완료) </br> 3) passed_visual_inspection : yes(육안검사Pass), no(육안검사 불량), Nan(결측값) </br>
```

- 양품 Case: worn and machining\_finalized(yes) and passed\_visual\_inspection(yes)
- 불량 Case: unworn and machining\_finalized(no) and passed\_visual\_inspection(no)
- 불량 Case: worn and machining\_finalized(yes) and passed\_visual\_inspection(no)

## 4. Pre-processing(Exploratory Data Analysis)

- 4차 산업의 핵심 기술인 빅데이터(Big Data)는 인공지능(AI), 사물인터넷(IoT) 빅 데이터 분석
- 빅 데이터의 복잡한 현상에서 의미 있는 패턴을 찾고, 의사 결정에 필요한 통찰을 데이터 분석이 중요하며

### 1. 확증적 데이터 분석(CDA)



### 2. 탐색적 데이터 분석(EDA)



- 이 데이터 분석에는 크게 두 가지 접근 방법

탐색적 데이터 분석(EDA) 은 우리가 존재하고 있다고 믿는 것들은 실제로 존재하지 않고 믿을 수 있는 발견하려는 태도

존 튜너키 (도서 Doing Data Science 중)

Data에서 추론적 모델을 만들고 확인하는 과정이다(piolla)

### 탐색적 데이터 분석방법

- 탐색적 데이터 분석은 한 번에 완전한 결론에 도달하는 것이 가능한 것이 아니라 반복하여 데이터를 이해하고 종료하는 과정입니다.</br> (1) 데이터에 대한 질문 & 문제 만들기</br> (2) 데이터를 치료하고, 대화하고, 풀어서 그 질문 & 문제에 대한 답을 찾아보기</br> (3) 질문에서 성인이 되어서 다시 질문을 만들고 또 다른 질문 & 문제 만들기</br>
- 이러한 것을 기반으로 데이터에서 흥미있는 패턴이 발견될 때까지, 과정이 더 찾는 것이 가능하다고 생각할 때까지, </br>

- 그래프 등의 요약, 요약 통계를 이용하여 데이터를 전체적으로 살펴보고 개별 속성의 값을 관찰합니다. </br>
- 데이터에서 발견되는 이상치를 찾아내 전체 패턴 데이터에 미치는 영향은 관찰을 하고, </br>
- 속성을 부여하는 관계에서 패턴을 발견합니다.
- 이상값 찾는 방법

1) 개별데이터 관찰 </br> 2) 통계값 활용 </br> 3) 시각화 도구 활용 </br> 4) 머신러닝 활용등 </br>

- <https://eda-ai-lab.tistory.com/13>

```
In [5]: exp_result = pd.read_csv(DIR + "train.csv")
print(f'train.csv : {exp_result.shape}')
exp_result
```

train.csv : (18, 8)

|    | exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection | class |
|----|--------|----------|----------|----------------|----------------|---------------------|--------------------------|-------|
| 0  | 1      | wax      | 6        | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 1  | 2      | wax      | 20       | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 2  | 3      | wax      | 6        | 3.0            | unworn         | yes                 | yes                      | NaN   |
| 3  | 4      | wax      | 6        | 2.5            | unworn         | no                  | NaN                      | NaN   |
| 4  | 5      | wax      | 20       | 3.0            | unworn         | no                  | NaN                      | NaN   |
| 5  | 6      | wax      | 6        | 4.0            | worn           | yes                 | no                       | NaN   |
| 6  | 7      | wax      | 20       | 4.0            | worn           | no                  | NaN                      | NaN   |
| 7  | 8      | wax      | 20       | 4.0            | worn           | yes                 | no                       | NaN   |
| 8  | 9      | wax      | 15       | 4.0            | worn           | yes                 | no                       | NaN   |
| 9  | 10     | wax      | 12       | 4.0            | worn           | yes                 | no                       | NaN   |
| 10 | 11     | wax      | 3        | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 11 | 12     | wax      | 3        | 3.0            | unworn         | yes                 | yes                      | NaN   |
| 12 | 13     | wax      | 3        | 4.0            | worn           | yes                 | yes                      | NaN   |
| 13 | 14     | wax      | 3        | 3.0            | worn           | yes                 | yes                      | NaN   |
| 14 | 15     | wax      | 6        | 3.0            | worn           | yes                 | yes                      | NaN   |
| 15 | 16     | wax      | 20       | 3.0            | worn           | no                  | NaN                      | NaN   |
| 16 | 17     | wax      | 3        | 2.5            | unworn         | yes                 | yes                      | NaN   |
| 17 | 18     | wax      | 3        | 2.5            | worn           | yes                 | yes                      | NaN   |

```
In [6]: exp_result.info()

<class 'pandas.core.frame.DataFrame'>
RangeIndex: 18 entries, 0 to 17
Data columns (total 8 columns):
#   Column              Non-Null Count  Dtype
---  -
0   exp_no              18 non-null    int64
1   material            18 non-null    object
2   feedrate            18 non-null    int64
3   clamp_pressure      18 non-null    float64
4   tool_condition      18 non-null    object
5   machining_finalized 18 non-null    object
6   passed_visual_inspection 14 non-null    object
7   class               0 non-null     float64
dtypes: float64(2), int64(2), object(4)
memory usage: 1.2+ KB
```

```
In [7]: exp_result.describe()
```

Out[7]:

|       | exp_no    | feedrate  | clamp_pressure | class |
|-------|-----------|-----------|----------------|-------|
| count | 18.000000 | 18.000000 | 18.000000      | 0.0   |
| mean  | 9.500000  | 9.722222  | 3.416667       | NaN   |
| std   | 5.338539  | 7.282578  | 0.624264       | NaN   |
| min   | 1.000000  | 3.000000  | 2.500000       | NaN   |
| 25%   | 5.250000  | 3.000000  | 3.000000       | NaN   |
| 50%   | 9.500000  | 6.000000  | 3.500000       | NaN   |
| 75%   | 13.750000 | 18.750000 | 4.000000       | NaN   |
| max   | 18.000000 | 20.000000 | 4.000000       | NaN   |

In [8]:

```
# corr메서드는 각 열 간의 상관 계수를 반환하는 메서드
exp_result.corr(method='pearson', min_periods=1)
```

Out[8]:

|                | exp_no    | feedrate  | clamp_pressure | class |
|----------------|-----------|-----------|----------------|-------|
| exp_no         | 1.000000  | -0.330594 | -0.419202      | NaN   |
| feedrate       | -0.330594 | 1.000000  | 0.337490       | NaN   |
| clamp_pressure | -0.419202 | 0.337490  | 1.000000       | NaN   |
| class          | NaN       | NaN       | NaN            | NaN   |

reload data

In [9]:

```
# fillnan -> 'no'
exp_result['passed_visual_inspection'] = exp_result['passed_visual_inspection'].fillna('no')
exp_result
```

Out[9]:

|    | exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection | class |
|----|--------|----------|----------|----------------|----------------|---------------------|--------------------------|-------|
| 0  | 1      | wax      | 6        | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 1  | 2      | wax      | 20       | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 2  | 3      | wax      | 6        | 3.0            | unworn         | yes                 | yes                      | NaN   |
| 3  | 4      | wax      | 6        | 2.5            | unworn         | no                  | no                       | NaN   |
| 4  | 5      | wax      | 20       | 3.0            | unworn         | no                  | no                       | NaN   |
| 5  | 6      | wax      | 6        | 4.0            | worn           | yes                 | no                       | NaN   |
| 6  | 7      | wax      | 20       | 4.0            | worn           | no                  | no                       | NaN   |
| 7  | 8      | wax      | 20       | 4.0            | worn           | yes                 | no                       | NaN   |
| 8  | 9      | wax      | 15       | 4.0            | worn           | yes                 | no                       | NaN   |
| 9  | 10     | wax      | 12       | 4.0            | worn           | yes                 | no                       | NaN   |
| 10 | 11     | wax      | 3        | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 11 | 12     | wax      | 3        | 3.0            | unworn         | yes                 | yes                      | NaN   |
| 12 | 13     | wax      | 3        | 4.0            | worn           | yes                 | yes                      | NaN   |
| 13 | 14     | wax      | 3        | 3.0            | worn           | yes                 | yes                      | NaN   |
| 14 | 15     | wax      | 6        | 3.0            | worn           | yes                 | yes                      | NaN   |
| 15 | 16     | wax      | 20       | 3.0            | worn           | no                  | no                       | NaN   |
| 16 | 17     | wax      | 3        | 2.5            | unworn         | yes                 | yes                      | NaN   |
| 17 | 18     | wax      | 3        | 2.5            | worn           | yes                 | yes                      | NaN   |

In [10]:

```
exp_result[['tool_condition', 'machining_finalized', 'passed_visual_inspection']]
```

```
Out[10]:
```

|    | tool_condition | machining_finalized | passed_visual_inspection |
|----|----------------|---------------------|--------------------------|
| 0  | unworn         | yes                 | yes                      |
| 1  | unworn         | yes                 | yes                      |
| 2  | unworn         | yes                 | yes                      |
| 3  | unworn         | no                  | no                       |
| 4  | unworn         | no                  | no                       |
| 5  | worn           | yes                 | no                       |
| 6  | worn           | no                  | no                       |
| 7  | worn           | yes                 | no                       |
| 8  | worn           | yes                 | no                       |
| 9  | worn           | yes                 | no                       |
| 10 | unworn         | yes                 | yes                      |
| 11 | unworn         | yes                 | yes                      |
| 12 | worn           | yes                 | yes                      |
| 13 | worn           | yes                 | yes                      |
| 14 | worn           | yes                 | yes                      |
| 15 | worn           | no                  | no                       |
| 16 | unworn         | yes                 | yes                      |
| 17 | worn           | yes                 | yes                      |

```
In [11]: exp_result.loc[exp_result['passed_visual_inspection'].isnull()]
```

```
Out[11]:
```

| exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection | class |
|--------|----------|----------|----------------|----------------|---------------------|--------------------------|-------|
|--------|----------|----------|----------------|----------------|---------------------|--------------------------|-------|

```
In [12]: exp_result['passed_visual_inspection'].isnull().sum()
```

```
Out[12]:
```

0

```
In [13]: exp_result[['tool_condition', 'machining_finalized', 'passed_visual_inspection']]
```

```
Out[13]:
```

|    | tool_condition | machining_finalized | passed_visual_inspection |
|----|----------------|---------------------|--------------------------|
| 0  | unworn         | yes                 | yes                      |
| 1  | unworn         | yes                 | yes                      |
| 2  | unworn         | yes                 | yes                      |
| 3  | unworn         | no                  | no                       |
| 4  | unworn         | no                  | no                       |
| 5  | worn           | yes                 | no                       |
| 6  | worn           | no                  | no                       |
| 7  | worn           | yes                 | no                       |
| 8  | worn           | yes                 | no                       |
| 9  | worn           | yes                 | no                       |
| 10 | unworn         | yes                 | yes                      |
| 11 | unworn         | yes                 | yes                      |
| 12 | worn           | yes                 | yes                      |
| 13 | worn           | yes                 | yes                      |
| 14 | worn           | yes                 | yes                      |
| 15 | worn           | no                  | no                       |
| 16 | unworn         | yes                 | yes                      |
| 17 | worn           | yes                 | yes                      |

```
In [14]: # pass
exp_result.loc[exp_result['passed_visual_inspection'].isnull()]
```

```
Out[14]:
```

| exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection | class |
|--------|----------|----------|----------------|----------------|---------------------|--------------------------|-------|
|--------|----------|----------|----------------|----------------|---------------------|--------------------------|-------|

```
In [15]: exp_result = exp_result.dropna(subset='passed_visual_inspection',axis=0)
exp_result
```



```
Out[15]:
```

|    | exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection | class |
|----|--------|----------|----------|----------------|----------------|---------------------|--------------------------|-------|
| 0  | 1      | wax      | 6        | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 1  | 2      | wax      | 20       | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 2  | 3      | wax      | 6        | 3.0            | unworn         | yes                 | yes                      | NaN   |
| 3  | 4      | wax      | 6        | 2.5            | unworn         | no                  | no                       | NaN   |
| 4  | 5      | wax      | 20       | 3.0            | unworn         | no                  | no                       | NaN   |
| 5  | 6      | wax      | 6        | 4.0            | worn           | yes                 | no                       | NaN   |
| 6  | 7      | wax      | 20       | 4.0            | worn           | no                  | no                       | NaN   |
| 7  | 8      | wax      | 20       | 4.0            | worn           | yes                 | no                       | NaN   |
| 8  | 9      | wax      | 15       | 4.0            | worn           | yes                 | no                       | NaN   |
| 9  | 10     | wax      | 12       | 4.0            | worn           | yes                 | no                       | NaN   |
| 10 | 11     | wax      | 3        | 4.0            | unworn         | yes                 | yes                      | NaN   |
| 11 | 12     | wax      | 3        | 3.0            | unworn         | yes                 | yes                      | NaN   |
| 12 | 13     | wax      | 3        | 4.0            | worn           | yes                 | yes                      | NaN   |
| 13 | 14     | wax      | 3        | 3.0            | worn           | yes                 | yes                      | NaN   |
| 14 | 15     | wax      | 6        | 3.0            | worn           | yes                 | yes                      | NaN   |
| 15 | 16     | wax      | 20       | 3.0            | worn           | no                  | no                       | NaN   |
| 16 | 17     | wax      | 3        | 2.5            | unworn         | yes                 | yes                      | NaN   |
| 17 | 18     | wax      | 3        | 2.5            | worn           | yes                 | yes                      | NaN   |

```
In [16]: exp_result.groupby('tool_condition').count()
```

```
Out[16]:
```

|                | exp_no | material | feedrate | clamp_pressure | machining_finalized | passed_visual_inspection | class |
|----------------|--------|----------|----------|----------------|---------------------|--------------------------|-------|
| tool_condition |        |          |          |                |                     |                          |       |
| unworn         | 8      | 8        | 8        | 8              | 8                   | 8                        | 0     |
| worn           | 10     | 10       | 10       | 10             | 10                  | 10                       | 0     |

```
In [17]: exp_result.groupby(['tool_condition', 'machining_finalized', 'passed_visual_inspection'], as_index=False).count()
```

```
Out[17]:
```

|   | tool_condition | machining_finalized | passed_visual_inspection | exp_no | material | feedrate | clamp_pressure | class |
|---|----------------|---------------------|--------------------------|--------|----------|----------|----------------|-------|
| 0 | unworn         | no                  | no                       | 2      | 2        | 2        | 2              | 0     |
| 1 | unworn         | yes                 | yes                      | 6      | 6        | 6        | 6              | 0     |
| 2 | worn           | no                  | no                       | 2      | 2        | 2        | 2              | 0     |
| 3 | worn           | yes                 | no                       | 4      | 4        | 4        | 4              | 0     |
| 4 | worn           | yes                 | yes                      | 4      | 4        | 4        | 4              | 0     |

```
In [18]: exp_result.groupby('passed_visual_inspection').size()
```

```
Out[18]:
```

| passed_visual_inspection |    |
|--------------------------|----|
| no                       | 8  |
| yes                      | 10 |

dtype: int64

```
In [19]: # defect
exp_result.loc[(exp_result['machining_finalized'] == 'yes') & (exp_result['passed_visual_inspection'] == 'no')]
```

Out[19]:

|  | exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection | class  |
|--|--------|----------|----------|----------------|----------------|---------------------|--------------------------|--------|
|  | 5      | 6        | wax      | 6              | 4.0            | worn                | yes                      | no NaN |
|  | 7      | 8        | wax      | 20             | 4.0            | worn                | yes                      | no NaN |
|  | 8      | 9        | wax      | 15             | 4.0            | worn                | yes                      | no NaN |
|  | 9      | 10       | wax      | 12             | 4.0            | worn                | yes                      | no NaN |

In [20]:

```
exp_result.loc[(exp_result['passed_visual_inspection'] == 'no'), 'class'] = 'defect' #공정완료, 육안검사 불합격
exp_result.loc[(exp_result['machining_finalized'] == 'yes') & (exp_result['passed_visual_inspection'] == 'no'), 'class'] = 'defect' #공정완료, 육안검사 불합격
exp_result.loc[(exp_result['machining_finalized'] == 'yes') & (exp_result['passed_visual_inspection'] == 'yes'), 'class'] = 'pass' #공정완료, 육안검사 합격
exp_result
```

Out[20]:

|  | exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection | class     |
|--|--------|----------|----------|----------------|----------------|---------------------|--------------------------|-----------|
|  | 0      | 1        | wax      | 6              | 4.0            | unworn              | yes                      | pass      |
|  | 1      | 2        | wax      | 20             | 4.0            | unworn              | yes                      | pass      |
|  | 2      | 3        | wax      | 6              | 3.0            | unworn              | yes                      | pass      |
|  | 3      | 4        | wax      | 6              | 2.5            | unworn              | no                       | no defect |
|  | 4      | 5        | wax      | 20             | 3.0            | unworn              | no                       | no defect |
|  | 5      | 6        | wax      | 6              | 4.0            | worn                | yes                      | no defect |
|  | 6      | 7        | wax      | 20             | 4.0            | worn                | no                       | no defect |
|  | 7      | 8        | wax      | 20             | 4.0            | worn                | yes                      | no defect |
|  | 8      | 9        | wax      | 15             | 4.0            | worn                | yes                      | no defect |
|  | 9      | 10       | wax      | 12             | 4.0            | worn                | yes                      | no defect |
|  | 10     | 11       | wax      | 3              | 4.0            | unworn              | yes                      | yes pass  |
|  | 11     | 12       | wax      | 3              | 3.0            | unworn              | yes                      | yes pass  |
|  | 12     | 13       | wax      | 3              | 4.0            | worn                | yes                      | yes pass  |
|  | 13     | 14       | wax      | 3              | 3.0            | worn                | yes                      | yes pass  |
|  | 14     | 15       | wax      | 6              | 3.0            | worn                | yes                      | yes pass  |
|  | 15     | 16       | wax      | 20             | 3.0            | worn                | no                       | no defect |
|  | 16     | 17       | wax      | 3              | 2.5            | unworn              | yes                      | yes pass  |
|  | 17     | 18       | wax      | 3              | 2.5            | worn                | yes                      | yes pass  |

In [21]:

```
exp_result.groupby('class').count()
```

Out[21]:

|        | exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection |
|--------|--------|----------|----------|----------------|----------------|---------------------|--------------------------|
| class  |        |          |          |                |                |                     |                          |
| defect | 8      | 8        | 8        | 8              | 8              | 8                   | 8                        |
| pass   | 10     | 10       | 10       | 10             | 10             | 10                  | 10                       |

In [22]:

```
aa = pd.read_csv(csv_path + "\\experiment_01.csv")
aa.info()
```

```
<class 'pandas.core.frame.DataFrame'>
```

```
RangeIndex: 1055 entries, 0 to 1054
```

```
Data columns (total 48 columns):
```

| #  | Column                    | Non-Null Count | Dtype   |
|----|---------------------------|----------------|---------|
| 0  | X1_ActualPosition         | 1055 non-null  | float64 |
| 1  | X1_ActualVelocity         | 1055 non-null  | float64 |
| 2  | X1_ActualAcceleration     | 1055 non-null  | float64 |
| 3  | X1_CommandPosition        | 1055 non-null  | float64 |
| 4  | X1_CommandVelocity        | 1055 non-null  | float64 |
| 5  | X1_CommandAcceleration    | 1055 non-null  | float64 |
| 6  | X1_CurrentFeedback        | 1055 non-null  | float64 |
| 7  | X1_DCBusVoltage           | 1055 non-null  | float64 |
| 8  | X1_OutputCurrent          | 1055 non-null  | float64 |
| 9  | X1_OutputVoltage          | 1055 non-null  | float64 |
| 10 | X1_OutputPower            | 1055 non-null  | float64 |
| 11 | Y1_ActualPosition         | 1055 non-null  | float64 |
| 12 | Y1_ActualVelocity         | 1055 non-null  | float64 |
| 13 | Y1_ActualAcceleration     | 1055 non-null  | float64 |
| 14 | Y1_CommandPosition        | 1055 non-null  | float64 |
| 15 | Y1_CommandVelocity        | 1055 non-null  | float64 |
| 16 | Y1_CommandAcceleration    | 1055 non-null  | float64 |
| 17 | Y1_CurrentFeedback        | 1055 non-null  | float64 |
| 18 | Y1_DCBusVoltage           | 1055 non-null  | float64 |
| 19 | Y1_OutputCurrent          | 1055 non-null  | float64 |
| 20 | Y1_OutputVoltage          | 1055 non-null  | float64 |
| 21 | Y1_OutputPower            | 1055 non-null  | float64 |
| 22 | Z1_ActualPosition         | 1055 non-null  | float64 |
| 23 | Z1_ActualVelocity         | 1055 non-null  | float64 |
| 24 | Z1_ActualAcceleration     | 1055 non-null  | float64 |
| 25 | Z1_CommandPosition        | 1055 non-null  | float64 |
| 26 | Z1_CommandVelocity        | 1055 non-null  | float64 |
| 27 | Z1_CommandAcceleration    | 1055 non-null  | float64 |
| 28 | Z1_CurrentFeedback        | 1055 non-null  | float64 |
| 29 | Z1_DCBusVoltage           | 1055 non-null  | float64 |
| 30 | Z1_OutputCurrent          | 1055 non-null  | float64 |
| 31 | Z1_OutputVoltage          | 1055 non-null  | float64 |
| 32 | S1_ActualPosition         | 1055 non-null  | float64 |
| 33 | S1_ActualVelocity         | 1055 non-null  | float64 |
| 34 | S1_ActualAcceleration     | 1055 non-null  | float64 |
| 35 | S1_CommandPosition        | 1055 non-null  | float64 |
| 36 | S1_CommandVelocity        | 1055 non-null  | float64 |
| 37 | S1_CommandAcceleration    | 1055 non-null  | float64 |
| 38 | S1_CurrentFeedback        | 1055 non-null  | float64 |
| 39 | S1_DCBusVoltage           | 1055 non-null  | float64 |
| 40 | S1_OutputCurrent          | 1055 non-null  | float64 |
| 41 | S1_OutputVoltage          | 1055 non-null  | float64 |
| 42 | S1_OutputPower            | 1055 non-null  | float64 |
| 43 | S1_SystemInertia          | 1055 non-null  | float64 |
| 44 | M1_CURRENT_PROGRAM_NUMBER | 1055 non-null  | float64 |
| 45 | M1_sequence_number        | 1055 non-null  | float64 |
| 46 | M1_CURRENT_FEEDRATE       | 1055 non-null  | float64 |
| 47 | Machining_Process         | 1055 non-null  | object  |

```
dtypes: float64(47), object(1)
```

```
memory usage: 395.8+ KB
```

```
In [23]:
```

```
frames = []
for i in range(1, csv_count+1):
    #load files
    exp_num = '0' + str(i) if i < 10 else str(i)
    frame = pd.read_csv(csv_path + f"\\experiment_{exp_num}.csv")

    #load each experiment result row
    exp_result_row = exp_result[exp_result['exp_no'] == i]
    frame['exp_no'] = i

    #add experiment settings to features
```

```
frame['material'] = exp_result_row.iloc[0]['material']
frame['feedrate'] = exp_result_row.iloc[0]['feedrate']
frame['clamp_pressure'] = exp_result_row.iloc[0]['clamp_pressure']

#add experiment result to features
frame['tool_condition'] = exp_result_row.iloc[0]['tool_condition']
frame['machining_finalized'] = exp_result_row.iloc[0]['machining_finalized']
frame['passed_visual_inspection'] = exp_result_row.iloc[0]['passed_visual_inspection']

frame['class'] = exp_result_row.iloc[0]['class']

frames.append(frame)

df = pd.concat(frames, ignore_index = True)
df.head()
#df.shape
```

Out[23]:

|   | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | mater: |
|---|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|------------------|-----|---------------------|-------------------|--------|--------|
| 0 | 198.0             | 0.0               | 0.00                  | 198.0              | 0.0                | 0.000000               | 0.18               | 0.0207          | 329.0            | 2.77             | ... | 50.0                | Starting          | 1      |        |
| 1 | 198.0             | -10.8             | -350.00               | 198.0              | -13.6              | -358.000000            | -10.90             | 0.1860          | 328.0            | 23.30            | ... | 50.0                | Prep              | 1      |        |
| 2 | 196.0             | -17.8             | -6.25                 | 196.0              | -17.9              | -0.000095              | -8.59              | 0.1400          | 328.0            | 30.60            | ... | 50.0                | Prep              | 1      |        |
| 3 | 194.0             | -18.0             | 0.00                  | 194.0              | -17.9              | -0.000095              | -6.11              | 0.1300          | 327.0            | 30.30            | ... | 50.0                | Prep              | 1      |        |
| 4 | 193.0             | -17.9             | -18.80                | 192.0              | -17.9              | 0.000095               | -5.70              | 0.1140          | 328.0            | 30.50            | ... | 50.0                | Prep              | 1      |        |

5 rows × 56 columns

In [24]: frames

| Out[24]: |                   |                   |                       |
|----------|-------------------|-------------------|-----------------------|
|          | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration |
| 0        | 198.0             | 0.000             | 0.00                  |
| 1        | 198.0             | -10.800           | -350.00               |
| 2        | 196.0             | -17.800           | -6.25                 |
| 3        | 194.0             | -18.000           | 0.00                  |
| 4        | 193.0             | -17.900           | -18.80                |
| ...      | ...               | ...               | ...                   |
| 1050     | 141.0             | 0.175             | 87.50                 |
| 1051     | 141.0             | -0.150            | -87.50                |
| 1052     | 141.0             | -0.175            | -87.50                |
| 1053     | 141.0             | 0.150             | 87.50                 |
| 1054     | 141.0             | 0.175             | 93.70                 |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 198.0              | 0.0                | 0.000000               |   |
| 1    | 198.0              | -13.6              | -358.000000            |   |
| 2    | 196.0              | -17.9              | -0.000095              |   |
| 3    | 194.0              | -17.9              | -0.000095              |   |
| 4    | 192.0              | -17.9              | 0.000095               |   |
| ...  | ...                | ...                | ...                    |   |
| 1050 | 141.0              | 0.0                | 0.000000               |   |
| 1051 | 141.0              | 0.0                | 0.000000               |   |
| 1052 | 141.0              | 0.0                | 0.000000               |   |
| 1053 | 141.0              | 0.0                | 0.000000               |   |
| 1054 | 141.0              | 0.0                | 0.000000               |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | 0.18               | 0.0207          | 329.0            | 2.77             |   |
| 1    | -10.90             | 0.1860          | 328.0            | 23.30            |   |
| 2    | -8.59              | 0.1400          | 328.0            | 30.60            |   |
| 3    | -6.11              | 0.1300          | 327.0            | 30.30            |   |
| 4    | -5.70              | 0.1140          | 328.0            | 30.50            |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 1050 | -2.84              | 0.0522          | 325.0            | 7.39             |   |
| 1051 | -1.85              | 0.0522          | 325.0            | 2.69             |   |
| 1052 | -2.20              | 0.0527          | 325.0            | 2.22             |   |
| 1053 | -4.02              | 0.0502          | 326.0            | 5.80             |   |
| 1054 | -4.23              | 0.0547          | 329.0            | 5.97             |   |

|      | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
|------|-----|---------------------|-------------------|--------|----------|----------|---|
| 0    | ... | 50.0                | Starting          | 1      | wax      | 6        |   |
| 1    | ... | 50.0                | Prep              | 1      | wax      | 6        |   |
| 2    | ... | 50.0                | Prep              | 1      | wax      | 6        |   |
| 3    | ... | 50.0                | Prep              | 1      | wax      | 6        |   |
| 4    | ... | 50.0                | Prep              | 1      | wax      | 6        |   |
| ...  | ... | ...                 | ...               | ...    | ...      | ...      |   |
| 1050 | ... | 50.0                | end               | 1      | wax      | 6        |   |
| 1051 | ... | 50.0                | end               | 1      | wax      | 6        |   |
| 1052 | ... | 50.0                | end               | 1      | wax      | 6        |   |
| 1053 | ... | 50.0                | end               | 1      | wax      | 6        |   |
| 1054 | ... | 50.0                | end               | 1      | wax      | 6        |   |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 4.0            | unworn         | yes                 |   |
| 1    | 4.0            | unworn         | yes                 |   |
| 2    | 4.0            | unworn         | yes                 |   |
| 3    | 4.0            | unworn         | yes                 |   |
| 4    | 4.0            | unworn         | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 1050 | 4.0            | unworn         | yes                 |   |
| 1051 | 4.0            | unworn         | yes                 |   |
| 1052 | 4.0            | unworn         | yes                 |   |
| 1053 | 4.0            | unworn         | yes                 |   |
| 1054 | 4.0            | unworn         | yes                 |   |

|      | passed_visual_inspection | class |
|------|--------------------------|-------|
| 0    | yes                      | pass  |
| 1    | yes                      | pass  |
| 2    | yes                      | pass  |
| 3    | yes                      | pass  |
| 4    | yes                      | pass  |
| ...  | ...                      | ...   |
| 1050 | yes                      | pass  |

|      |     |      |
|------|-----|------|
| 1051 | yes | pass |
| 1052 | yes | pass |
| 1053 | yes | pass |
| 1054 | yes | pass |

[1055 rows x 56 columns],

|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|------|-------------------|-------------------|-----------------------|---|
| 0    | 198.0             | 0.0               | 0.0                   |   |
| 1    | 198.0             | 0.0               | 0.0                   |   |
| 2    | 198.0             | 0.0               | 0.0                   |   |
| 3    | 198.0             | 0.0               | 0.0                   |   |
| 4    | 198.0             | 0.0               | 0.0                   |   |
| ...  | ...               | ...               | ...                   |   |
| 1663 | 198.0             | 0.0               | 0.0                   |   |
| 1664 | 198.0             | 0.0               | 0.0                   |   |
| 1665 | 198.0             | 0.0               | 0.0                   |   |
| 1666 | 198.0             | 0.0               | 0.0                   |   |
| 1667 | 198.0             | 0.0               | 0.0                   |   |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 198.0              | 0.0                | 0.0                    |   |
| 1    | 198.0              | 0.0                | 0.0                    |   |
| 2    | 198.0              | 0.0                | 0.0                    |   |
| 3    | 198.0              | 0.0                | 0.0                    |   |
| 4    | 198.0              | 0.0                | 0.0                    |   |
| ...  | ...                | ...                | ...                    |   |
| 1663 | 198.0              | 0.0                | 0.0                    |   |
| 1664 | 198.0              | 0.0                | 0.0                    |   |
| 1665 | 198.0              | 0.0                | 0.0                    |   |
| 1666 | 198.0              | 0.0                | 0.0                    |   |
| 1667 | 198.0              | 0.0                | 0.0                    |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | -0.284             | 2.790000e-19    | 329.0            | 0.0              |   |
| 1    | -0.284             | 2.790000e-19    | 329.0            | 0.0              |   |
| 2    | 1.170              | 2.780000e-19    | 325.0            | 0.0              |   |
| 3    | -0.230             | 2.790000e-19    | 329.0            | 0.0              |   |
| 4    | -0.230             | 2.790000e-19    | 329.0            | 0.0              |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 1663 | -0.638             | 2.790000e-19    | 328.0            | 0.0              |   |
| 1664 | 1.450              | 2.780000e-19    | 325.0            | 0.0              |   |
| 1665 | 0.208              | 2.790000e-19    | 329.0            | 0.0              |   |
| 1666 | 0.208              | 2.790000e-19    | 329.0            | 0.0              |   |
| 1667 | 0.884              | 2.780000e-19    | 325.0            | 0.0              |   |

|      | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W   |
|------|---------------------|-------------------|--------|----------|----------|-----|
| 0    | ...                 | 50.0              | Prep   | 2        | wax      | 20  |
| 1    | ...                 | 50.0              | Prep   | 2        | wax      | 20  |
| 2    | ...                 | 50.0              | Prep   | 2        | wax      | 20  |
| 3    | ...                 | 50.0              | Prep   | 2        | wax      | 20  |
| 4    | ...                 | 50.0              | Prep   | 2        | wax      | 20  |
| ...  | ...                 | ...               | ...    | ...      | ...      | ... |
| 1663 | ...                 | 50.0              | End    | 2        | wax      | 20  |
| 1664 | ...                 | 50.0              | End    | 2        | wax      | 20  |
| 1665 | ...                 | 50.0              | End    | 2        | wax      | 20  |
| 1666 | ...                 | 50.0              | End    | 2        | wax      | 20  |
| 1667 | ...                 | 50.0              | End    | 2        | wax      | 20  |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 4.0            | unworn         | yes                 |   |
| 1    | 4.0            | unworn         | yes                 |   |
| 2    | 4.0            | unworn         | yes                 |   |
| 3    | 4.0            | unworn         | yes                 |   |
| 4    | 4.0            | unworn         | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 1663 | 4.0            | unworn         | yes                 |   |
| 1664 | 4.0            | unworn         | yes                 |   |
| 1665 | 4.0            | unworn         | yes                 |   |
| 1666 | 4.0            | unworn         | yes                 |   |
| 1667 | 4.0            | unworn         | yes                 |   |

|   | passed_visual_inspection | class |
|---|--------------------------|-------|
| 0 | yes                      | pass  |

|      |     |      |
|------|-----|------|
| 1    | yes | pass |
| 2    | yes | pass |
| 3    | yes | pass |
| 4    | yes | pass |
| ...  | ... | ...  |
| 1663 | yes | pass |
| 1664 | yes | pass |
| 1665 | yes | pass |
| 1666 | yes | pass |
| 1667 | yes | pass |

[1668 rows x 56 columns].

|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|------|-------------------|-------------------|-----------------------|---|
| 0    | 198.0             | -0.025            | -12.50                |   |
| 1    | 198.0             | 0.025             | 18.80                 |   |
| 2    | 198.0             | 0.025             | 6.25                  |   |
| 3    | 198.0             | 0.000             | 6.25                  |   |
| 4    | 198.0             | 0.000             | -6.25                 |   |
| ...  | ...               | ...               | ...                   |   |
| 1516 | 198.0             | -0.050            | -18.80                |   |
| 1517 | 198.0             | 0.025             | 18.80                 |   |
| 1518 | 198.0             | 0.000             | -6.25                 |   |
| 1519 | 198.0             | 0.000             | 0.00                  |   |
| 1520 | 198.0             | 0.000             | 6.25                  |   |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 198.0              | 0.0                | 0.0                    |   |
| 1    | 198.0              | 0.0                | 0.0                    |   |
| 2    | 198.0              | 0.0                | 0.0                    |   |
| 3    | 198.0              | 0.0                | 0.0                    |   |
| 4    | 198.0              | 0.0                | 0.0                    |   |
| ...  | ...                | ...                | ...                    |   |
| 1516 | 198.0              | 0.0                | 0.0                    |   |
| 1517 | 198.0              | 0.0                | 0.0                    |   |
| 1518 | 198.0              | 0.0                | 0.0                    |   |
| 1519 | 198.0              | 0.0                | 0.0                    |   |
| 1520 | 198.0              | 0.0                | 0.0                    |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | 0.340              | 0.0252          | 330.0            | 0.576            |   |
| 1    | -0.459             | 0.0226          | 329.0            | 1.790            |   |
| 2    | -0.459             | 0.0170          | 329.0            | 0.929            |   |
| 3    | 0.659              | 0.0171          | 329.0            | 1.360            |   |
| 4    | -1.420             | 0.0222          | 329.0            | 2.660            |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 1516 | -0.779             | 0.0212          | 329.0            | 1.670            |   |
| 1517 | -0.140             | 0.0150          | 329.0            | 0.964            |   |
| 1518 | -0.939             | 0.0195          | 329.0            | 1.620            |   |
| 1519 | -2.060             | 0.0288          | 329.0            | 4.040            |   |
| 1520 | -1.420             | 0.0188          | 329.0            | 1.910            |   |

|      | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W   |
|------|---------------------|-------------------|--------|----------|----------|-----|
| 0    | ...                 | 6.0               | Prep   | 3        | wax      | 6   |
| 1    | ...                 | 6.0               | Prep   | 3        | wax      | 6   |
| 2    | ...                 | 6.0               | Prep   | 3        | wax      | 6   |
| 3    | ...                 | 6.0               | Prep   | 3        | wax      | 6   |
| 4    | ...                 | 6.0               | Prep   | 3        | wax      | 6   |
| ...  | ...                 | ...               | ...    | ...      | ...      | ... |
| 1516 | ...                 | 6.0               | End    | 3        | wax      | 6   |
| 1517 | ...                 | 6.0               | End    | 3        | wax      | 6   |
| 1518 | ...                 | 6.0               | End    | 3        | wax      | 6   |
| 1519 | ...                 | 6.0               | End    | 3        | wax      | 6   |
| 1520 | ...                 | 6.0               | End    | 3        | wax      | 6   |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 3.0            | unworn         | yes                 |   |
| 1    | 3.0            | unworn         | yes                 |   |
| 2    | 3.0            | unworn         | yes                 |   |
| 3    | 3.0            | unworn         | yes                 |   |
| 4    | 3.0            | unworn         | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 1516 | 3.0            | unworn         | yes                 |   |
| 1517 | 3.0            | unworn         | yes                 |   |

|      |     |        |     |
|------|-----|--------|-----|
| 1518 | 3.0 | unworn | yes |
| 1519 | 3.0 | unworn | yes |
| 1520 | 3.0 | unworn | yes |

|      | passed_visual_inspection | class |
|------|--------------------------|-------|
| 0    | yes                      | pass  |
| 1    | yes                      | pass  |
| 2    | yes                      | pass  |
| 3    | yes                      | pass  |
| 4    | yes                      | pass  |
| ...  | ...                      | ...   |
| 1516 | yes                      | pass  |
| 1517 | yes                      | pass  |
| 1518 | yes                      | pass  |
| 1519 | yes                      | pass  |
| 1520 | yes                      | pass  |

[1521 rows x 56 columns],

|     | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|-----|-------------------|-------------------|-----------------------|---|
| 0   | 198.0             | 0.025             | 6.25                  |   |
| 1   | 198.0             | 0.000             | 0.00                  |   |
| 2   | 198.0             | 0.000             | 0.00                  |   |
| 3   | 198.0             | 0.025             | 6.25                  |   |
| 4   | 198.0             | -0.025            | -6.25                 |   |
| ..  | ...               | ...               | ...                   |   |
| 527 | 198.0             | 0.025             | 12.50                 |   |
| 528 | 198.0             | 0.000             | 0.00                  |   |
| 529 | 198.0             | 0.025             | 12.50                 |   |
| 530 | 198.0             | 0.025             | 12.50                 |   |
| 531 | 198.0             | 0.000             | -6.25                 |   |

|     | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|-----|--------------------|--------------------|------------------------|---|
| 0   | 198.0              | 0.0                | 0.0                    |   |
| 1   | 198.0              | 0.0                | 0.0                    |   |
| 2   | 198.0              | 0.0                | 0.0                    |   |
| 3   | 198.0              | 0.0                | 0.0                    |   |
| 4   | 198.0              | 0.0                | 0.0                    |   |
| ..  | ...                | ...                | ...                    |   |
| 527 | 198.0              | 0.0                | 0.0                    |   |
| 528 | 198.0              | 0.0                | 0.0                    |   |
| 529 | 198.0              | 0.0                | 0.0                    |   |
| 530 | 198.0              | 0.0                | 0.0                    |   |
| 531 | 198.0              | 0.0                | 0.0                    |   |

|     | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|-----|--------------------|-----------------|------------------|------------------|---|
| 0   | -1.420             | 0.0219          | 328.0            | 0.557            |   |
| 1   | -1.900             | 0.0206          | 329.0            | 1.920            |   |
| 2   | -2.060             | 0.0237          | 329.0            | 1.810            |   |
| 3   | -2.220             | 0.0225          | 329.0            | 1.870            |   |
| 4   | 0.499              | 0.0260          | 329.0            | 1.790            |   |
| ..  | ...                | ...             | ...              | ...              |   |
| 527 | 0.819              | 0.0182          | 329.0            | 1.990            |   |
| 528 | -0.140             | 0.0209          | 329.0            | 0.916            |   |
| 529 | 0.180              | 0.0172          | 329.0            | 0.926            |   |
| 530 | 0.020              | 0.0203          | 329.0            | 1.280            |   |
| 531 | -0.140             | 0.0185          | 329.0            | 1.140            |   |

|     | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W   |
|-----|---------------------|-------------------|--------|----------|----------|-----|
| 0   | ...                 | 50.0              | Prep   | 4        | wax      | 6   |
| 1   | ...                 | 50.0              | Prep   | 4        | wax      | 6   |
| 2   | ...                 | 50.0              | Prep   | 4        | wax      | 6   |
| 3   | ...                 | 50.0              | Prep   | 4        | wax      | 6   |
| 4   | ...                 | 50.0              | Prep   | 4        | wax      | 6   |
| ..  | ...                 | ...               | ...    | ...      | ...      | ... |
| 527 | ...                 | 6.0               | End    | 4        | wax      | 6   |
| 528 | ...                 | 6.0               | End    | 4        | wax      | 6   |
| 529 | ...                 | 6.0               | End    | 4        | wax      | 6   |
| 530 | ...                 | 6.0               | End    | 4        | wax      | 6   |
| 531 | ...                 | 6.0               | End    | 4        | wax      | 6   |

|   | clamp_pressure | tool_condition | machining_finalized | W |
|---|----------------|----------------|---------------------|---|
| 0 | 2.5            | unworn         | no                  |   |
| 1 | 2.5            | unworn         | no                  |   |



|     |     |        |     |
|-----|-----|--------|-----|
| 2   | 2.5 | unworn | no  |
| 3   | 2.5 | unworn | no  |
| 4   | 2.5 | unworn | no  |
| ..  | ... | ...    | ... |
| 527 | 2.5 | unworn | no  |
| 528 | 2.5 | unworn | no  |
| 529 | 2.5 | unworn | no  |
| 530 | 2.5 | unworn | no  |
| 531 | 2.5 | unworn | no  |

|     | passed_visual_inspection | class  |
|-----|--------------------------|--------|
| 0   | no                       | defect |
| 1   | no                       | defect |
| 2   | no                       | defect |
| 3   | no                       | defect |
| 4   | no                       | defect |
| ..  | ...                      | ...    |
| 527 | no                       | defect |
| 528 | no                       | defect |
| 529 | no                       | defect |
| 530 | no                       | defect |
| 531 | no                       | defect |

[532 rows x 56 columns],

|     | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|-----|-------------------|-------------------|-----------------------|---|
| 0   | 198.0             | 0.000             | 0.00                  |   |
| 1   | 198.0             | 0.000             | 0.00                  |   |
| 2   | 198.0             | 0.000             | 0.00                  |   |
| 3   | 198.0             | 0.025             | 12.50                 |   |
| 4   | 198.0             | -0.025            | -12.50                |   |
| ..  | ...               | ...               | ...                   |   |
| 457 | 152.0             | 0.000             | 0.00                  |   |
| 458 | 152.0             | 0.000             | 0.00                  |   |
| 459 | 152.0             | 0.050             | 18.80                 |   |
| 460 | 152.0             | 0.000             | -6.25                 |   |
| 461 | 152.0             | 0.000             | 6.25                  |   |

|     | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|-----|--------------------|--------------------|------------------------|---|
| 0   | 198.0              | 0.0                | 0.0                    |   |
| 1   | 198.0              | 0.0                | 0.0                    |   |
| 2   | 198.0              | 0.0                | 0.0                    |   |
| 3   | 198.0              | 0.0                | 0.0                    |   |
| 4   | 198.0              | 0.0                | 0.0                    |   |
| ..  | ...                | ...                | ...                    |   |
| 457 | 152.0              | 0.0                | 0.0                    |   |
| 458 | 152.0              | 0.0                | 0.0                    |   |
| 459 | 152.0              | 0.0                | 0.0                    |   |
| 460 | 152.0              | 0.0                | 0.0                    |   |
| 461 | 152.0              | 0.0                | 0.0                    |   |

|     | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|-----|--------------------|-----------------|------------------|------------------|---|
| 0   | -0.620             | 0.0194          | 327.0            | 0.709            |   |
| 1   | -0.779             | 0.0198          | 328.0            | 1.040            |   |
| 2   | 0.979              | 0.0192          | 327.0            | 2.620            |   |
| 3   | -0.779             | 0.0179          | 327.0            | 1.840            |   |
| 4   | -1.260             | 0.0164          | 328.0            | 1.350            |   |
| ..  | ...                | ...             | ...              | ...              |   |
| 457 | 0.555              | 0.0226          | 327.0            | 2.220            |   |
| 458 | 1.670              | 0.0268          | 327.0            | 3.000            |   |
| 459 | 0.544              | 0.0274          | 327.0            | 1.510            |   |
| 460 | 1.100              | 0.0275          | 327.0            | 1.900            |   |
| 461 | 0.507              | 0.0192          | 327.0            | 0.363            |   |

|     | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
|-----|-----|---------------------|-------------------|--------|----------|----------|---|
| 0   | ... | 6.0                 | Prep              | 5      | wax      | 20       |   |
| 1   | ... | 6.0                 | Prep              | 5      | wax      | 20       |   |
| 2   | ... | 6.0                 | Prep              | 5      | wax      | 20       |   |
| 3   | ... | 6.0                 | Prep              | 5      | wax      | 20       |   |
| 4   | ... | 6.0                 | Prep              | 5      | wax      | 20       |   |
| ..  | ... | ...                 | ...               | ...    | ...      | ...      |   |
| 457 | ... | 50.0                | End               | 5      | wax      | 20       |   |
| 458 | ... | 50.0                | End               | 5      | wax      | 20       |   |
| 459 | ... | 50.0                | End               | 5      | wax      | 20       |   |

|     |     |      |     |   |     |    |
|-----|-----|------|-----|---|-----|----|
| 460 | ... | 50.0 | End | 5 | wax | 20 |
| 461 | ... | 50.0 | End | 5 | wax | 20 |

|     | clamp_pressure | tool_condition | machining_finalized | W |
|-----|----------------|----------------|---------------------|---|
| 0   | 3.0            | unworn         | no                  |   |
| 1   | 3.0            | unworn         | no                  |   |
| 2   | 3.0            | unworn         | no                  |   |
| 3   | 3.0            | unworn         | no                  |   |
| 4   | 3.0            | unworn         | no                  |   |
| ... | ...            | ...            | ...                 |   |
| 457 | 3.0            | unworn         | no                  |   |
| 458 | 3.0            | unworn         | no                  |   |
| 459 | 3.0            | unworn         | no                  |   |
| 460 | 3.0            | unworn         | no                  |   |
| 461 | 3.0            | unworn         | no                  |   |

|     | passed_visual_inspection | class     |
|-----|--------------------------|-----------|
| 0   |                          | no defect |
| 1   |                          | no defect |
| 2   |                          | no defect |
| 3   |                          | no defect |
| 4   |                          | no defect |
| ... | ...                      | ...       |
| 457 |                          | no defect |
| 458 |                          | no defect |
| 459 |                          | no defect |
| 460 |                          | no defect |
| 461 |                          | no defect |

[462 rows x 56 columns],

|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|------|-------------------|-------------------|-----------------------|---|
| 0    | 198.0             | 0.000             | 6.25                  |   |
| 1    | 198.0             | 0.025             | 18.80                 |   |
| 2    | 198.0             | 0.000             | 12.50                 |   |
| 3    | 198.0             | 0.000             | 0.00                  |   |
| 4    | 198.0             | 0.000             | 0.00                  |   |
| ...  | ...               | ...               | ...                   |   |
| 1291 | 143.0             | -5.720            | -12.50                |   |
| 1292 | 143.0             | -5.350            | 18.80                 |   |
| 1293 | 142.0             | -4.550            | -12.50                |   |
| 1294 | 142.0             | -3.550            | -25.00                |   |
| 1295 | 142.0             | -2.250            | 12.50                 |   |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 198.0              | 0.00               | 0.00                   |   |
| 1    | 198.0              | 0.00               | 0.00                   |   |
| 2    | 198.0              | 0.00               | 0.00                   |   |
| 3    | 198.0              | 0.00               | 0.00                   |   |
| 4    | 198.0              | 0.00               | 0.00                   |   |
| ...  | ...                | ...                | ...                    |   |
| 1291 | 143.0              | -5.78              | 3.64                   |   |
| 1292 | 143.0              | -5.26              | 6.56                   |   |
| 1293 | 142.0              | -4.47              | 9.13                   |   |
| 1294 | 142.0              | -3.44              | 11.20                  |   |
| 1295 | 142.0              | -2.24              | 12.70                  |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | -1.100             | 0.0191          | 328.0            | 1.670            |   |
| 1    | 0.499              | 0.0211          | 328.0            | 1.540            |   |
| 2    | 1.140              | 0.0170          | 328.0            | 2.320            |   |
| 3    | -0.300             | 0.0152          | 328.0            | 0.812            |   |
| 4    | -0.459             | 0.0237          | 328.0            | 1.120            |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 1291 | -4.800             | 0.1010          | 324.0            | 13.900           |   |
| 1292 | -5.640             | 0.0948          | 324.0            | 12.500           |   |
| 1293 | -5.730             | 0.1040          | 324.0            | 10.500           |   |
| 1294 | -5.690             | 0.1010          | 324.0            | 10.100           |   |
| 1295 | -6.730             | 0.1040          | 324.0            | 7.740            |   |

|   | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
|---|---------------------|-------------------|--------|----------|----------|---|
| 0 | ...                 | 50.0              | Prep   | 6        | wax      | 6 |
| 1 | ...                 | 50.0              | Prep   | 6        | wax      | 6 |
| 2 | ...                 | 50.0              | Prep   | 6        | wax      | 6 |

|      |     |      |      |     |     |     |
|------|-----|------|------|-----|-----|-----|
| 3    | ... | 50.0 | Prep | 6   | wax | 6   |
| 4    | ... | 50.0 | Prep | 6   | wax | 6   |
| ...  | ... | ...  | ...  | ... | ... | ... |
| 1291 | ... | 6.0  | End  | 6   | wax | 6   |
| 1292 | ... | 6.0  | End  | 6   | wax | 6   |
| 1293 | ... | 6.0  | End  | 6   | wax | 6   |
| 1294 | ... | 6.0  | End  | 6   | wax | 6   |
| 1295 | ... | 6.0  | End  | 6   | wax | 6   |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 4.0            | worn           | yes                 |   |
| 1    | 4.0            | worn           | yes                 |   |
| 2    | 4.0            | worn           | yes                 |   |
| 3    | 4.0            | worn           | yes                 |   |
| 4    | 4.0            | worn           | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 1291 | 4.0            | worn           | yes                 |   |
| 1292 | 4.0            | worn           | yes                 |   |
| 1293 | 4.0            | worn           | yes                 |   |
| 1294 | 4.0            | worn           | yes                 |   |
| 1295 | 4.0            | worn           | yes                 |   |

|      | passed_visual_inspection | class  |
|------|--------------------------|--------|
| 0    | no                       | defect |
| 1    | no                       | defect |
| 2    | no                       | defect |
| 3    | no                       | defect |
| 4    | no                       | defect |
| ...  | ...                      | ...    |
| 1291 | no                       | defect |
| 1292 | no                       | defect |
| 1293 | no                       | defect |
| 1294 | no                       | defect |
| 1295 | no                       | defect |

[1296 rows x 56 columns],

|     | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|-----|-------------------|-------------------|-----------------------|---|
| 0   | 198.0             | 0.000             | 0.0                   |   |
| 1   | 198.0             | 0.050             | 31.3                  |   |
| 2   | 198.0             | 0.000             | 0.0                   |   |
| 3   | 198.0             | 0.000             | 0.0                   |   |
| 4   | 198.0             | 0.000             | 0.0                   |   |
| ... | ...               | ...               | ...                   |   |
| 560 | 198.0             | -0.025            | -12.5                 |   |
| 561 | 198.0             | -0.050            | -12.5                 |   |
| 562 | 198.0             | -0.025            | -12.5                 |   |
| 563 | 198.0             | -0.025            | -25.0                 |   |
| 564 | 198.0             | 0.075             | 37.5                  |   |

|     | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|-----|--------------------|--------------------|------------------------|---|
| 0   | 198.0              | 0.0                | 0.0                    |   |
| 1   | 198.0              | 0.0                | 0.0                    |   |
| 2   | 198.0              | 0.0                | 0.0                    |   |
| 3   | 198.0              | 0.0                | 0.0                    |   |
| 4   | 198.0              | 0.0                | 0.0                    |   |
| ... | ...                | ...                | ...                    |   |
| 560 | 198.0              | 0.0                | 0.0                    |   |
| 561 | 198.0              | 0.0                | 0.0                    |   |
| 562 | 198.0              | 0.0                | 0.0                    |   |
| 563 | 198.0              | 0.0                | 0.0                    |   |
| 564 | 198.0              | 0.0                | 0.0                    |   |

|     | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|-----|--------------------|-----------------|------------------|------------------|---|
| 0   | -1.420             | 0.0227          | 327.0            | 0.355            |   |
| 1   | -1.740             | 0.0224          | 327.0            | 0.589            |   |
| 2   | 0.180              | 0.0329          | 327.0            | 2.190            |   |
| 3   | -0.619             | 0.0198          | 327.0            | 1.010            |   |
| 4   | -0.779             | 0.0311          | 327.0            | 0.372            |   |
| ... | ...                | ...             | ...              | ...              |   |
| 560 | -0.941             | 0.0215          | 328.0            | 1.790            |   |
| 561 | -0.780             | 0.0202          | 328.0            | 1.070            |   |
| 562 | 0.501              | 0.0190          | 328.0            | 0.990            |   |
| 563 | -0.298             | 0.0193          | 328.0            | 1.370            |   |

|     |     |                     |                   |        |          |          |
|-----|-----|---------------------|-------------------|--------|----------|----------|
| 564 |     | 0.340               |                   | 0.0258 | 328.0    | 1.090    |
|     | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate |
| 0   | ... | 50.0                | Prep              | 7      | wax      | 20       |
| 1   | ... | 50.0                | Prep              | 7      | wax      | 20       |
| 2   | ... | 50.0                | Prep              | 7      | wax      | 20       |
| 3   | ... | 50.0                | Prep              | 7      | wax      | 20       |
| 4   | ... | 50.0                | Prep              | 7      | wax      | 20       |
| ..  | ... | ...                 | ...               | ...    | ...      | ...      |
| 560 | ... | 20.0                | End               | 7      | wax      | 20       |
| 561 | ... | 20.0                | End               | 7      | wax      | 20       |
| 562 | ... | 20.0                | End               | 7      | wax      | 20       |
| 563 | ... | 20.0                | End               | 7      | wax      | 20       |
| 564 | ... | 20.0                | End               | 7      | wax      | 20       |

|     |                |                |                     |   |
|-----|----------------|----------------|---------------------|---|
|     | clamp_pressure | tool_condition | machining_finalized | W |
| 0   | 4.0            | worn           | no                  |   |
| 1   | 4.0            | worn           | no                  |   |
| 2   | 4.0            | worn           | no                  |   |
| 3   | 4.0            | worn           | no                  |   |
| 4   | 4.0            | worn           | no                  |   |
| ..  | ...            | ...            | ...                 |   |
| 560 | 4.0            | worn           | no                  |   |
| 561 | 4.0            | worn           | no                  |   |
| 562 | 4.0            | worn           | no                  |   |
| 563 | 4.0            | worn           | no                  |   |
| 564 | 4.0            | worn           | no                  |   |

|     |                          |        |
|-----|--------------------------|--------|
|     | passed_visual_inspection | class  |
| 0   | no                       | defect |
| 1   | no                       | defect |
| 2   | no                       | defect |
| 3   | no                       | defect |
| 4   | no                       | defect |
| ..  | ...                      | ...    |
| 560 | no                       | defect |
| 561 | no                       | defect |
| 562 | no                       | defect |
| 563 | no                       | defect |
| 564 | no                       | defect |

[565 rows x 56 columns],

|     |                   |                   |                       |   |
|-----|-------------------|-------------------|-----------------------|---|
|     | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
| 0   | 144.0             | 3.850             | 188.00                |   |
| 1   | 145.0             | 12.600            | -56.30                |   |
| 2   | 147.0             | 18.600            | -18.80                |   |
| 3   | 148.0             | 6.280             | 1440.00               |   |
| 4   | 150.0             | 20.000            | -6.25                 |   |
| ..  | ...               | ...               | ...                   |   |
| 600 | 198.0             | 0.025             | 6.25                  |   |
| 601 | 198.0             | -0.100            | -43.80                |   |
| 602 | 198.0             | -0.025            | -12.50                |   |
| 603 | 198.0             | -0.050            | -18.80                |   |
| 604 | 198.0             | 0.000             | 6.25                  |   |

|     |                    |                    |                        |   |
|-----|--------------------|--------------------|------------------------|---|
|     | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
| 0   | 144.0              | 4.69               | 98.2                   |   |
| 1   | 145.0              | 13.50              | 75.0                   |   |
| 2   | 147.0              | 18.90              | 33.2                   |   |
| 3   | 148.0              | 14.00              | 1000.0                 |   |
| 4   | 150.0              | 20.00              | 0.0                    |   |
| ..  | ...                | ...                | ...                    |   |
| 600 | 198.0              | 0.00               | 0.0                    |   |
| 601 | 198.0              | 0.00               | 0.0                    |   |
| 602 | 198.0              | 0.00               | 0.0                    |   |
| 603 | 198.0              | 0.00               | 0.0                    |   |
| 604 | 198.0              | 0.00               | 0.0                    |   |

|   |                    |                 |                  |                  |   |
|---|--------------------|-----------------|------------------|------------------|---|
|   | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
| 0 | 5.770              | 0.1070          | 324.0            | 13.000           |   |
| 1 | 7.680              | 0.1320          | 324.0            | 25.900           |   |
| 2 | 6.020              | 0.1030          | 324.0            | 30.100           |   |
| 3 | 24.400             | 0.3140          | 325.0            | 26.100           |   |

|     |        |        |       |        |
|-----|--------|--------|-------|--------|
| 4   | 5.070  | 0.1200 | 324.0 | 34.900 |
| ... | ...    | ...    | ...   | ...    |
| 600 | 0.821  | 0.0166 | 327.0 | 1.890  |
| 601 | 0.020  | 0.0196 | 328.0 | 0.745  |
| 602 | -0.619 | 0.0177 | 328.0 | 1.370  |
| 603 | -1.740 | 0.0194 | 327.0 | 1.520  |
| 604 | -0.939 | 0.0224 | 327.0 | 0.669  |

|     | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W   |
|-----|---------------------|-------------------|--------|----------|----------|-----|
| 0   | ...                 | 20.0              | Prep   | 8        | wax      | 20  |
| 1   | ...                 | 20.0              | Prep   | 8        | wax      | 20  |
| 2   | ...                 | 20.0              | Prep   | 8        | wax      | 20  |
| 3   | ...                 | 20.0              | Prep   | 8        | wax      | 20  |
| 4   | ...                 | 20.0              | Prep   | 8        | wax      | 20  |
| ... | ...                 | ...               | ...    | ...      | ...      | ... |
| 600 | ...                 | 20.0              | End    | 8        | wax      | 20  |
| 601 | ...                 | 20.0              | End    | 8        | wax      | 20  |
| 602 | ...                 | 20.0              | End    | 8        | wax      | 20  |
| 603 | ...                 | 20.0              | End    | 8        | wax      | 20  |
| 604 | ...                 | 20.0              | End    | 8        | wax      | 20  |

|     | clamp_pressure | tool_condition | machining_finalized | W   |
|-----|----------------|----------------|---------------------|-----|
| 0   | 4.0            | worn           | yes                 |     |
| 1   | 4.0            | worn           | yes                 |     |
| 2   | 4.0            | worn           | yes                 |     |
| 3   | 4.0            | worn           | yes                 |     |
| 4   | 4.0            | worn           | yes                 |     |
| ... | ...            | ...            | ...                 | ... |
| 600 | 4.0            | worn           | yes                 |     |
| 601 | 4.0            | worn           | yes                 |     |
| 602 | 4.0            | worn           | yes                 |     |
| 603 | 4.0            | worn           | yes                 |     |
| 604 | 4.0            | worn           | yes                 |     |

|     | passed_visual_inspection | class     |
|-----|--------------------------|-----------|
| 0   |                          | no defect |
| 1   |                          | no defect |
| 2   |                          | no defect |
| 3   |                          | no defect |
| 4   |                          | no defect |
| ... | ...                      | ...       |
| 600 |                          | no defect |
| 601 |                          | no defect |
| 602 |                          | no defect |
| 603 |                          | no defect |
| 604 |                          | no defect |

[605 rows x 56 columns],

|     | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W      |
|-----|-------------------|-------------------|-----------------------|--------|
| 0   | 152.0             | -15.100           |                       | 18.80  |
| 1   | 151.0             | -15.100           |                       | -68.70 |
| 2   | 149.0             | -14.900           |                       | 125.00 |
| 3   | 148.0             | -14.700           |                       | 113.00 |
| 4   | 146.0             | -14.800           |                       | 25.00  |
| ... | ...               | ...               | ...                   | ...    |
| 735 | 162.0             | -0.025            |                       | -18.80 |
| 736 | 162.0             | -0.025            |                       | -18.80 |
| 737 | 162.0             | -0.050            |                       | -25.00 |
| 738 | 162.0             | -0.075            |                       | -37.50 |
| 739 | 162.0             | 0.000             |                       | -6.25  |

|     | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W   |
|-----|--------------------|--------------------|------------------------|-----|
| 0   | 152.0              | -15.0              |                        | 0.0 |
| 1   | 151.0              | -15.0              |                        | 0.0 |
| 2   | 149.0              | -15.0              |                        | 0.0 |
| 3   | 148.0              | -15.0              |                        | 0.0 |
| 4   | 146.0              | -15.0              |                        | 0.0 |
| ... | ...                | ...                | ...                    | ... |
| 735 | 162.0              | 0.0                |                        | 0.0 |
| 736 | 162.0              | 0.0                |                        | 0.0 |
| 737 | 162.0              | 0.0                |                        | 0.0 |
| 738 | 162.0              | 0.0                |                        | 0.0 |
| 739 | 162.0              | 0.0                |                        | 0.0 |

|     | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|-----|--------------------|-----------------|------------------|------------------|---|
| 0   | -6.07              | 0.1030          | 324.0            | 26.30            |   |
| 1   | -6.29              | 0.0941          | 324.0            | 26.40            |   |
| 2   | -5.31              | 0.1240          | 324.0            | 26.90            |   |
| 3   | -7.06              | 0.1310          | 324.0            | 26.70            |   |
| 4   | -10.70             | 0.1430          | 324.0            | 25.10            |   |
| ... | ...                | ...             | ...              | ...              |   |
| 735 | 3.88               | 0.0546          | 324.0            | 1.04             |   |
| 736 | 1.66               | 0.0584          | 324.0            | 4.08             |   |
| 737 | 2.22               | 0.0573          | 324.0            | 3.23             |   |
| 738 | 2.21               | 0.0598          | 325.0            | 3.16             |   |
| 739 | 2.48               | 0.0582          | 324.0            | 2.12             |   |

|     | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W   |
|-----|---------------------|-------------------|--------|----------|----------|-----|
| 0   | ...                 | 15.0              | Prep   | 9        | wax      | 15  |
| 1   | ...                 | 15.0              | Prep   | 9        | wax      | 15  |
| 2   | ...                 | 15.0              | Prep   | 9        | wax      | 15  |
| 3   | ...                 | 15.0              | Prep   | 9        | wax      | 15  |
| 4   | ...                 | 15.0              | Prep   | 9        | wax      | 15  |
| ... | ...                 | ...               | ...    | ...      | ...      | ... |
| 735 | ...                 | 15.0              | End    | 9        | wax      | 15  |
| 736 | ...                 | 15.0              | End    | 9        | wax      | 15  |
| 737 | ...                 | 15.0              | End    | 9        | wax      | 15  |
| 738 | ...                 | 15.0              | End    | 9        | wax      | 15  |
| 739 | ...                 | 15.0              | End    | 9        | wax      | 15  |

|     | clamp_pressure | tool_condition | machining_finalized | W |
|-----|----------------|----------------|---------------------|---|
| 0   | 4.0            | worn           | yes                 |   |
| 1   | 4.0            | worn           | yes                 |   |
| 2   | 4.0            | worn           | yes                 |   |
| 3   | 4.0            | worn           | yes                 |   |
| 4   | 4.0            | worn           | yes                 |   |
| ... | ...            | ...            | ...                 |   |
| 735 | 4.0            | worn           | yes                 |   |
| 736 | 4.0            | worn           | yes                 |   |
| 737 | 4.0            | worn           | yes                 |   |
| 738 | 4.0            | worn           | yes                 |   |
| 739 | 4.0            | worn           | yes                 |   |

|     | passed_visual_inspection | class  |
|-----|--------------------------|--------|
| 0   | no                       | defect |
| 1   | no                       | defect |
| 2   | no                       | defect |
| 3   | no                       | defect |
| 4   | no                       | defect |
| ... | ...                      | ...    |
| 735 | no                       | defect |
| 736 | no                       | defect |
| 737 | no                       | defect |
| 738 | no                       | defect |
| 739 | no                       | defect |

[740 rows x 56 columns],

|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|------|-------------------|-------------------|-----------------------|---|
| 0    | 146.0             | 12.100            | 106.00                |   |
| 1    | 147.0             | 11.900            | -100.00               |   |
| 2    | 148.0             | 12.300            | 100.00                |   |
| 3    | 149.0             | 11.900            | -81.20                |   |
| 4    | 151.0             | 11.700            | -150.00               |   |
| ...  | ...               | ...               | ...                   |   |
| 1296 | 151.0             | 0.025             | 6.25                  |   |
| 1297 | 150.0             | -11.800           | 12.50                 |   |
| 1298 | 149.0             | -11.900           | 68.70                 |   |
| 1299 | 148.0             | -12.100           | -37.50                |   |
| 1300 | 147.0             | -11.900           | 68.70                 |   |

|   | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|---|--------------------|--------------------|------------------------|---|
| 0 | 146.0              | 12.0               | 0.0                    |   |
| 1 | 147.0              | 12.0               | 0.0                    |   |
| 2 | 148.0              | 12.0               | 0.0                    |   |
| 3 | 149.0              | 12.0               | 0.0                    |   |
| 4 | 151.0              | 12.0               | 0.0                    |   |

|      |       |       |     |
|------|-------|-------|-----|
| ...  | ...   | ...   | ... |
| 1296 | 151.0 | 0.0   | 0.0 |
| 1297 | 150.0 | -12.0 | 0.0 |
| 1298 | 149.0 | -12.0 | 0.0 |
| 1299 | 148.0 | -12.0 | 0.0 |
| 1300 | 146.0 | -12.0 | 0.0 |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | 5.780              | 0.1100          | 324.0            | 20.70            |   |
| 1    | 6.370              | 0.0994          | 324.0            | 22.30            |   |
| 2    | 3.530              | 0.0864          | 324.0            | 21.10            |   |
| 3    | 6.850              | 0.1050          | 324.0            | 21.70            |   |
| 4    | 9.120              | 0.1210          | 324.0            | 20.70            |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 1296 | 0.108              | 0.0215          | 324.0            | 2.71             |   |
| 1297 | -5.450             | 0.1200          | 324.0            | 22.30            |   |
| 1298 | -5.080             | 0.0881          | 324.0            | 24.40            |   |
| 1299 | -3.750             | 0.1030          | 324.0            | 22.40            |   |
| 1300 | -6.840             | 0.1170          | 324.0            | 23.40            |   |

|      | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W   |
|------|---------------------|-------------------|--------|----------|----------|-----|
| 0    | ...                 | 12.0              | Prep   | 10       | wax      | 12  |
| 1    | ...                 | 12.0              | Prep   | 10       | wax      | 12  |
| 2    | ...                 | 12.0              | Prep   | 10       | wax      | 12  |
| 3    | ...                 | 12.0              | Prep   | 10       | wax      | 12  |
| 4    | ...                 | 12.0              | Prep   | 10       | wax      | 12  |
| ...  | ...                 | ...               | ...    | ...      | ...      | ... |
| 1296 | ...                 | 12.0              | End    | 10       | wax      | 12  |
| 1297 | ...                 | 12.0              | End    | 10       | wax      | 12  |
| 1298 | ...                 | 12.0              | End    | 10       | wax      | 12  |
| 1299 | ...                 | 12.0              | End    | 10       | wax      | 12  |
| 1300 | ...                 | 12.0              | End    | 10       | wax      | 12  |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 4.0            | worn           | yes                 |   |
| 1    | 4.0            | worn           | yes                 |   |
| 2    | 4.0            | worn           | yes                 |   |
| 3    | 4.0            | worn           | yes                 |   |
| 4    | 4.0            | worn           | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 1296 | 4.0            | worn           | yes                 |   |
| 1297 | 4.0            | worn           | yes                 |   |
| 1298 | 4.0            | worn           | yes                 |   |
| 1299 | 4.0            | worn           | yes                 |   |
| 1300 | 4.0            | worn           | yes                 |   |

|      | passed_visual_inspection | class  |
|------|--------------------------|--------|
| 0    | no                       | defect |
| 1    | no                       | defect |
| 2    | no                       | defect |
| 3    | no                       | defect |
| 4    | no                       | defect |
| ...  | ...                      | ...    |
| 1296 | no                       | defect |
| 1297 | no                       | defect |
| 1298 | no                       | defect |
| 1299 | no                       | defect |
| 1300 | no                       | defect |

[1301 rows x 56 columns],

|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|------|-------------------|-------------------|-----------------------|---|
| 0    | 162.0             | -1.150            | 87.5                  |   |
| 1    | 162.0             | -1.350            | 87.5                  |   |
| 2    | 162.0             | -1.750            | 87.5                  |   |
| 3    | 161.0             | -2.130            | 56.3                  |   |
| 4    | 161.0             | -2.200            | 68.7                  |   |
| ...  | ...               | ...               | ...                   |   |
| 2309 | 148.0             | -0.875            | -25.0                 |   |
| 2310 | 148.0             | -3.170            | -31.3                 |   |
| 2311 | 148.0             | -2.970            | -18.8                 |   |
| 2312 | 147.0             | -2.850            | -25.0                 |   |
| 2313 | 147.0             | -2.750            | 0.0                   |   |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 162.0              | -1.34              | -3.0800                |   |
| 1    | 162.0              | -1.64              | -2.8800                |   |
| 2    | 162.0              | -1.92              | -2.6500                |   |
| 3    | 161.0              | -2.17              | -2.3800                |   |
| 4    | 161.0              | -2.39              | -2.0800                |   |
| ...  | ...                | ...                | ...                    |   |
| 2309 | 148.0              | -3.00              | 0.0111                 |   |
| 2310 | 148.0              | -2.99              | 0.1830                 |   |
| 2311 | 148.0              | -2.96              | 0.3530                 |   |
| 2312 | 147.0              | -2.92              | 0.5210                 |   |
| 2313 | 147.0              | -2.86              | 0.6860                 |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | -5.16              | 0.0750          | 327.0            | 6.02             |   |
| 1    | -5.78              | 0.0898          | 327.0            | 7.15             |   |
| 2    | -4.28              | 0.0684          | 327.0            | 6.68             |   |
| 3    | -4.47              | 0.0783          | 327.0            | 7.79             |   |
| 4    | -2.86              | 0.0762          | 327.0            | 10.30            |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 2309 | -13.80             | 0.2350          | 327.0            | 13.60            |   |
| 2310 | -3.86              | 0.0858          | 327.0            | 10.50            |   |
| 2311 | -5.35              | 0.0969          | 327.0            | 10.70            |   |
| 2312 | -5.05              | 0.1050          | 327.0            | 11.70            |   |
| 2313 | -3.88              | 0.0636          | 327.0            | 9.71             |   |

|      | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
|------|-----|---------------------|-------------------|--------|----------|----------|---|
| 0    | ... | 3.0                 | Prep              | 11     | wax      | 3        |   |
| 1    | ... | 3.0                 | Prep              | 11     | wax      | 3        |   |
| 2    | ... | 3.0                 | Prep              | 11     | wax      | 3        |   |
| 3    | ... | 3.0                 | Prep              | 11     | wax      | 3        |   |
| 4    | ... | 3.0                 | Prep              | 11     | wax      | 3        |   |
| ...  | ... | ...                 | ...               | ...    | ...      | ...      |   |
| 2309 | ... | 3.0                 | End               | 11     | wax      | 3        |   |
| 2310 | ... | 3.0                 | End               | 11     | wax      | 3        |   |
| 2311 | ... | 3.0                 | End               | 11     | wax      | 3        |   |
| 2312 | ... | 3.0                 | End               | 11     | wax      | 3        |   |
| 2313 | ... | 3.0                 | End               | 11     | wax      | 3        |   |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 4.0            | unworn         | yes                 |   |
| 1    | 4.0            | unworn         | yes                 |   |
| 2    | 4.0            | unworn         | yes                 |   |
| 3    | 4.0            | unworn         | yes                 |   |
| 4    | 4.0            | unworn         | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 2309 | 4.0            | unworn         | yes                 |   |
| 2310 | 4.0            | unworn         | yes                 |   |
| 2311 | 4.0            | unworn         | yes                 |   |
| 2312 | 4.0            | unworn         | yes                 |   |
| 2313 | 4.0            | unworn         | yes                 |   |

|      | passed_visual_inspection | class |
|------|--------------------------|-------|
| 0    | yes                      | pass  |
| 1    | yes                      | pass  |
| 2    | yes                      | pass  |
| 3    | yes                      | pass  |
| 4    | yes                      | pass  |
| ...  | ...                      | ...   |
| 2309 | yes                      | pass  |
| 2310 | yes                      | pass  |
| 2311 | yes                      | pass  |
| 2312 | yes                      | pass  |
| 2313 | yes                      | pass  |

[2314 rows x 56 columns],

|     | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|-----|-------------------|-------------------|-----------------------|---|
| 0   | 144.0             | -0.050            | -12.50                |   |
| 1   | 144.0             | 0.000             | 6.25                  |   |
| 2   | 144.0             | -0.050            | -12.50                |   |
| 3   | 144.0             | -0.075            | -37.50                |   |
| 4   | 144.0             | -0.050            | -18.80                |   |
| ... | ...               | ...               | ...                   |   |



|      |       |        |        |
|------|-------|--------|--------|
| 2271 | 153.0 | -3.030 | 0.00   |
| 2272 | 152.0 | -3.200 | -25.00 |
| 2273 | 152.0 | -3.250 | -37.50 |
| 2274 | 152.0 | -3.150 | -50.00 |
| 2275 | 152.0 | -3.030 | -56.30 |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 144.0              | 0.0                | 0.0                    |   |
| 1    | 144.0              | 0.0                | 0.0                    |   |
| 2    | 144.0              | 0.0                | 0.0                    |   |
| 3    | 144.0              | 0.0                | 0.0                    |   |
| 4    | 144.0              | 0.0                | 0.0                    |   |
| ...  | ...                | ...                | ...                    |   |
| 2271 | 153.0              | -3.0               | 0.0                    |   |
| 2272 | 152.0              | -3.0               | 0.0                    |   |
| 2273 | 152.0              | -3.0               | 0.0                    |   |
| 2274 | 152.0              | -3.0               | 0.0                    |   |
| 2275 | 152.0              | -3.0               | 0.0                    |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | -1.890             | 0.0452          | 327.0            | 5.59             |   |
| 1    | -0.833             | 0.0578          | 327.0            | 6.44             |   |
| 2    | -3.370             | 0.0444          | 327.0            | 3.11             |   |
| 3    | -2.220             | 0.0419          | 328.0            | 5.02             |   |
| 4    | -2.220             | 0.0455          | 327.0            | 4.61             |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 2271 | -3.070             | 0.0604          | 327.0            | 8.40             |   |
| 2272 | -3.150             | 0.0773          | 327.0            | 9.32             |   |
| 2273 | -3.530             | 0.0672          | 327.0            | 7.96             |   |
| 2274 | -5.380             | 0.1010          | 327.0            | 9.85             |   |
| 2275 | -6.140             | 0.0978          | 327.0            | 9.20             |   |

|      | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
|------|-----|---------------------|-------------------|--------|----------|----------|---|
| 0    | ... | 3.0                 | Prep              | 12     | wax      | 3        |   |
| 1    | ... | 3.0                 | Prep              | 12     | wax      | 3        |   |
| 2    | ... | 3.0                 | Prep              | 12     | wax      | 3        |   |
| 3    | ... | 3.0                 | Prep              | 12     | wax      | 3        |   |
| 4    | ... | 3.0                 | Prep              | 12     | wax      | 3        |   |
| ...  | ... | ...                 | ...               | ...    | ...      | ...      |   |
| 2271 | ... | 3.0                 | End               | 12     | wax      | 3        |   |
| 2272 | ... | 3.0                 | End               | 12     | wax      | 3        |   |
| 2273 | ... | 3.0                 | End               | 12     | wax      | 3        |   |
| 2274 | ... | 3.0                 | End               | 12     | wax      | 3        |   |
| 2275 | ... | 3.0                 | End               | 12     | wax      | 3        |   |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 3.0            | unworn         | yes                 |   |
| 1    | 3.0            | unworn         | yes                 |   |
| 2    | 3.0            | unworn         | yes                 |   |
| 3    | 3.0            | unworn         | yes                 |   |
| 4    | 3.0            | unworn         | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 2271 | 3.0            | unworn         | yes                 |   |
| 2272 | 3.0            | unworn         | yes                 |   |
| 2273 | 3.0            | unworn         | yes                 |   |
| 2274 | 3.0            | unworn         | yes                 |   |
| 2275 | 3.0            | unworn         | yes                 |   |

|      | passed_visual_inspection | class |
|------|--------------------------|-------|
| 0    | yes                      | pass  |
| 1    | yes                      | pass  |
| 2    | yes                      | pass  |
| 3    | yes                      | pass  |
| 4    | yes                      | pass  |
| ...  | ...                      | ...   |
| 2271 | yes                      | pass  |
| 2272 | yes                      | pass  |
| 2273 | yes                      | pass  |
| 2274 | yes                      | pass  |
| 2275 | yes                      | pass  |

[2276 rows x 56 columns],

|  | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|--|-------------------|-------------------|-----------------------|---|
|--|-------------------|-------------------|-----------------------|---|

|      |       |       |       |
|------|-------|-------|-------|
| 0    | 144.0 | 2.970 | 12.50 |
| 1    | 144.0 | 3.100 | 0.00  |
| 2    | 144.0 | 2.920 | 31.30 |
| 3    | 145.0 | 2.900 | 6.25  |
| 4    | 145.0 | 3.000 | 25.00 |
| ...  | ...   | ...   | ...   |
| 2228 | 162.0 | 0.200 | 25.00 |
| 2229 | 162.0 | 0.125 | 68.70 |
| 2230 | 162.0 | 0.100 | 56.30 |
| 2231 | 162.0 | 0.125 | 62.50 |
| 2232 | 162.0 | 0.125 | 56.30 |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 144.0              | 2.960              | 0.536                  |   |
| 1    | 144.0              | 3.000              | 0.145                  |   |
| 2    | 144.0              | 3.000              | 0.000                  |   |
| 3    | 145.0              | 3.000              | 0.000                  |   |
| 4    | 145.0              | 3.000              | 0.000                  |   |
| ...  | ...                | ...                | ...                    |   |
| 2228 | 162.0              | 0.133              | -3.430                 |   |
| 2229 | 162.0              | 0.000              | 0.000                  |   |
| 2230 | 162.0              | 0.000              | 0.000                  |   |
| 2231 | 162.0              | 0.000              | 0.000                  |   |
| 2232 | 162.0              | 0.000              | 0.000                  |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | 4.16               | 0.0585          | 326.0            | 8.07             |   |
| 1    | 1.80               | 0.0716          | 327.0            | 11.00            |   |
| 2    | 4.19               | 0.0890          | 327.0            | 11.20            |   |
| 3    | 5.05               | 0.0883          | 327.0            | 10.20            |   |
| 4    | 3.35               | 0.0607          | 327.0            | 8.51             |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 2228 | 2.19               | 0.0639          | 327.0            | 7.28             |   |
| 2229 | 1.11               | 0.0511          | 327.0            | 4.99             |   |
| 2230 | 1.66               | 0.0536          | 327.0            | 4.81             |   |
| 2231 | 2.77               | 0.0494          | 327.0            | 3.02             |   |
| 2232 | 3.60               | 0.0520          | 327.0            | 1.23             |   |

|      | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
|------|---------------------|-------------------|--------|----------|----------|---|
| 0    | ...                 | ...               | ...    | ...      | ...      |   |
| 1    | ...                 | 3.0               | Prep   | 13       | wax      | 3 |
| 2    | ...                 | 3.0               | Prep   | 13       | wax      | 3 |
| 3    | ...                 | 3.0               | Prep   | 13       | wax      | 3 |
| 4    | ...                 | 3.0               | Prep   | 13       | wax      | 3 |
| ...  | ...                 | ...               | ...    | ...      | ...      |   |
| 2228 | ...                 | 3.0               | End    | 13       | wax      | 3 |
| 2229 | ...                 | 3.0               | End    | 13       | wax      | 3 |
| 2230 | ...                 | 3.0               | End    | 13       | wax      | 3 |
| 2231 | ...                 | 3.0               | End    | 13       | wax      | 3 |
| 2232 | ...                 | 3.0               | End    | 13       | wax      | 3 |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 4.0            | worn           | yes                 |   |
| 1    | 4.0            | worn           | yes                 |   |
| 2    | 4.0            | worn           | yes                 |   |
| 3    | 4.0            | worn           | yes                 |   |
| 4    | 4.0            | worn           | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 2228 | 4.0            | worn           | yes                 |   |
| 2229 | 4.0            | worn           | yes                 |   |
| 2230 | 4.0            | worn           | yes                 |   |
| 2231 | 4.0            | worn           | yes                 |   |
| 2232 | 4.0            | worn           | yes                 |   |

|      | passed_visual_inspection | class |
|------|--------------------------|-------|
| 0    | yes                      | pass  |
| 1    | yes                      | pass  |
| 2    | yes                      | pass  |
| 3    | yes                      | pass  |
| 4    | yes                      | pass  |
| ...  | ...                      | ...   |
| 2228 | yes                      | pass  |
| 2229 | yes                      | pass  |

|      |  |     |      |
|------|--|-----|------|
| 2230 |  | yes | pass |
| 2231 |  | yes | pass |
| 2232 |  | yes | pass |

[2233 rows x 56 columns],

|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|------|-------------------|-------------------|-----------------------|---|
| 0    | 141.0             | 0.125             | 50.00                 |   |
| 1    | 141.0             | -0.100            | -50.00                |   |
| 2    | 141.0             | -0.125            | -62.50                |   |
| 3    | 141.0             | 0.150             | 68.70                 |   |
| 4    | 141.0             | -0.100            | -50.00                |   |
| ...  | ...               | ...               | ...                   |   |
| 2327 | 165.0             | -17.900           | 37.50                 |   |
| 2328 | 163.0             | -18.100           | -6.25                 |   |
| 2329 | 162.0             | -18.100           | -81.20                |   |
| 2330 | 160.0             | -18.000           | -6.25                 |   |
| 2331 | 158.0             | -17.800           | 25.00                 |   |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 141.0              | 0.0                | 0.000000               |   |
| 1    | 141.0              | 0.0                | 0.000000               |   |
| 2    | 141.0              | 0.0                | 0.000000               |   |
| 3    | 141.0              | 0.0                | 0.000000               |   |
| 4    | 141.0              | 0.0                | 0.000000               |   |
| ...  | ...                | ...                | ...                    |   |
| 2327 | 165.0              | -17.9              | -0.000095              |   |
| 2328 | 163.0              | -17.9              | 0.000000               |   |
| 2329 | 161.0              | -17.9              | 0.000000               |   |
| 2330 | 160.0              | -17.9              | 0.000000               |   |
| 2331 | 158.0              | -17.9              | 0.000191               |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | -3.38              | 0.0710          | 327.0            | 5.93             |   |
| 1    | -2.54              | 0.0492          | 327.0            | 5.04             |   |
| 2    | -2.70              | 0.0508          | 327.0            | 3.93             |   |
| 3    | -4.18              | 0.0710          | 327.0            | 5.20             |   |
| 4    | -2.15              | 0.0561          | 327.0            | 5.42             |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 2327 | -5.43              | 0.1080          | 329.0            | 28.30            |   |
| 2328 | -4.77              | 0.1070          | 329.0            | 30.00            |   |
| 2329 | -5.61              | 0.1040          | 328.0            | 30.30            |   |
| 2330 | -7.79              | 0.1340          | 328.0            | 30.30            |   |
| 2331 | -8.14              | 0.1380          | 328.0            | 29.60            |   |

|      | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W   |
|------|---------------------|-------------------|--------|----------|----------|-----|
| 0    | ...                 | 3.0               | Prep   | 14       | wax      | 3   |
| 1    | ...                 | 3.0               | Prep   | 14       | wax      | 3   |
| 2    | ...                 | 3.0               | Prep   | 14       | wax      | 3   |
| 3    | ...                 | 3.0               | Prep   | 14       | wax      | 3   |
| 4    | ...                 | 3.0               | Prep   | 14       | wax      | 3   |
| ...  | ...                 | ...               | ...    | ...      | ...      | ... |
| 2327 | ...                 | 50.0              | End    | 14       | wax      | 3   |
| 2328 | ...                 | 50.0              | End    | 14       | wax      | 3   |
| 2329 | ...                 | 50.0              | End    | 14       | wax      | 3   |
| 2330 | ...                 | 50.0              | End    | 14       | wax      | 3   |
| 2331 | ...                 | 50.0              | End    | 14       | wax      | 3   |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 3.0            | worn           | yes                 |   |
| 1    | 3.0            | worn           | yes                 |   |
| 2    | 3.0            | worn           | yes                 |   |
| 3    | 3.0            | worn           | yes                 |   |
| 4    | 3.0            | worn           | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 2327 | 3.0            | worn           | yes                 |   |
| 2328 | 3.0            | worn           | yes                 |   |
| 2329 | 3.0            | worn           | yes                 |   |
| 2330 | 3.0            | worn           | yes                 |   |
| 2331 | 3.0            | worn           | yes                 |   |

|   | passed_visual_inspection | class |
|---|--------------------------|-------|
| 0 | yes                      | pass  |
| 1 | yes                      | pass  |

|      |     |      |
|------|-----|------|
| 2    | yes | pass |
| 3    | yes | pass |
| 4    | yes | pass |
| ...  | ... | ...  |
| 2327 | yes | pass |
| 2328 | yes | pass |
| 2329 | yes | pass |
| 2330 | yes | pass |
| 2331 | yes | pass |

[2332 rows x 56 columns],

|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|------|-------------------|-------------------|-----------------------|---|
| 0    | 141.0             | -0.200            | -100.0                |   |
| 1    | 141.0             | -0.300            | -144.0                |   |
| 2    | 141.0             | -0.250            | -131.0                |   |
| 3    | 141.0             | -0.175            | -93.7                 |   |
| 4    | 141.0             | -0.200            | -106.0                |   |
| ...  | ...               | ...               | ...                   |   |
| 1376 | 141.0             | -0.100            | -62.5                 |   |
| 1377 | 141.0             | -0.050            | -31.3                 |   |
| 1378 | 141.0             | 0.100             | 50.0                  |   |
| 1379 | 141.0             | -0.125            | -62.5                 |   |
| 1380 | 141.0             | -0.100            | -56.3                 |   |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 141.0              | 0.0                | 0.0                    |   |
| 1    | 141.0              | 0.0                | 0.0                    |   |
| 2    | 141.0              | 0.0                | 0.0                    |   |
| 3    | 141.0              | 0.0                | 0.0                    |   |
| 4    | 141.0              | 0.0                | 0.0                    |   |
| ...  | ...                | ...                | ...                    |   |
| 1376 | 141.0              | 0.0                | 0.0                    |   |
| 1377 | 141.0              | 0.0                | 0.0                    |   |
| 1378 | 141.0              | 0.0                | 0.0                    |   |
| 1379 | 141.0              | 0.0                | 0.0                    |   |
| 1380 | 141.0              | 0.0                | 0.0                    |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | -2.450             | 0.0512          | 327.0            | 2.69             |   |
| 1    | -1.400             | 0.0479          | 327.0            | 3.18             |   |
| 2    | -2.290             | 0.0483          | 327.0            | 2.10             |   |
| 3    | -0.851             | 0.0488          | 327.0            | 4.08             |   |
| 4    | -2.290             | 0.0502          | 327.0            | 2.17             |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 1376 | -2.790             | 0.0678          | 327.0            | 3.30             |   |
| 1377 | -1.240             | 0.0617          | 327.0            | 4.23             |   |
| 1378 | -3.180             | 0.0425          | 327.0            | 6.53             |   |
| 1379 | -0.601             | 0.0602          | 327.0            | 4.48             |   |
| 1380 | -2.150             | 0.0561          | 327.0            | 2.50             |   |

|      | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W   |
|------|---------------------|-------------------|--------|----------|----------|-----|
| 0    | ...                 | 6.0               | Prep   | 15       | wax      | 6   |
| 1    | ...                 | 6.0               | Prep   | 15       | wax      | 6   |
| 2    | ...                 | 6.0               | Prep   | 15       | wax      | 6   |
| 3    | ...                 | 6.0               | Prep   | 15       | wax      | 6   |
| 4    | ...                 | 6.0               | Prep   | 15       | wax      | 6   |
| ...  | ...                 | ...               | ...    | ...      | ...      | ... |
| 1376 | ...                 | 6.0               | End    | 15       | wax      | 6   |
| 1377 | ...                 | 6.0               | End    | 15       | wax      | 6   |
| 1378 | ...                 | 6.0               | End    | 15       | wax      | 6   |
| 1379 | ...                 | 6.0               | End    | 15       | wax      | 6   |
| 1380 | ...                 | 6.0               | End    | 15       | wax      | 6   |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 3.0            | worn           | yes                 |   |
| 1    | 3.0            | worn           | yes                 |   |
| 2    | 3.0            | worn           | yes                 |   |
| 3    | 3.0            | worn           | yes                 |   |
| 4    | 3.0            | worn           | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 1376 | 3.0            | worn           | yes                 |   |
| 1377 | 3.0            | worn           | yes                 |   |
| 1378 | 3.0            | worn           | yes                 |   |

|      |     |      |     |
|------|-----|------|-----|
| 1379 | 3.0 | worn | yes |
| 1380 | 3.0 | worn | yes |

|      | passed_visual_inspection | class |
|------|--------------------------|-------|
| 0    | yes                      | pass  |
| 1    | yes                      | pass  |
| 2    | yes                      | pass  |
| 3    | yes                      | pass  |
| 4    | yes                      | pass  |
| ...  | ...                      | ...   |
| 1376 | yes                      | pass  |
| 1377 | yes                      | pass  |
| 1378 | yes                      | pass  |
| 1379 | yes                      | pass  |
| 1380 | yes                      | pass  |

[1381 rows x 56 columns],

|     | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|-----|-------------------|-------------------|-----------------------|---|
| 0   | 151.0             | 0.050             | 25.00                 |   |
| 1   | 151.0             | 0.025             | 12.50                 |   |
| 2   | 151.0             | 0.050             | 25.00                 |   |
| 3   | 151.0             | -0.025            | -12.50                |   |
| 4   | 151.0             | 0.025             | 12.50                 |   |
| ... | ...               | ...               | ...                   |   |
| 597 | 198.0             | 0.000             | 0.00                  |   |
| 598 | 198.0             | 0.000             | 0.00                  |   |
| 599 | 198.0             | 0.000             | 0.00                  |   |
| 600 | 198.0             | 0.000             | 6.25                  |   |
| 601 | 198.0             | 0.000             | 0.00                  |   |

|     | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|-----|--------------------|--------------------|------------------------|---|
| 0   | 151.0              | 0.0                | 0.0                    |   |
| 1   | 151.0              | 0.0                | 0.0                    |   |
| 2   | 151.0              | 0.0                | 0.0                    |   |
| 3   | 151.0              | 0.0                | 0.0                    |   |
| 4   | 151.0              | 0.0                | 0.0                    |   |
| ... | ...                | ...                | ...                    |   |
| 597 | 198.0              | 0.0                | 0.0                    |   |
| 598 | 198.0              | 0.0                | 0.0                    |   |
| 599 | 198.0              | 0.0                | 0.0                    |   |
| 600 | 198.0              | 0.0                | 0.0                    |   |
| 601 | 198.0              | 0.0                | 0.0                    |   |

|     | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|-----|--------------------|-----------------|------------------|------------------|---|
| 0   | 0.451              | 2.280000e-02    | 330.0            | 0.632            |   |
| 1   | 0.223              | 2.430000e-02    | 330.0            | 1.510            |   |
| 2   | 0.237              | 1.880000e-02    | 330.0            | 0.869            |   |
| 3   | 0.451              | 2.020000e-02    | 329.0            | 1.900            |   |
| 4   | 0.367              | 2.440000e-02    | 329.0            | 1.910            |   |
| ... | ...                | ...             | ...              | ...              |   |
| 597 | -0.460             | 2.780000e-19    | 330.0            | 0.000            |   |
| 598 | -1.580             | 2.780000e-19    | 330.0            | 0.000            |   |
| 599 | 0.659              | 2.780000e-19    | 330.0            | 0.000            |   |
| 600 | -0.461             | 2.780000e-19    | 330.0            | 0.000            |   |
| 601 | 0.979              | 2.780000e-19    | 330.0            | 0.000            |   |

|     | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
|-----|-----|---------------------|-------------------|--------|----------|----------|---|
| 0   | ... | 50.0                | Prep              | 16     | wax      | 20       |   |
| 1   | ... | 50.0                | Prep              | 16     | wax      | 20       |   |
| 2   | ... | 50.0                | Prep              | 16     | wax      | 20       |   |
| 3   | ... | 50.0                | Prep              | 16     | wax      | 20       |   |
| 4   | ... | 50.0                | Prep              | 16     | wax      | 20       |   |
| ... | ... | ...                 | ...               | ...    | ...      | ...      |   |
| 597 | ... | 50.0                | End               | 16     | wax      | 20       |   |
| 598 | ... | 50.0                | End               | 16     | wax      | 20       |   |
| 599 | ... | 50.0                | End               | 16     | wax      | 20       |   |
| 600 | ... | 50.0                | End               | 16     | wax      | 20       |   |
| 601 | ... | 50.0                | End               | 16     | wax      | 20       |   |

|   | clamp_pressure | tool_condition | machining_finalized | W |
|---|----------------|----------------|---------------------|---|
| 0 | 3.0            | worn           | no                  |   |
| 1 | 3.0            | worn           | no                  |   |
| 2 | 3.0            | worn           | no                  |   |

|     |     |      |     |
|-----|-----|------|-----|
| 3   | 3.0 | worn | no  |
| 4   | 3.0 | worn | no  |
| ... | ... | ...  | ... |
| 597 | 3.0 | worn | no  |
| 598 | 3.0 | worn | no  |
| 599 | 3.0 | worn | no  |
| 600 | 3.0 | worn | no  |
| 601 | 3.0 | worn | no  |

|     | passed_visual_inspection | class  |
|-----|--------------------------|--------|
| 0   | no                       | defect |
| 1   | no                       | defect |
| 2   | no                       | defect |
| 3   | no                       | defect |
| 4   | no                       | defect |
| ... | ...                      | ...    |
| 597 | no                       | defect |
| 598 | no                       | defect |
| 599 | no                       | defect |
| 600 | no                       | defect |
| 601 | no                       | defect |

[602 rows x 56 columns],

|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
|------|-------------------|-------------------|-----------------------|---|
| 0    | 151.0             | -2.920            | -31.30                |   |
| 1    | 150.0             | -2.950            | -37.50                |   |
| 2    | 150.0             | -2.750            | 62.50                 |   |
| 3    | 150.0             | -3.080            | -6.25                 |   |
| 4    | 149.0             | -3.150            | -6.25                 |   |
| ...  | ...               | ...               | ...                   |   |
| 2145 | 141.0             | -0.200            | -106.00               |   |
| 2146 | 141.0             | 0.300             | 144.00                |   |
| 2147 | 141.0             | -0.175            | -87.50                |   |
| 2148 | 141.0             | -0.150            | -75.00                |   |
| 2149 | 141.0             | 0.175             | 87.50                 |   |

|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
|------|--------------------|--------------------|------------------------|---|
| 0    | 151.0              | -3.0               | 0.0                    |   |
| 1    | 150.0              | -3.0               | 0.0                    |   |
| 2    | 150.0              | -3.0               | 0.0                    |   |
| 3    | 150.0              | -3.0               | 0.0                    |   |
| 4    | 149.0              | -3.0               | 0.0                    |   |
| ...  | ...                | ...                | ...                    |   |
| 2145 | 141.0              | 0.0                | 0.0                    |   |
| 2146 | 141.0              | 0.0                | 0.0                    |   |
| 2147 | 141.0              | 0.0                | 0.0                    |   |
| 2148 | 141.0              | 0.0                | 0.0                    |   |
| 2149 | 141.0              | 0.0                | 0.0                    |   |

|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
|------|--------------------|-----------------|------------------|------------------|---|
| 0    | -5.89              | 0.1040          | 327.0            | 10.60            |   |
| 1    | -5.83              | 0.0927          | 327.0            | 10.40            |   |
| 2    | -6.45              | 0.0974          | 327.0            | 10.10            |   |
| 3    | -3.89              | 0.0735          | 327.0            | 9.02             |   |
| 4    | -3.81              | 0.0735          | 327.0            | 8.67             |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 2145 | -2.49              | 0.0480          | 327.0            | 2.54             |   |
| 2146 | -4.14              | 0.0681          | 327.0            | 6.05             |   |
| 2147 | -2.04              | 0.0490          | 327.0            | 3.57             |   |
| 2148 | -2.79              | 0.0479          | 327.0            | 2.73             |   |
| 2149 | -4.27              | 0.0637          | 327.0            | 5.16             |   |

|      | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
|------|-----|---------------------|-------------------|--------|----------|----------|---|
| 0    | ... | 3.0                 | Prep              | 17     | wax      | 3        |   |
| 1    | ... | 3.0                 | Prep              | 17     | wax      | 3        |   |
| 2    | ... | 3.0                 | Prep              | 17     | wax      | 3        |   |
| 3    | ... | 3.0                 | Prep              | 17     | wax      | 3        |   |
| 4    | ... | 3.0                 | Prep              | 17     | wax      | 3        |   |
| ...  | ... | ...                 | ...               | ...    | ...      | ...      |   |
| 2145 | ... | 3.0                 | End               | 17     | wax      | 3        |   |
| 2146 | ... | 3.0                 | End               | 17     | wax      | 3        |   |
| 2147 | ... | 3.0                 | End               | 17     | wax      | 3        |   |
| 2148 | ... | 3.0                 | End               | 17     | wax      | 3        |   |

|      |                |                |                     |    |     |   |
|------|----------------|----------------|---------------------|----|-----|---|
| 2149 | ...            | 3.0            | End                 | 17 | wax | 3 |
|      | clamp_pressure | tool_condition | machining_finalized | W  |     |   |
| 0    | 2.5            | unworn         | yes                 |    |     |   |
| 1    | 2.5            | unworn         | yes                 |    |     |   |
| 2    | 2.5            | unworn         | yes                 |    |     |   |
| 3    | 2.5            | unworn         | yes                 |    |     |   |
| 4    | 2.5            | unworn         | yes                 |    |     |   |
| ...  | ...            | ...            | ...                 |    |     |   |
| 2145 | 2.5            | unworn         | yes                 |    |     |   |
| 2146 | 2.5            | unworn         | yes                 |    |     |   |
| 2147 | 2.5            | unworn         | yes                 |    |     |   |
| 2148 | 2.5            | unworn         | yes                 |    |     |   |
| 2149 | 2.5            | unworn         | yes                 |    |     |   |

|      |                          |       |  |
|------|--------------------------|-------|--|
|      | passed_visual_inspection | class |  |
| 0    | yes                      | pass  |  |
| 1    | yes                      | pass  |  |
| 2    | yes                      | pass  |  |
| 3    | yes                      | pass  |  |
| 4    | yes                      | pass  |  |
| ...  | ...                      | ...   |  |
| 2145 | yes                      | pass  |  |
| 2146 | yes                      | pass  |  |
| 2147 | yes                      | pass  |  |
| 2148 | yes                      | pass  |  |
| 2149 | yes                      | pass  |  |

[2150 rows x 56 columns],

|      |                   |                   |                       |   |
|------|-------------------|-------------------|-----------------------|---|
|      | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | W |
| 0    | 151.0             | 3.08              | 0.0                   |   |
| 1    | 152.0             | 3.20              | 25.0                  |   |
| 2    | 152.0             | 3.20              | 50.0                  |   |
| 3    | 152.0             | 3.13              | 50.0                  |   |
| 4    | 153.0             | 2.97              | 56.3                  |   |
| ...  | ...               | ...               | ...                   |   |
| 2248 | 144.0             | -2.30             | 100.0                 |   |
| 2249 | 144.0             | -2.47             | 25.0                  |   |
| 2250 | 143.0             | -2.20             | 81.2                  |   |
| 2251 | 143.0             | -2.05             | 68.7                  |   |
| 2252 | 143.0             | -2.15             | -68.7                 |   |

|      |                    |                    |                        |   |
|------|--------------------|--------------------|------------------------|---|
|      | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | W |
| 0    | 151.0              | 3.00               | 0.000                  |   |
| 1    | 152.0              | 3.00               | 0.000                  |   |
| 2    | 152.0              | 3.00               | 0.000                  |   |
| 3    | 152.0              | 3.00               | 0.000                  |   |
| 4    | 153.0              | 3.00               | 0.000                  |   |
| ...  | ...                | ...                | ...                    |   |
| 2248 | 144.0              | -2.57              | 0.977                  |   |
| 2249 | 144.0              | -2.46              | 1.080                  |   |
| 2250 | 143.0              | -2.35              | 1.170                  |   |
| 2251 | 143.0              | -2.23              | 1.260                  |   |
| 2252 | 143.0              | -2.09              | 1.350                  |   |

|      |                    |                 |                  |                  |   |
|------|--------------------|-----------------|------------------|------------------|---|
|      | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | W |
| 0    | 3.48               | 0.0684          | 327.0            | 8.56             |   |
| 1    | 3.09               | 0.0621          | 327.0            | 6.74             |   |
| 2    | 3.96               | 0.0796          | 327.0            | 8.78             |   |
| 3    | 4.70               | 0.0946          | 327.0            | 10.20            |   |
| 4    | 5.97               | 0.1020          | 327.0            | 11.30            |   |
| ...  | ...                | ...             | ...              | ...              |   |
| 2248 | -5.05              | 0.0732          | 327.0            | 9.56             |   |
| 2249 | -5.62              | 0.0996          | 327.0            | 10.30            |   |
| 2250 | -4.42              | 0.0539          | 327.0            | 7.79             |   |
| 2251 | -5.83              | 0.0809          | 327.0            | 8.32             |   |
| 2252 | -4.37              | 0.0857          | 327.0            | 8.01             |   |

|   |     |                     |                   |        |          |          |   |
|---|-----|---------------------|-------------------|--------|----------|----------|---|
|   | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material | feedrate | W |
| 0 | ... | 3.0                 | Prep              | 18     | wax      | 3        |   |
| 1 | ... | 3.0                 | Prep              | 18     | wax      | 3        |   |
| 2 | ... | 3.0                 | Prep              | 18     | wax      | 3        |   |
| 3 | ... | 3.0                 | Prep              | 18     | wax      | 3        |   |

|      |     |     |      |     |     |     |
|------|-----|-----|------|-----|-----|-----|
| 4    | ... | 3.0 | Prep | 18  | wax | 3   |
| ...  | ... | ... | ...  | ... | ... | ... |
| 2248 | ... | 3.0 | End  | 18  | wax | 3   |
| 2249 | ... | 3.0 | End  | 18  | wax | 3   |
| 2250 | ... | 3.0 | End  | 18  | wax | 3   |
| 2251 | ... | 3.0 | End  | 18  | wax | 3   |
| 2252 | ... | 3.0 | End  | 18  | wax | 3   |

|      | clamp_pressure | tool_condition | machining_finalized | W |
|------|----------------|----------------|---------------------|---|
| 0    | 2.5            | worn           | yes                 |   |
| 1    | 2.5            | worn           | yes                 |   |
| 2    | 2.5            | worn           | yes                 |   |
| 3    | 2.5            | worn           | yes                 |   |
| 4    | 2.5            | worn           | yes                 |   |
| ...  | ...            | ...            | ...                 |   |
| 2248 | 2.5            | worn           | yes                 |   |
| 2249 | 2.5            | worn           | yes                 |   |
| 2250 | 2.5            | worn           | yes                 |   |
| 2251 | 2.5            | worn           | yes                 |   |
| 2252 | 2.5            | worn           | yes                 |   |

|      | passed_visual_inspection | class |
|------|--------------------------|-------|
| 0    | yes                      | pass  |
| 1    | yes                      | pass  |
| 2    | yes                      | pass  |
| 3    | yes                      | pass  |
| 4    | yes                      | pass  |
| ...  | ...                      | ...   |
| 2248 | yes                      | pass  |
| 2249 | yes                      | pass  |
| 2250 | yes                      | pass  |
| 2251 | yes                      | pass  |
| 2252 | yes                      | pass  |

[2253 rows x 56 columns]]

## Label Normalization

- Count of 'Starting' and 'end' label in Machining\_Process column is relatively small.
- So we need to normalize these outlier labels into alternative label.

Starting -> Prep  
end -> End

In [25]: `df['Machining_Process'].value_counts().sort_index()`

Out[25]:

|               |      |
|---------------|------|
| End           | 2585 |
| Layer 1 Down  | 2655 |
| Layer 1 Up    | 4085 |
| Layer 2 Down  | 2528 |
| Layer 2 Up    | 3104 |
| Layer 3 Down  | 2354 |
| Layer 3 Up    | 2794 |
| Prep          | 1795 |
| Repositioning | 3377 |
| Starting      | 1    |
| end           | 8    |

Name: Machining\_Process, dtype: int64

In [26]:

```
print(f"Count of Starting label in Machining_Process column is 1 only in experimet_{df[df['Machining_Process']=='Starting'].exp_no.value_counts().index[0]}")
print(f"Count of end label in Machining_Process column is 8 only in experimet_{df[df['Machining_Process']=='end'].exp_no.value_counts().index[0]}")
```

Count of Starting label in Machining\_Process column is 1 only in experimet\_1  
Count of end label in Machining\_Process column is 8 only in experimet\_1

In [27]: `df.replace({'Machining_Process': {'Starting':'Prep','end':'End'}}, inplace=True)`

In [28]: `df['Machining_Process'].value_counts().sort_index()`



```
Out[28]: End 2593
Layer 1 Down 2655
Layer 1 Up 4085
Layer 2 Down 2528
Layer 2 Up 3104
Layer 3 Down 2354
Layer 3 Up 2794
Prep 1796
Repositioning 3377
Name: Machining_Process, dtype: int64
```

## 5. EDA

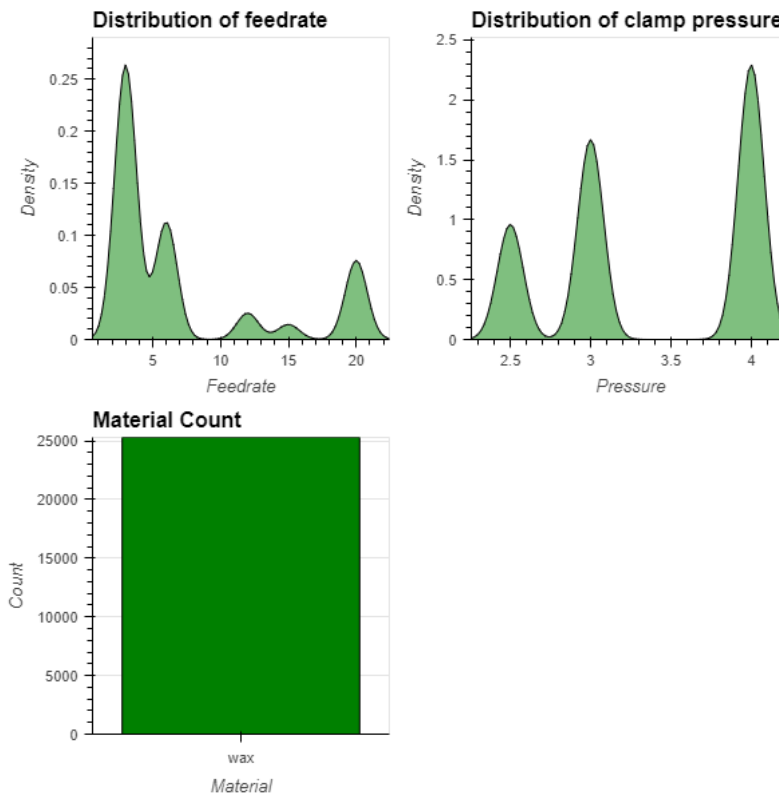
### Some points to focus on

- Machining Process Unique
- Mean value of velocity,voltage,feedrate(x,y,z)
- distribution of feedrate, clamp\_pressure
- correlation of each features
- time series plot of each experiment
- difference of distribution for each output feature

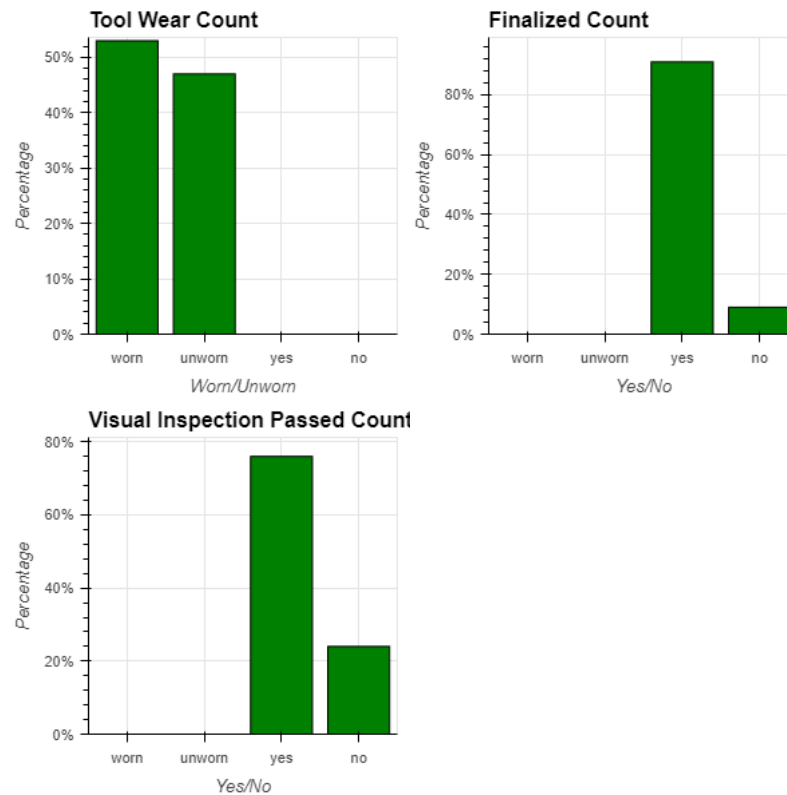
```
In [29]: import holoviews as hv
from holoviews import opts
hv.extension('bokeh')
import lightgbm as lgb
import shap

feedrate = hv.Distribution(df['feedrate']).opts(title="Distribution of feedrate", color="green", xlabel="Feedrate", ylabel="Density")
clamp = hv.Distribution(df['clamp_pressure']).opts(title="Distribution of clamp pressure", color="green", xlabel="Pressure", ylabel="Density")
material = hv.Bars(df['material'].value_counts()).opts(title="Material Count", color="green", xlabel="Material", ylabel="Count")
(feedrate + clamp + material).opts(opts.Bars(width=300, height=300,tools=['hover'],show_grid=True)).cols(2)
```

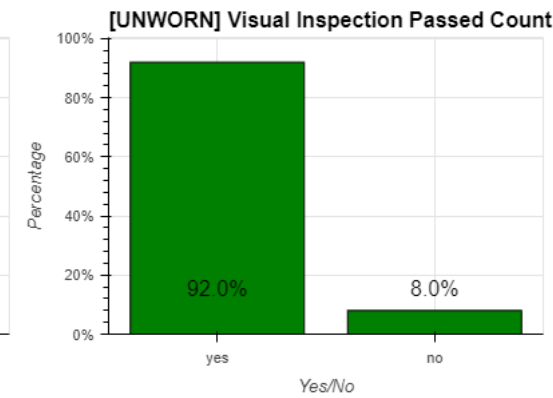
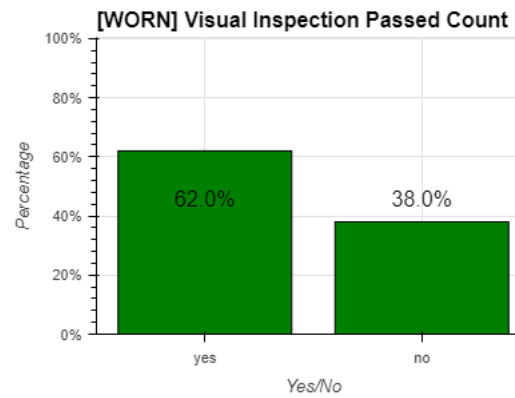
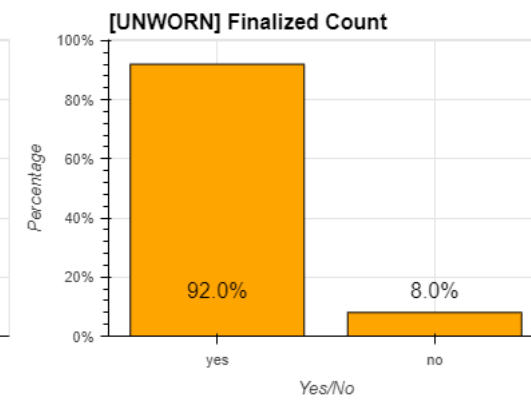
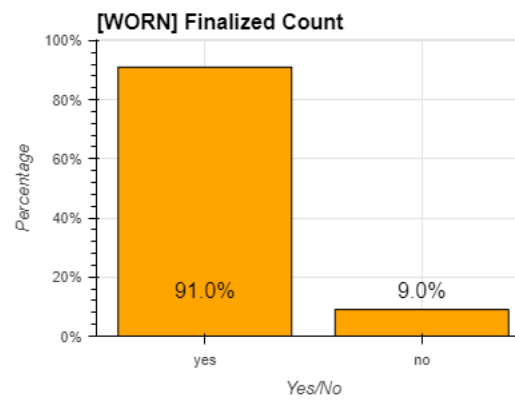




```
In [30]: tool_df = np.round(df['tool_condition'].value_counts(normalize=True) * 100)
finalized_df = np.round(df['machining_finalized'].value_counts(normalize=True) * 100)
vis_passed_df = np.round(df['passed_visual_inspection'].value_counts(normalize=True) * 100)
tool_wear = hv.Bars(tool_df).opts(title="Tool Wear Count", color="green", xlabel="Worn/Unworn", ylabel="Percentage", yformatter='%d%%')
finalized = hv.Bars(finalized_df).opts(title="Finalized Count", color="green", xlabel="Yes/No", ylabel="Percentage", yformatter='%d%%')
vis_inspection = hv.Bars(vis_passed_df).opts(title="Visual Inspection Passed Count", color="green", xlabel="Yes/No", ylabel="Percentage", yformatter='%d%%')
(tool_wear + finalized + vis_inspection).opts(opts.Bars(width=300, height=300, tools=['hover'], show_grid=True)).cols(2)
```



```
In [31]: finalized_df_worn = np.round(df[df['tool_condition']=='worn']['machining_finalized'].value_counts(normalize=True) * 100)
finalized_df_unworn = np.round(df[df['tool_condition']=='unworn']['machining_finalized'].value_counts(normalize=True) * 100)
vis_passed_df_worn = np.round(df[df['tool_condition']=='worn']['passed_visual_inspection'].value_counts(normalize=True) * 100)
vis_passed_df_unworn = np.round(df[df['tool_condition']=='unworn']['passed_visual_inspection'].value_counts(normalize=True) * 100)
finalized_worn = hv.Bars(finalized_df_worn).opts(title="[WORN] Finalized Count", color="orange", xlabel="Yes/No", ylabel="Percentage", yformatter='%d%%')\
    * hv.Text('yes', 15, f"{np.round(finalized_df_worn['yes']/sum(finalized_df_worn)*100)}%")\
    * hv.Text('no', 15, f"{np.round(finalized_df_worn['no']/sum(finalized_df_worn)*100)}%")
finalized_unworn = hv.Bars(finalized_df_unworn).opts(title="[UNWORN] Finalized Count", color="orange", xlabel="Yes/No", ylabel="Percentage", yformatter='%d%%')\
    * hv.Text('yes', 15, f"{np.round(finalized_df_unworn['yes']/sum(finalized_df_unworn)*100)}%")\
    * hv.Text('no', 15, f"{np.round(finalized_df_unworn['no']/sum(finalized_df_unworn)*100)}%")
vis_inspection_worn = hv.Bars(vis_passed_df_worn).opts(title="[WORN] Visual Inspection Passed Count", color="green", xlabel="Yes/No", ylabel="Percentage", yformatter='%d%%')\
    * hv.Text('yes', 45, f"{np.round(vis_passed_df_worn['yes']/sum(vis_passed_df_worn)*100)}%")\
    * hv.Text('no', 45, f"{np.round(vis_passed_df_worn['no']/sum(vis_passed_df_worn)*100)}%")
vis_inspection_unworn = hv.Bars(vis_passed_df_unworn).opts(title="[UNWORN] Visual Inspection Passed Count", color="green", xlabel="Yes/No", ylabel="Percentage", yformatter='%d%%')\
    * hv.Text('yes', 15, f"{np.round(vis_passed_df_unworn['yes']/sum(vis_passed_df_unworn)*100)}%")\
    * hv.Text('no', 15, f"{np.round(vis_passed_df_unworn['no']/sum(vis_passed_df_unworn)*100)}%")
((finalized_worn + finalized_unworn) + (vis_inspection_worn + vis_inspection_unworn)).opts(opts.Bars(width=400, height=300, tools=['hover'], show_grid=True)).cols(2)
```

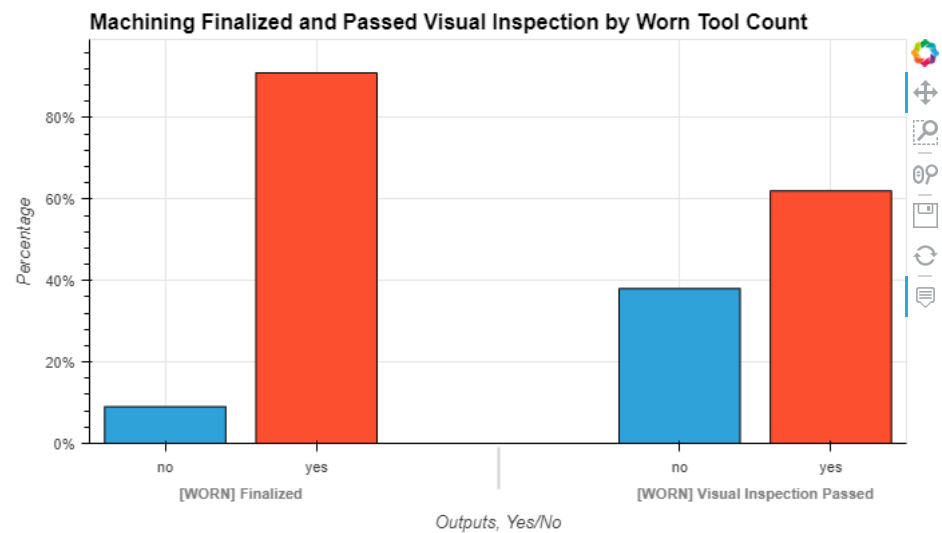


```

In [32]: worn_fin_vis = pd.concat([finalized_df_worn, vis_passed_df_worn], axis=1, sort=True).rename(columns={'machining_finalized': '[WORN] Finalized', 'passed_visual_inspection': '[WORN] Visual Inspection Passed'})
worn_fin_vis = pd.melt(worn_fin_vis.reset_index(), ['index']).rename(columns={'index': 'Yes/No', 'variable': 'Outputs'})
hv.Bars(worn_fin_vis, ['Outputs', 'Yes/No'], 'value').opts(opts.Bars(title="Machining Finalized and Passed Visual Inspection by Worn Tool Count", width=700, height=400,
show_grid=True, ylabel="Percentage", yformatter='%d%'))

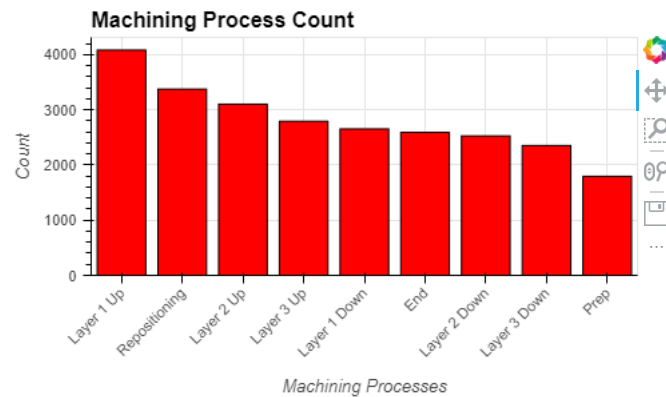
```

Out[32]:



```
In [33]: hv.Bars(df['Machining_Process'].value_counts()).opts(title="Machining Process Count", color="red", xlabel="Machining Processes", ylabel="Count")\
        .opts(opts.Bars(width=500, height=300,tools=['hover'],xrotation=45,show_grid=True))
```

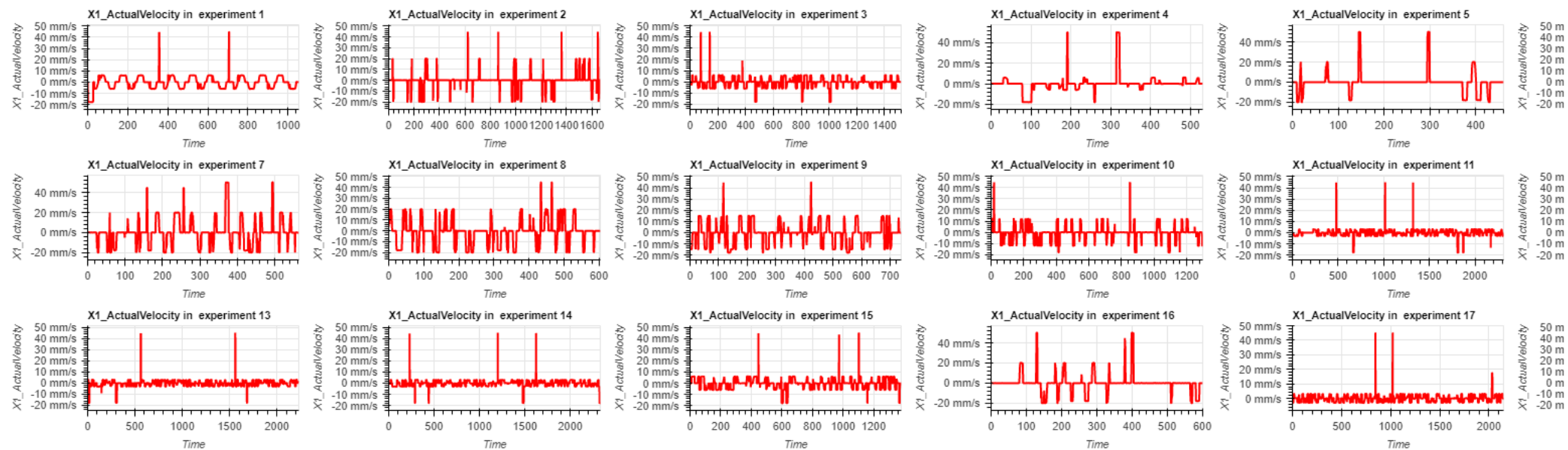
Out[33]:



```
In [34]: def plot_ts(col, color='red', yformat='%d%%'):\
        v_list = []\
        for i in range(0, csv_count + 1):\
            v = hv.Curve(df[df['exp_no']==i].reset_index()[col]).opts(title=f"{col} in experiment {i}", xlabel="Time", ylabel=f"{col}", yformatter=yformat)\
                .opts(width=300, height=150,tools=['hover'],show_grid=True,fontsize=8, color=color)\
            v_list.append(v)\
        return (v_list[1] + v_list[2] + v_list[3] + v_list[4] + v_list[5] + v_list[6] + v_list[7] + v_list[8] + v_list[9] \
            + v_list[10] + v_list[11] + v_list[12] + v_list[13] + v_list[14] + v_list[15] + v_list[16] + v_list[17] + v_list[18]).opts(shared_axes=False).cols(6)
```

```
In [35]: plot_ts('X1_ActualVelocity', color='red', yformat='%d mm/s')
```

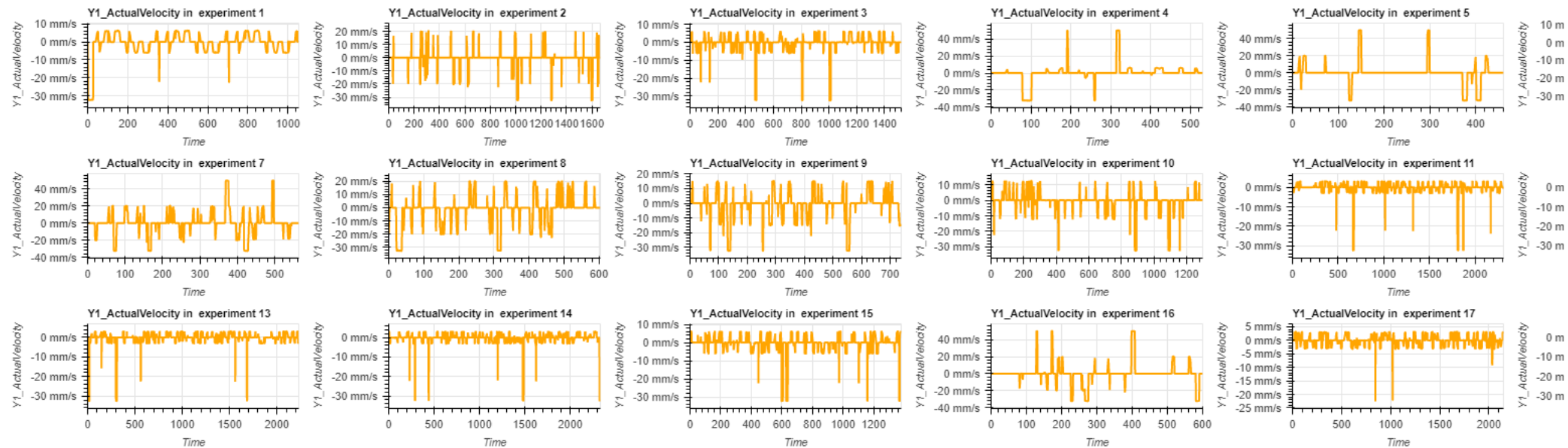
Out[35]:



In [59]:

```
plot_ts('Y1_ActualVelocity', color='orange', yformat='%d mm/s')
```

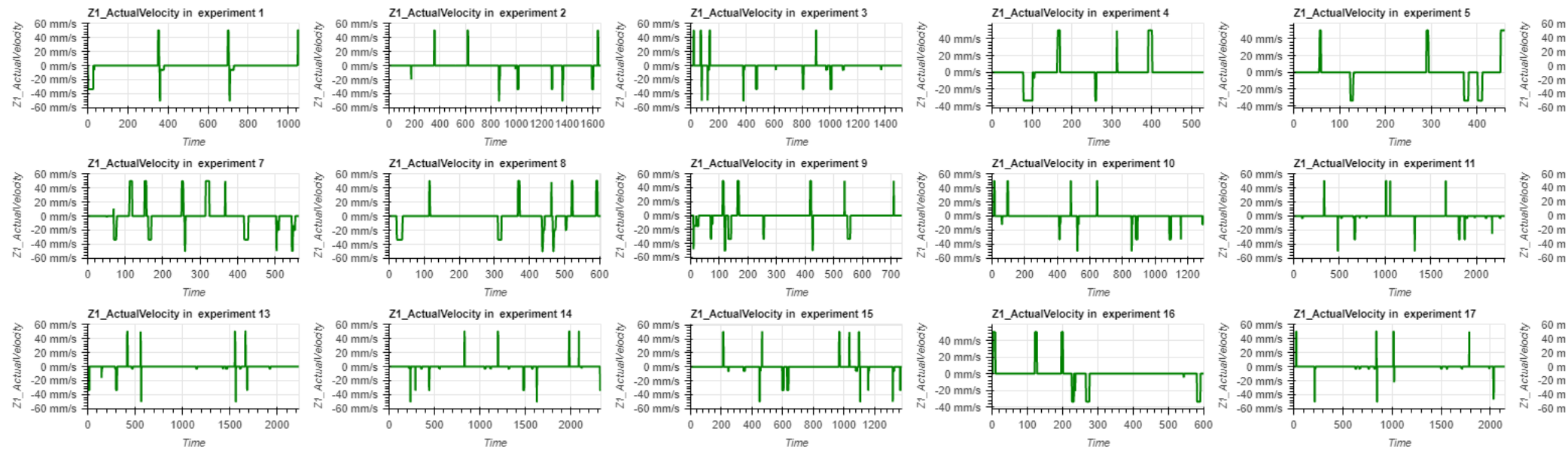
Out[59]:



In [60]:

```
plot_ts('Z1_ActualVelocity', color='green', yformat='%d mm/s')
```

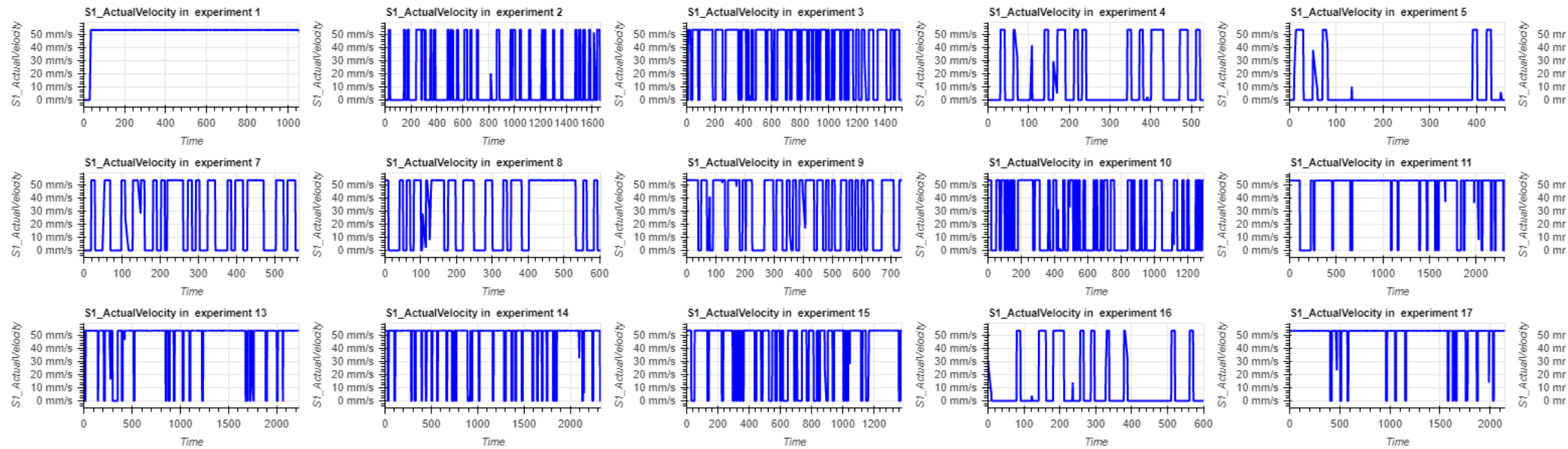
Out[60]:



In [61]:

```
plot_ts('S1_ActualVelocity', color='blue', yformat='%d mm/s')
```

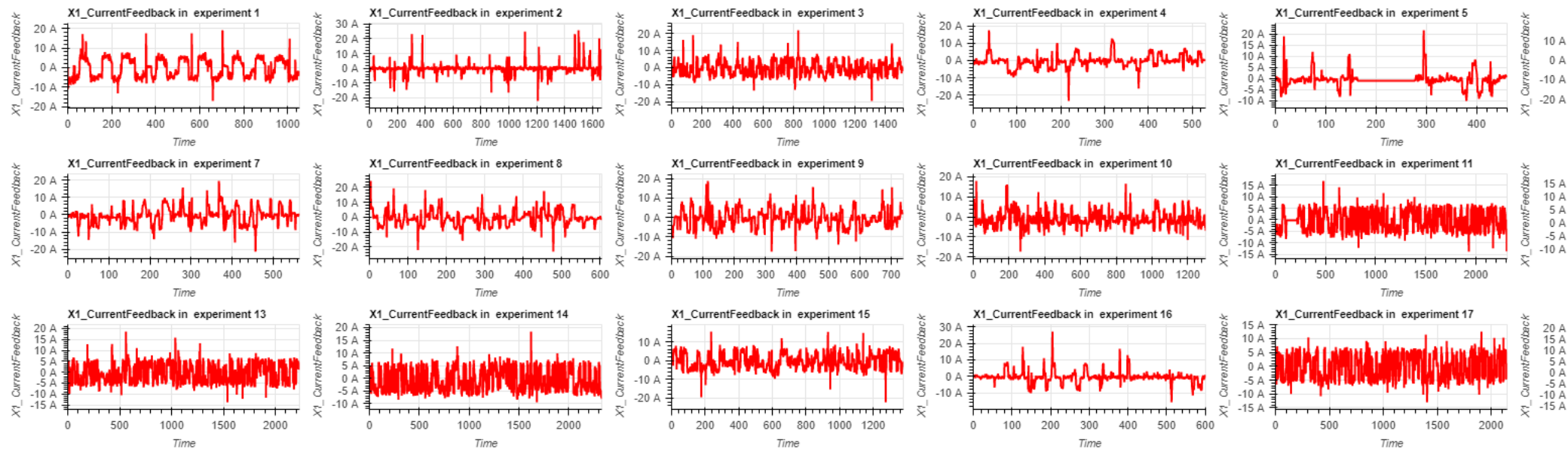
Out[61]:



In [62]:

```
plot_ts('X1_CurrentFeedback', color='red', yformat='%d A')
```

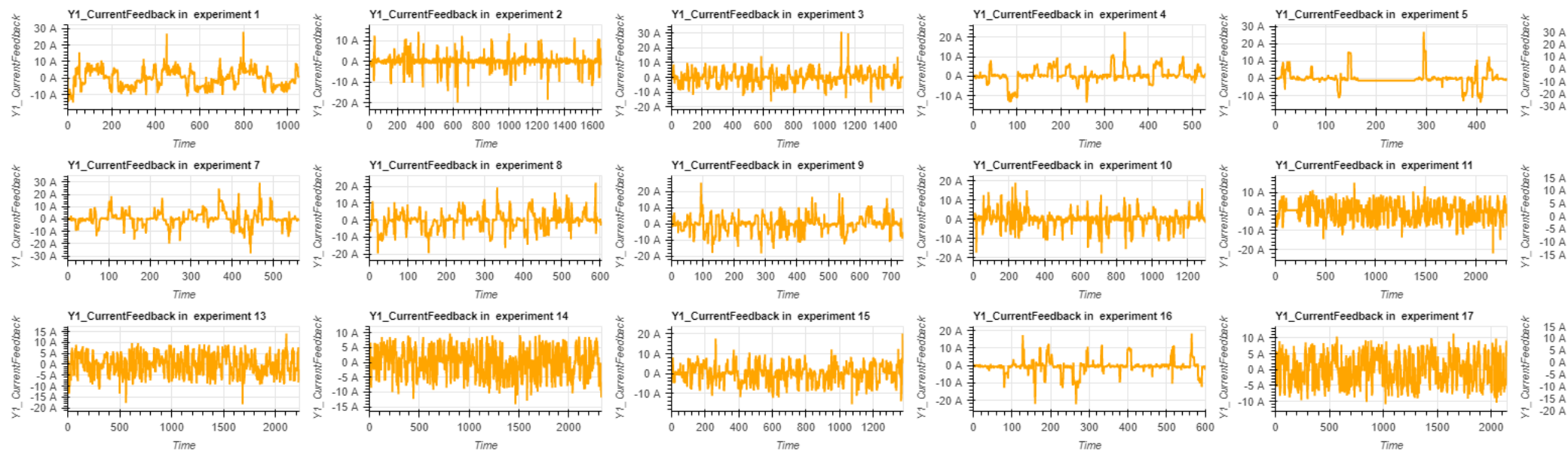
Out[62]:



In [63]:

```
plot_ts('Y1_CurrentFeedback', color='orange', yformat='%d A')
```

Out[63]:

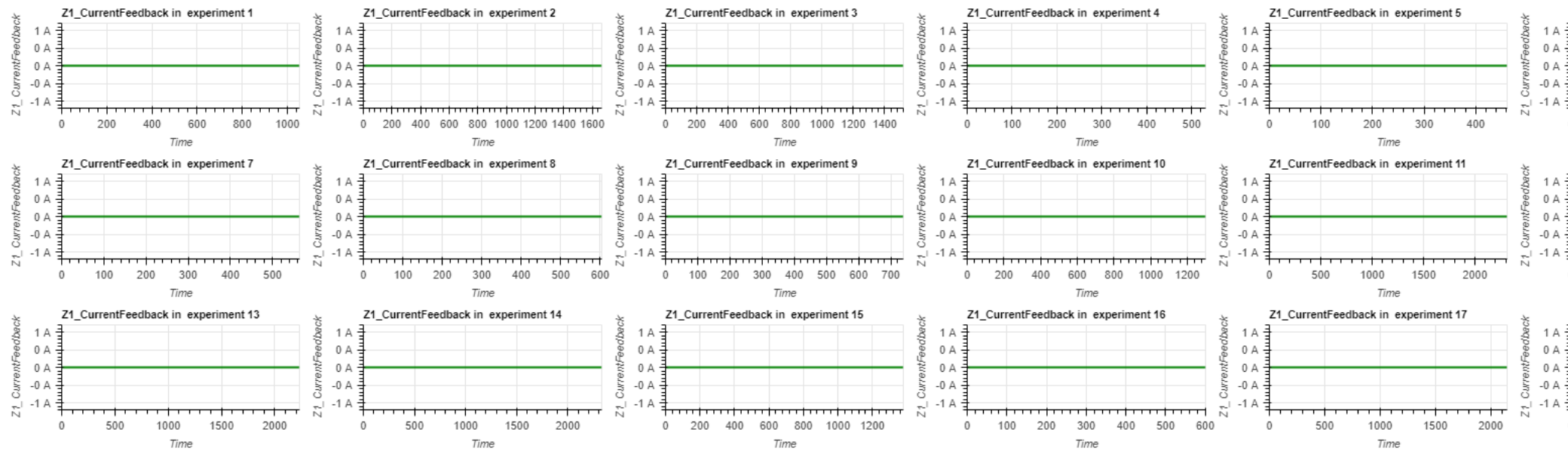


In [64]:

```
plot_ts('Z1_CurrentFeedback', color='green', yformat='%d A')
```

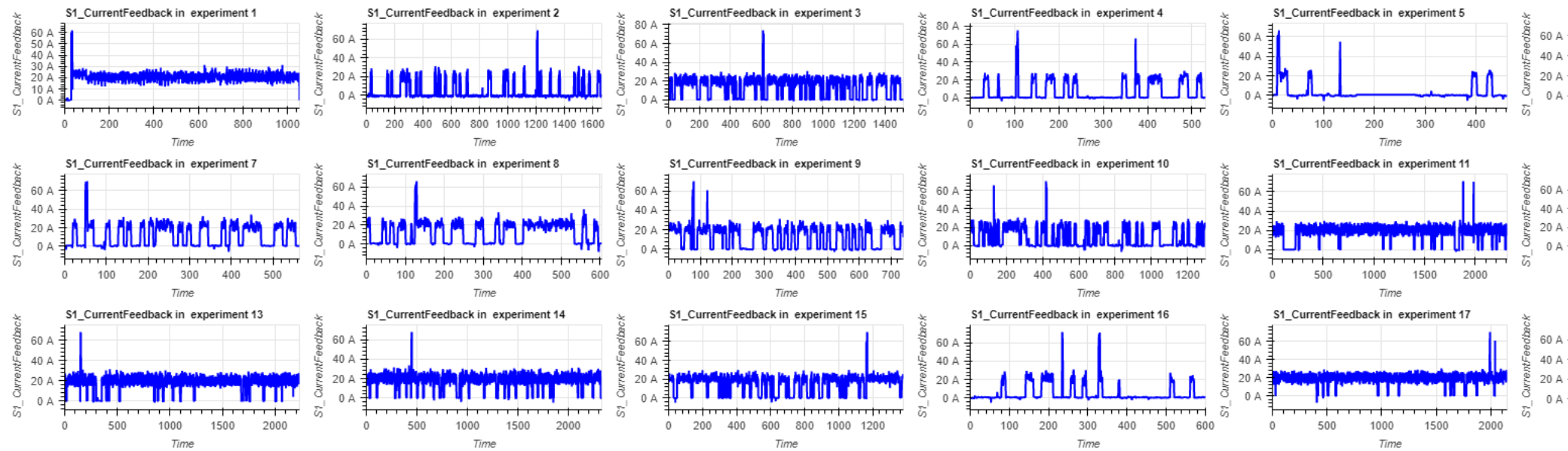


Out[64]:



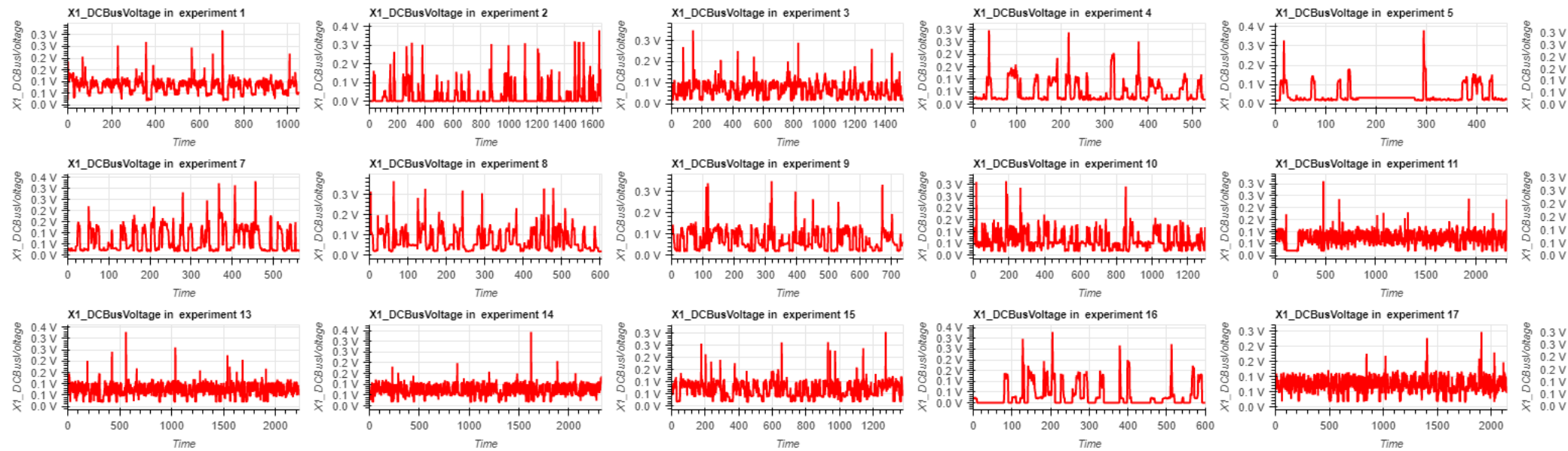
```
In [65]: plot_ts('S1_CurrentFeedback', color='blue', yformat='%d A')
```

Out[65]:



```
In [66]: plot_ts('X1_DCBusVoltage', color='red', yformat='%0.1f V')
```

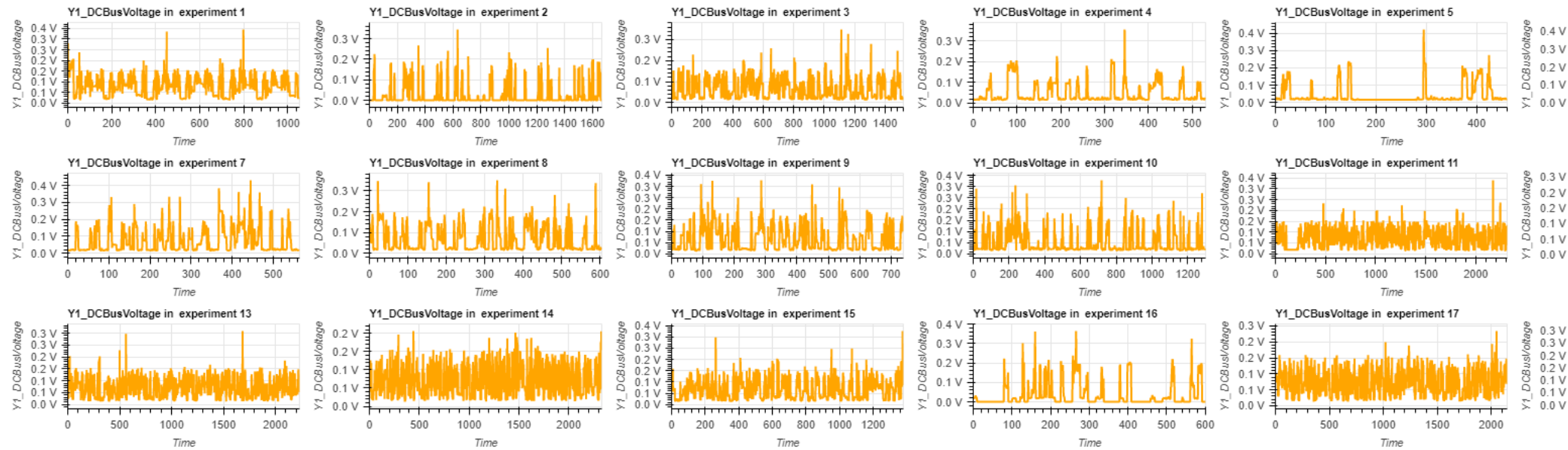
Out[66]:



In [67]:

```
plot_ts('Y1_DCBusVoltage', color='orange', yformat='%.1f V')
```

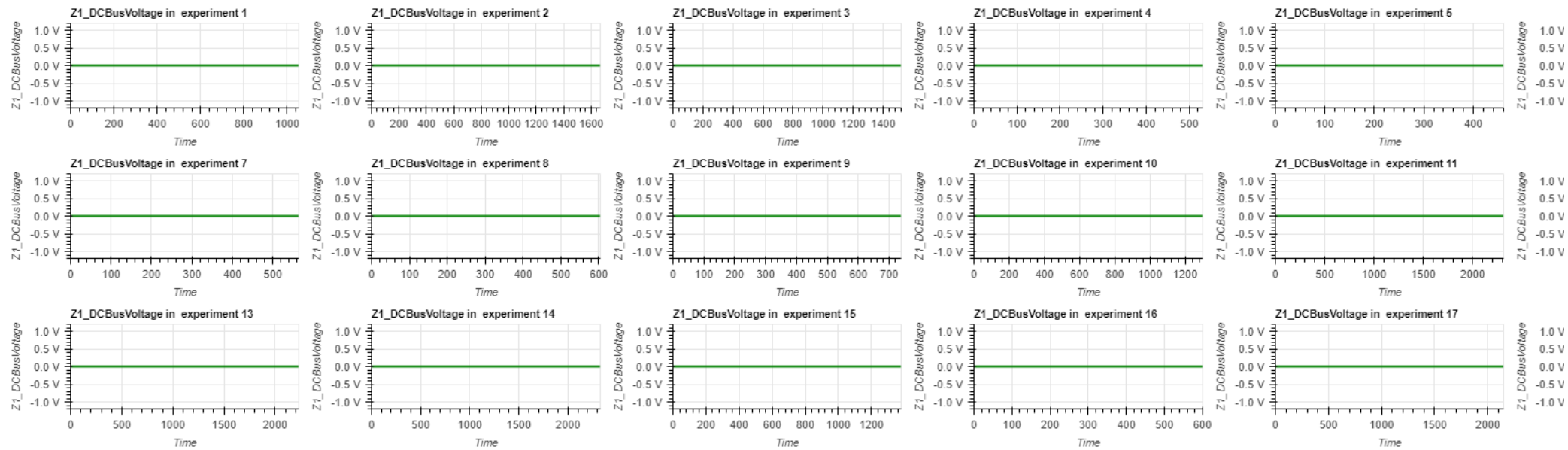
Out[67]:



In [68]:

```
plot_ts('Z1_DCBusVoltage', color='green', yformat='%.1f V')
```

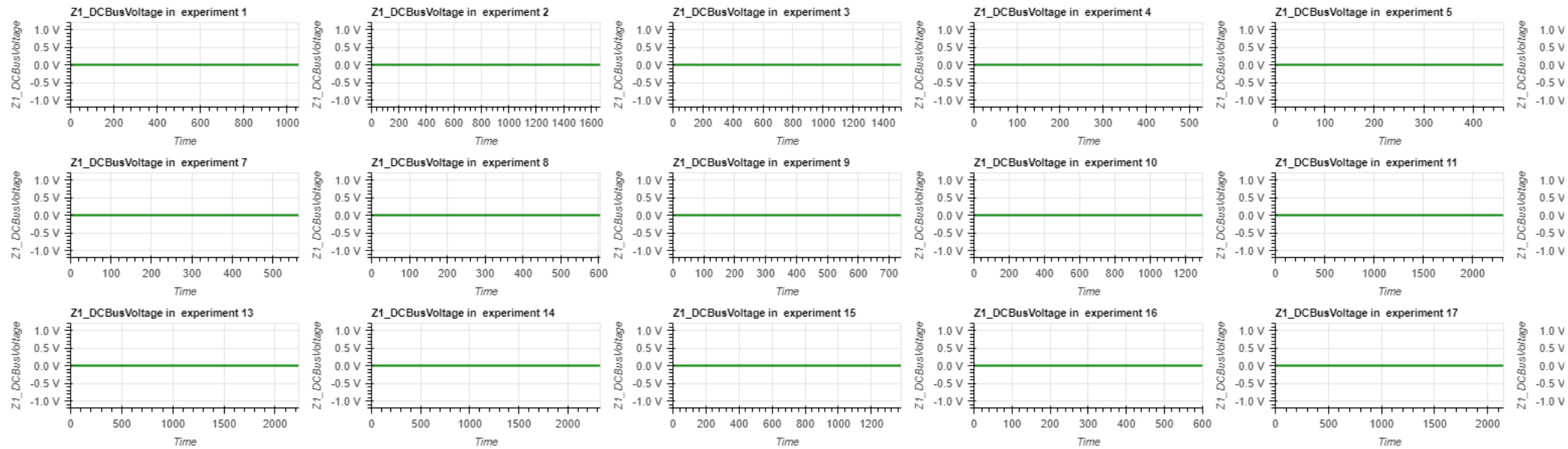
Out[68]:



In [69]:

```
plot_ts('Z1_DCBusVoltage', color='green', yformat='%.1f V')
```

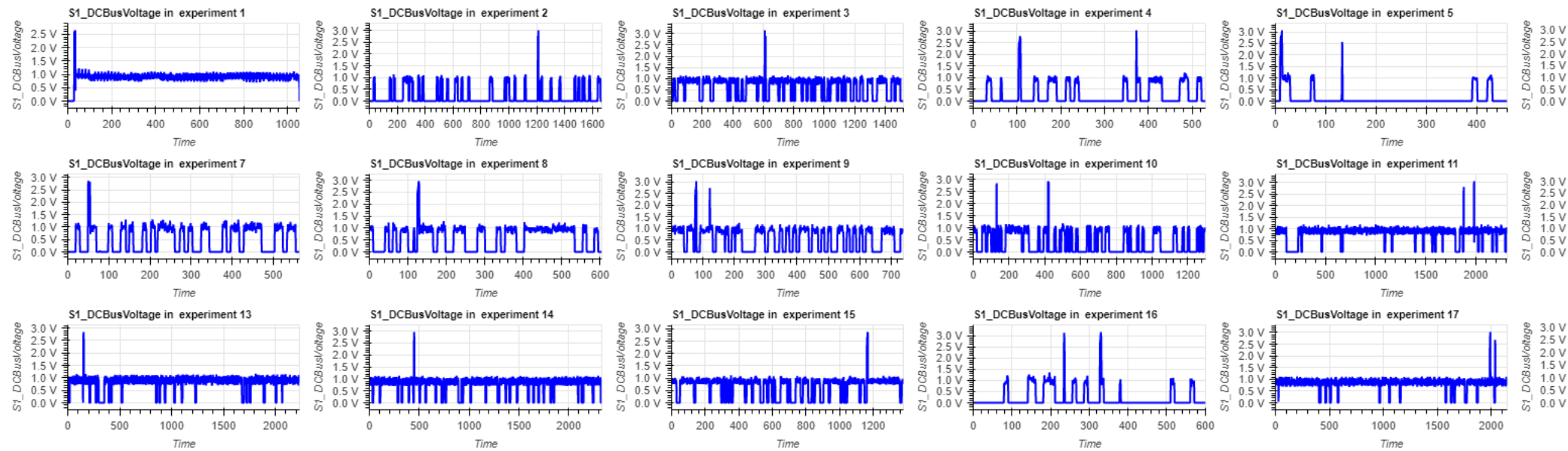
Out[69]:



In [70]:

```
plot_ts('S1_DCBusVoltage', color='blue', yformat='%.1f V')
```

Out[70]:



## Multivariate Analysis

### Feedrate / Clamp Pressure

- Tool Condition

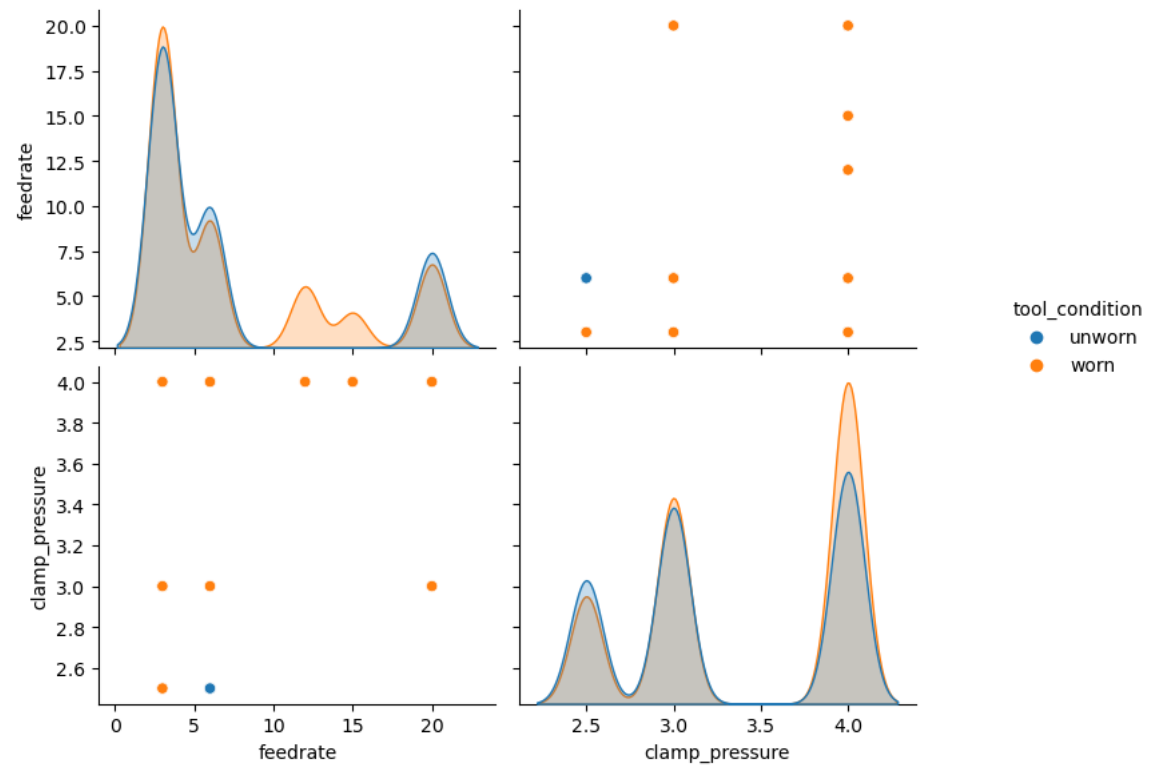
distributions of clamp pressure with unworn/worn tool are almost same. </br> distribution of feedrate with worn tool is more wider than that with unworn tool.</br>

- Machining Finalized</br>

distribution of clamp pressure in machining not finalized experiment has lower kurtosis.</br> distribution of feedrate in machining not finalized experiment has higher kurtosis. </br>

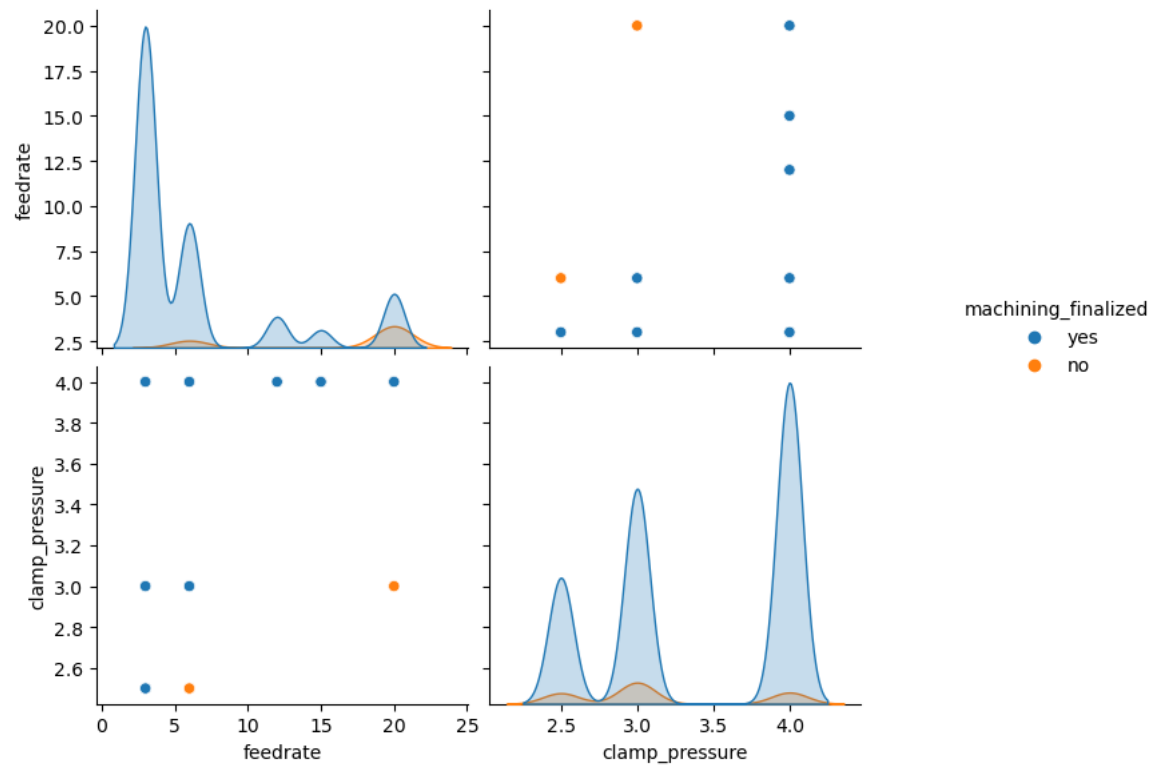
```
In [71]: g = sns.pairplot(df, hue='tool_condition', vars=["feedrate","clamp_pressure"])
g.fig.suptitle("Tool Condition - feedrate/clamp pressure", y=1.1, fontsize=20)
g.fig.set_figheight(6)
g.fig.set_figwidth(9)
plt.show()
```

## Tool Condition - feedrate/clamp pressure



```
In [72]: g = sns.pairplot(df, hue='machining_finalized', vars=["feedrate","clamp_pressure"])
g.fig.suptitle("Machining Finalized - feedrate/clamp pressure", y=1.1, fontsize=20)
g.fig.set_figheight(6)
g.fig.set_figwidth(9)
plt.show()
```

# Machining Finalized - feedrate/clamp pressure



## Velocity

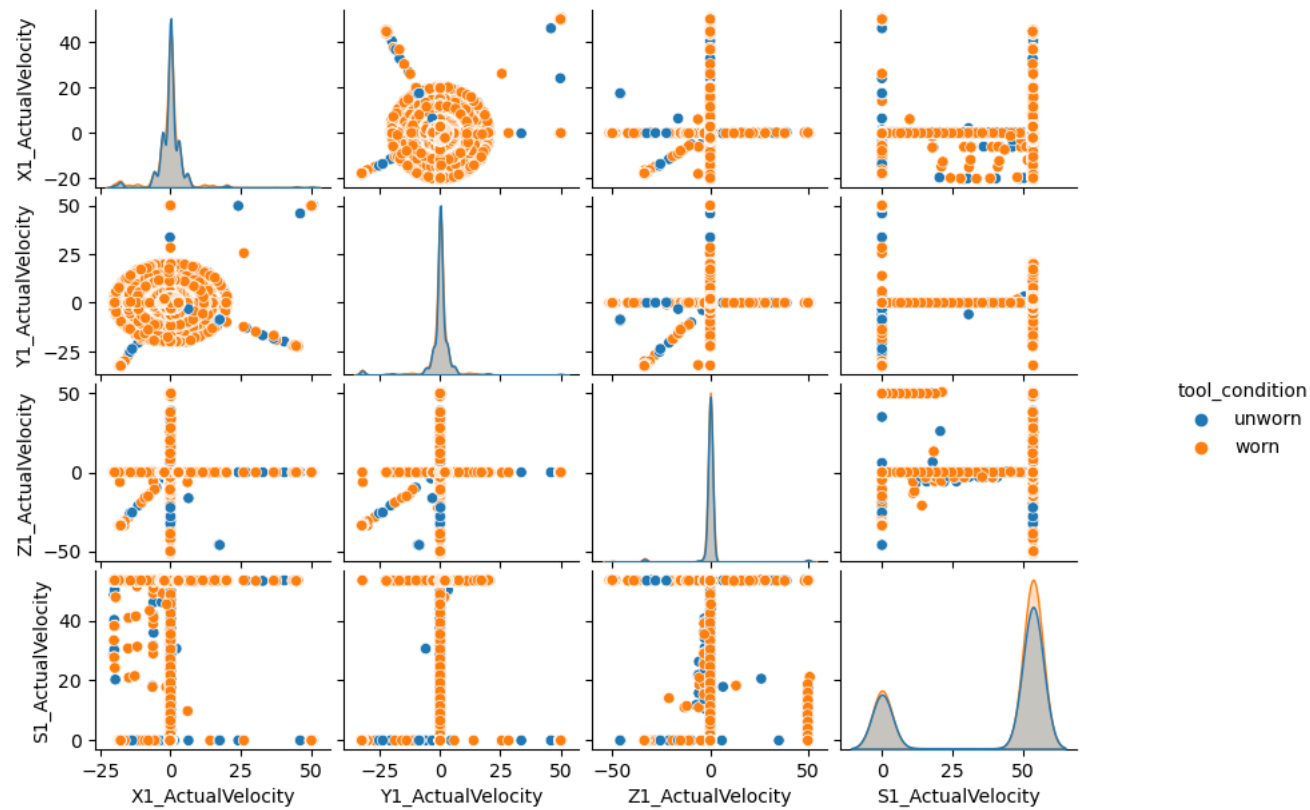
- Machining Finalized

distribution of velocity in S axis in machining not finalized experiment has lower kurtosis.

In [73]:

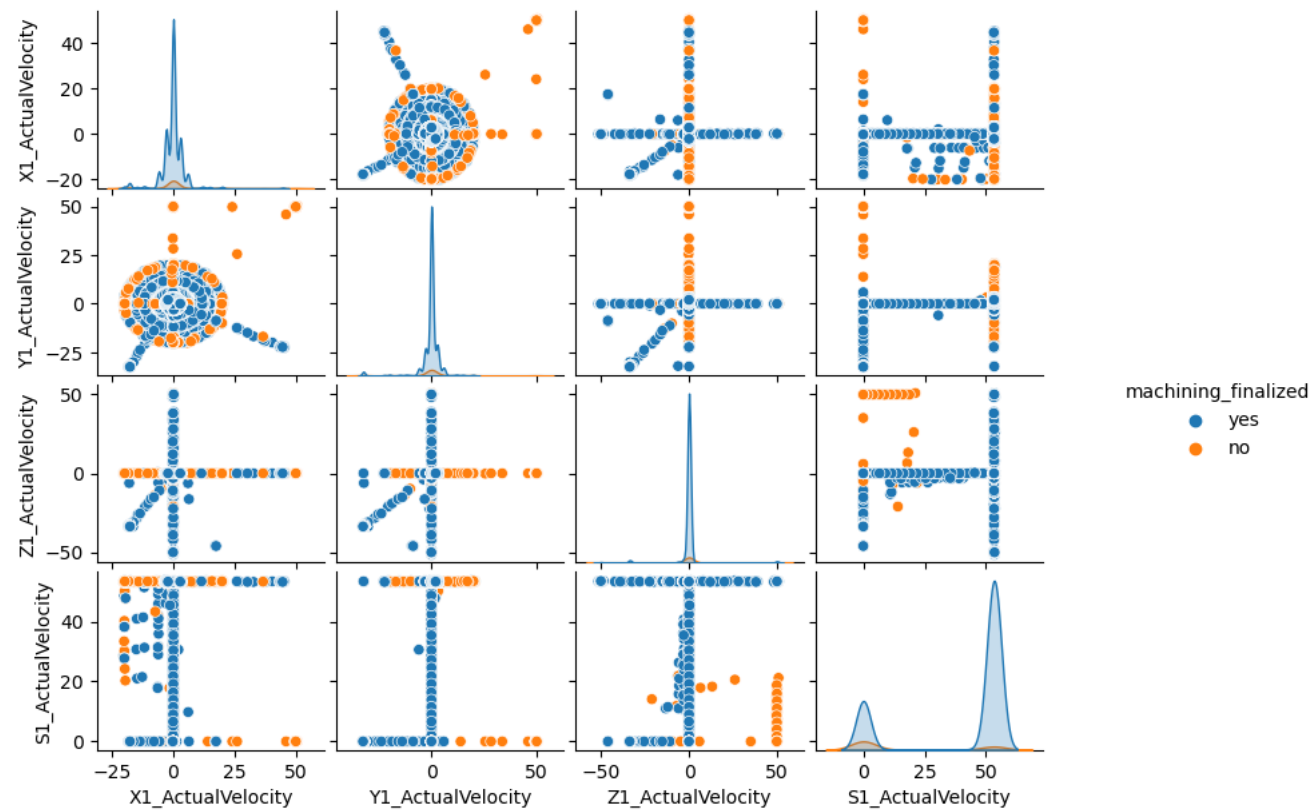
```
g = sns.pairplot(df, hue='tool_condition', vars=['X1_ActualVelocity', 'Y1_ActualVelocity', 'Z1_ActualVelocity', 'S1_ActualVelocity'])
g.fig.suptitle("Tool Condition - velocity", y=1.1, fontsize=20)
g.fig.set_figheight(6)
g.fig.set_figwidth(9)
g.fig.get_children()[-1].set_bbox_to_anchor((1.1, 0.5, 0, 0))
plt.show()
```

## Tool Condition - velocity



```
In [74]: g = sns.pairplot(df, hue='machining_finalized', vars=['X1_ActualVelocity', 'Y1_ActualVelocity', 'Z1_ActualVelocity', 'S1_ActualVelocity'])
g.fig.suptitle("Machining Finalized - velocity", y=1.1, fontsize=20)
g.fig.set_figheight(6)
g.fig.set_figwidth(9)
g.fig.get_children()[-1].set_bbox_to_anchor((1.1, 0.5, 0, 0))
plt.show()
```

## Machining Finalized - velocity



In [75]: exp\_result



Out[75]:

|    | exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection | class  |
|----|--------|----------|----------|----------------|----------------|---------------------|--------------------------|--------|
| 0  | 1      | wax      | 6        | 4.0            | unworn         | yes                 | yes                      | pass   |
| 1  | 2      | wax      | 20       | 4.0            | unworn         | yes                 | yes                      | pass   |
| 2  | 3      | wax      | 6        | 3.0            | unworn         | yes                 | yes                      | pass   |
| 3  | 4      | wax      | 6        | 2.5            | unworn         | no                  | no                       | defect |
| 4  | 5      | wax      | 20       | 3.0            | unworn         | no                  | no                       | defect |
| 5  | 6      | wax      | 6        | 4.0            | worn           | yes                 | no                       | defect |
| 6  | 7      | wax      | 20       | 4.0            | worn           | no                  | no                       | defect |
| 7  | 8      | wax      | 20       | 4.0            | worn           | yes                 | no                       | defect |
| 8  | 9      | wax      | 15       | 4.0            | worn           | yes                 | no                       | defect |
| 9  | 10     | wax      | 12       | 4.0            | worn           | yes                 | no                       | defect |
| 10 | 11     | wax      | 3        | 4.0            | unworn         | yes                 | yes                      | pass   |
| 11 | 12     | wax      | 3        | 3.0            | unworn         | yes                 | yes                      | pass   |
| 12 | 13     | wax      | 3        | 4.0            | worn           | yes                 | yes                      | pass   |
| 13 | 14     | wax      | 3        | 3.0            | worn           | yes                 | yes                      | pass   |
| 14 | 15     | wax      | 6        | 3.0            | worn           | yes                 | yes                      | pass   |
| 15 | 16     | wax      | 20       | 3.0            | worn           | no                  | no                       | defect |
| 16 | 17     | wax      | 3        | 2.5            | unworn         | yes                 | yes                      | pass   |
| 17 | 18     | wax      | 3        | 2.5            | worn           | yes                 | yes                      | pass   |

## DataFrame Save to csv

In [76]:

```
save_csv = "exp_pkk.csv"
df.to_csv(save_csv)
```

## csv load

In [77]:

```
exp_df = pd.read_csv(save_csv, header=0, encoding="utf-8")
exp_df
```

Out[77]:

|       | Unnamed: 0 | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | ... | M1_CURRENT_FEEDRATE | Machining_Process | exp_no | material |
|-------|------------|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|-----|---------------------|-------------------|--------|----------|
| 0     | 0          | 198.0             | 0.00              | 0.00                  | 198.0              | 0.00               | 0.000000               | 0.18               | 0.0207          | 329.0            | ... | 50.0                | Prep              | 1      | wax      |
| 1     | 1          | 198.0             | -10.80            | -350.00               | 198.0              | -13.60             | -358.000000            | -10.90             | 0.1860          | 328.0            | ... | 50.0                | Prep              | 1      | wax      |
| 2     | 2          | 196.0             | -17.80            | -6.25                 | 196.0              | -17.90             | -0.000095              | -8.59              | 0.1400          | 328.0            | ... | 50.0                | Prep              | 1      | wax      |
| 3     | 3          | 194.0             | -18.00            | 0.00                  | 194.0              | -17.90             | -0.000095              | -6.11              | 0.1300          | 327.0            | ... | 50.0                | Prep              | 1      | wax      |
| 4     | 4          | 193.0             | -17.90            | -18.80                | 192.0              | -17.90             | 0.000095               | -5.70              | 0.1140          | 328.0            | ... | 50.0                | Prep              | 1      | wax      |
| ...   | ...        | ...               | ...               | ...                   | ...                | ...                | ...                    | ...                | ...             | ...              | ... | ...                 | ...               | ...    | ...      |
| 25281 | 25281      | 144.0             | -2.30             | 100.00                | 144.0              | -2.57              | 0.977000               | -5.05              | 0.0732          | 327.0            | ... | 3.0                 | End               | 18     | wax      |
| 25282 | 25282      | 144.0             | -2.47             | 25.00                 | 144.0              | -2.46              | 1.080000               | -5.62              | 0.0996          | 327.0            | ... | 3.0                 | End               | 18     | wax      |
| 25283 | 25283      | 143.0             | -2.20             | 81.20                 | 143.0              | -2.35              | 1.170000               | -4.42              | 0.0539          | 327.0            | ... | 3.0                 | End               | 18     | wax      |
| 25284 | 25284      | 143.0             | -2.05             | 68.70                 | 143.0              | -2.23              | 1.260000               | -5.83              | 0.0809          | 327.0            | ... | 3.0                 | End               | 18     | wax      |
| 25285 | 25285      | 143.0             | -2.15             | -68.70                | 143.0              | -2.09              | 1.350000               | -4.37              | 0.0857          | 327.0            | ... | 3.0                 | End               | 18     | wax      |

25286 rows × 57 columns

◀

▶

In [78]:

exp\_df.info()

```
<class 'pandas.core.frame.DataFrame'>
RangeIndex: 25286 entries, 0 to 25285
Data columns (total 57 columns):
#   Column                                Non-Null Count  Dtype
---  -
0   Unnamed: 0                            25286 non-null  int64
1   X1_ActualPosition                     25286 non-null  float64
2   X1_ActualVelocity                     25286 non-null  float64
3   X1_ActualAcceleration                 25286 non-null  float64
4   X1_CommandPosition                   25286 non-null  float64
5   X1_CommandVelocity                   25286 non-null  float64
6   X1_CommandAcceleration                25286 non-null  float64
7   X1_CurrentFeedback                   25286 non-null  float64
8   X1_DCBusVoltage                      25286 non-null  float64
9   X1_OutputCurrent                     25286 non-null  float64
10  X1_OutputVoltage                     25286 non-null  float64
11  X1_OutputPower                       25286 non-null  float64
12  Y1_ActualPosition                     25286 non-null  float64
13  Y1_ActualVelocity                     25286 non-null  float64
14  Y1_ActualAcceleration                 25286 non-null  float64
15  Y1_CommandPosition                   25286 non-null  float64
16  Y1_CommandVelocity                   25286 non-null  float64
17  Y1_CommandAcceleration                25286 non-null  float64
18  Y1_CurrentFeedback                   25286 non-null  float64
19  Y1_DCBusVoltage                      25286 non-null  float64
20  Y1_OutputCurrent                     25286 non-null  float64
21  Y1_OutputVoltage                     25286 non-null  float64
22  Y1_OutputPower                       25286 non-null  float64
23  Z1_ActualPosition                     25286 non-null  float64
24  Z1_ActualVelocity                     25286 non-null  float64
25  Z1_ActualAcceleration                 25286 non-null  float64
26  Z1_CommandPosition                   25286 non-null  float64
27  Z1_CommandVelocity                   25286 non-null  float64
28  Z1_CommandAcceleration                25286 non-null  float64
29  Z1_CurrentFeedback                   25286 non-null  float64
30  Z1_DCBusVoltage                      25286 non-null  float64
31  Z1_OutputCurrent                     25286 non-null  float64
32  Z1_OutputVoltage                     25286 non-null  float64
33  S1_ActualPosition                     25286 non-null  float64
34  S1_ActualVelocity                     25286 non-null  float64
35  S1_ActualAcceleration                 25286 non-null  float64
36  S1_CommandPosition                   25286 non-null  float64
37  S1_CommandVelocity                   25286 non-null  float64
38  S1_CommandAcceleration                25286 non-null  float64
39  S1_CurrentFeedback                   25286 non-null  float64
40  S1_DCBusVoltage                      25286 non-null  float64
41  S1_OutputCurrent                     25286 non-null  float64
42  S1_OutputVoltage                     25286 non-null  float64
43  S1_OutputPower                       25286 non-null  float64
44  S1_SystemInertia                     25286 non-null  float64
45  M1_CURRENT_PROGRAM_NUMBER            25286 non-null  float64
46  M1_sequence_number                   25286 non-null  float64
47  M1_CURRENT_FEEDRATE                  25286 non-null  float64
48  Machining_Process                    25286 non-null  object
49  exp_no                               25286 non-null  int64
50  material                             25286 non-null  object
51  feedrate                             25286 non-null  int64
52  clamp_pressure                       25286 non-null  float64
53  tool_condition                       25286 non-null  object
54  machining_finalized                  25286 non-null  object
55  passed_visual_inspection             25286 non-null  object
56  class                                25286 non-null  object
dtypes: float64(48), int64(3), object(6)
memory usage: 11.0+ MB
```

In [79]:

```
exp_df = exp_df.drop(columns = ['material'])

exp_df.head()
```

Out[79]:

|   | Unnamed: 0 | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | ... | M1_sequence_number | M1_CURRENT_FEEDRATE | Machining_Process | e: |
|---|------------|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|-----|--------------------|---------------------|-------------------|----|
| 0 | 0          | 198.0             | 0.0               | 0.00                  | 198.0              | 0.0                | 0.000000               | 0.18               | 0.0207          | 329.0            | ... | 0.0                | 50.0                | Prep              |    |
| 1 | 1          | 198.0             | -10.8             | -350.00               | 198.0              | -13.6              | -358.000000            | -10.90             | 0.1860          | 328.0            | ... | 4.0                | 50.0                | Prep              |    |
| 2 | 2          | 196.0             | -17.8             | -6.25                 | 196.0              | -17.9              | -0.000095              | -8.59              | 0.1400          | 328.0            | ... | 7.0                | 50.0                | Prep              |    |
| 3 | 3          | 194.0             | -18.0             | 0.00                  | 194.0              | -17.9              | -0.000095              | -6.11              | 0.1300          | 327.0            | ... | 7.0                | 50.0                | Prep              |    |
| 4 | 4          | 193.0             | -17.9             | -18.80                | 192.0              | -17.9              | 0.000095               | -5.70              | 0.1140          | 328.0            | ... | 7.0                | 50.0                | Prep              |    |

5 rows × 56 columns

In [80]:

```
exp_df.groupby('tool_condition').count()
```

Out[80]:

|                | Unnamed: 0 | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | ...   | M1_CURRENT_PROGRAM_NUMBER | M1_sequence_number | M     |
|----------------|------------|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|-------|---------------------------|--------------------|-------|
| tool_condition |            |                   |                   |                       |                    |                    |                        |                    |                 |                  |       |                           |                    |       |
| unworn         | 11978      | 11978             | 11978             | 11978                 | 11978              | 11978              | 11978                  | 11978              | 11978           | 11978            | 11978 | ...                       | 11978              | 11978 |
| worn           | 13308      | 13308             | 13308             | 13308                 | 13308              | 13308              | 13308                  | 13308              | 13308           | 13308            | 13308 | ...                       | 13308              | 13308 |

2 rows × 55 columns

In [81]:

```
exp_df['Machining_Process'].value_counts().sort_index()
```

Out[81]:

```
End                2593
Layer 1 Down       2655
Layer 1 Up         4085
Layer 2 Down       2528
Layer 2 Up         3104
Layer 3 Down       2354
Layer 3 Up         2794
Prep               1796
Repositioning      3377
Name: Machining_Process, dtype: int64
```

In [82]:

```
exp_df.loc[exp_df['tool_condition'] == 'unworn', 'tool_condition'] = 0 # unworn(비마모) : 0
exp_df.loc[exp_df['tool_condition'] == 'worn', 'tool_condition'] = 1  # worn(마모) : 1

exp_df.loc[exp_df['machining_finalized'] == 'yes', 'machining_finalized'] = 0 # 공정완료: 0
exp_df.loc[exp_df['machining_finalized'] == 'no', 'machining_finalized'] = 1  # 공정미완료: 1

exp_df.loc[exp_df['machining_finalized'] == 1, 'passed_visual_inspection'] = 2 # 공정미완료

exp_df.loc[(exp_df['machining_finalized'] == 0) & (df['passed_visual_inspection'] == 'no'), 'passed_visual_inspection'] = 1 #공정완료, 육안검사 불합격
exp_df.loc[(exp_df['machining_finalized'] == 0) & (df['passed_visual_inspection'] == 'yes'), 'passed_visual_inspection'] = 0 #공정완료, 육안검사 합격

exp_df
```

Out[82]:

|  | Unnamed: 0 | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | ...       | M1_sequence_number | M1_CURRENT_FEEDRATE | Machining_Proces: |
|--|------------|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|-----------|--------------------|---------------------|-------------------|
|  | 0          | 0                 | 198.0             | 0.00                  | 0.00               | 198.0              | 0.00                   | 0.000000           | 0.18            | 0.0207           | 329.0 ... | 0.0                | 50.0                | Prej              |
|  | 1          | 1                 | 198.0             | -10.80                | -350.00            | 198.0              | -13.60                 | -358.000000        | -10.90          | 0.1860           | 328.0 ... | 4.0                | 50.0                | Prej              |
|  | 2          | 2                 | 196.0             | -17.80                | -6.25              | 196.0              | -17.90                 | -0.000095          | -8.59           | 0.1400           | 328.0 ... | 7.0                | 50.0                | Prej              |
|  | 3          | 3                 | 194.0             | -18.00                | 0.00               | 194.0              | -17.90                 | -0.000095          | -6.11           | 0.1300           | 327.0 ... | 7.0                | 50.0                | Prej              |
|  | 4          | 4                 | 193.0             | -17.90                | -18.80             | 192.0              | -17.90                 | 0.000095           | -5.70           | 0.1140           | 328.0 ... | 7.0                | 50.0                | Prej              |
|  | ...        | ...               | ...               | ...                   | ...                | ...                | ...                    | ...                | ...             | ...              | ...       | ...                | ...                 | ...               |
|  | 25281      | 25281             | 144.0             | -2.30                 | 100.00             | 144.0              | -2.57                  | 0.977000           | -5.05           | 0.0732           | 327.0 ... | 57.0               | 3.0                 | Eni               |
|  | 25282      | 25282             | 144.0             | -2.47                 | 25.00              | 144.0              | -2.46                  | 1.080000           | -5.62           | 0.0996           | 327.0 ... | 57.0               | 3.0                 | Eni               |
|  | 25283      | 25283             | 143.0             | -2.20                 | 81.20              | 143.0              | -2.35                  | 1.170000           | -4.42           | 0.0539           | 327.0 ... | 57.0               | 3.0                 | Eni               |
|  | 25284      | 25284             | 143.0             | -2.05                 | 68.70              | 143.0              | -2.23                  | 1.260000           | -5.83           | 0.0809           | 327.0 ... | 57.0               | 3.0                 | Eni               |
|  | 25285      | 25285             | 143.0             | -2.15                 | -68.70             | 143.0              | -2.09                  | 1.350000           | -4.37           | 0.0857           | 327.0 ... | 57.0               | 3.0                 | Eni               |

25286 rows × 56 columns

In [83]:

exp\_df.loc[(exp\_df['class'] == 'pass'), 'class'] = 0 #공정완료, 육안검사 불합격  
exp\_df.loc[(exp\_df['class'] == 'defect'), 'class'] = 1  
exp\_df

Out[83]:

|  | Unnamed: 0 | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | ...       | M1_sequence_number | M1_CURRENT_FEEDRATE | Machining_Proces: |
|--|------------|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|-----------|--------------------|---------------------|-------------------|
|  | 0          | 0                 | 198.0             | 0.00                  | 0.00               | 198.0              | 0.00                   | 0.000000           | 0.18            | 0.0207           | 329.0 ... | 0.0                | 50.0                | Prej              |
|  | 1          | 1                 | 198.0             | -10.80                | -350.00            | 198.0              | -13.60                 | -358.000000        | -10.90          | 0.1860           | 328.0 ... | 4.0                | 50.0                | Prej              |
|  | 2          | 2                 | 196.0             | -17.80                | -6.25              | 196.0              | -17.90                 | -0.000095          | -8.59           | 0.1400           | 328.0 ... | 7.0                | 50.0                | Prej              |
|  | 3          | 3                 | 194.0             | -18.00                | 0.00               | 194.0              | -17.90                 | -0.000095          | -6.11           | 0.1300           | 327.0 ... | 7.0                | 50.0                | Prej              |
|  | 4          | 4                 | 193.0             | -17.90                | -18.80             | 192.0              | -17.90                 | 0.000095           | -5.70           | 0.1140           | 328.0 ... | 7.0                | 50.0                | Prej              |
|  | ...        | ...               | ...               | ...                   | ...                | ...                | ...                    | ...                | ...             | ...              | ...       | ...                | ...                 | ...               |
|  | 25281      | 25281             | 144.0             | -2.30                 | 100.00             | 144.0              | -2.57                  | 0.977000           | -5.05           | 0.0732           | 327.0 ... | 57.0               | 3.0                 | Eni               |
|  | 25282      | 25282             | 144.0             | -2.47                 | 25.00              | 144.0              | -2.46                  | 1.080000           | -5.62           | 0.0996           | 327.0 ... | 57.0               | 3.0                 | Eni               |
|  | 25283      | 25283             | 143.0             | -2.20                 | 81.20              | 143.0              | -2.35                  | 1.170000           | -4.42           | 0.0539           | 327.0 ... | 57.0               | 3.0                 | Eni               |
|  | 25284      | 25284             | 143.0             | -2.05                 | 68.70              | 143.0              | -2.23                  | 1.260000           | -5.83           | 0.0809           | 327.0 ... | 57.0               | 3.0                 | Eni               |
|  | 25285      | 25285             | 143.0             | -2.15                 | -68.70             | 143.0              | -2.09                  | 1.350000           | -4.37           | 0.0857           | 327.0 ... | 57.0               | 3.0                 | Eni               |

25286 rows × 56 columns

In [84]:

exp\_df['Machining\_Process'].value\_counts().sort\_index()

Out[84]:

|               |      |
|---------------|------|
| End           | 2593 |
| Layer 1 Down  | 2655 |
| Layer 1 Up    | 4085 |
| Layer 2 Down  | 2528 |
| Layer 2 Up    | 3104 |
| Layer 3 Down  | 2354 |
| Layer 3 Up    | 2794 |
| Prep          | 1796 |
| Repositioning | 3377 |

Name: Machining\_Process, dtype: int64

In [85]:

exp\_df.loc[exp\_df['Machining\_Process'] == 'Starting']

Out[85]: Unnamed: 0 X1\_ActualPosition X1\_ActualVelocity X1\_ActualAcceleration X1\_CommandPosition X1\_CommandVelocity X1\_CommandAcceleration X1\_CurrentFeedback X1\_DCBusVoltage X1\_OutputCurrent ... M1\_sequence\_number M1\_CURRENT\_FEEDRATE Machining\_Process exi

0 rows × 56 columns

```
In [86]: # exp_df.replace({'Machining_Process': {'Starting': 'Prep', 'end': 'End'}}, inplace=True)
exp_df.replace({'Machining_Process': {'end': 'End'}}, inplace=True)
```

```
In [87]: exp_df.loc[exp_df['Machining_Process'] == 'Prep', 'Machining_Process'] = 0
exp_df.loc[exp_df['Machining_Process'] == 'Layer 1 Up', 'Machining_Process'] = 1
exp_df.loc[exp_df['Machining_Process'] == 'Layer 1 Down', 'Machining_Process'] = 2
exp_df.loc[exp_df['Machining_Process'] == 'Layer 2 Up', 'Machining_Process'] = 3
exp_df.loc[exp_df['Machining_Process'] == 'Layer 2 Down', 'Machining_Process'] = 4
exp_df.loc[exp_df['Machining_Process'] == 'Layer 3 Up', 'Machining_Process'] = 5
exp_df.loc[exp_df['Machining_Process'] == 'Layer 3 Down', 'Machining_Process'] = 6
exp_df.loc[exp_df['Machining_Process'] == 'Repositioning', 'Machining_Process'] = 7
exp_df.loc[exp_df['Machining_Process'] == 'End', 'Machining_Process'] = 8
exp_df.loc[exp_df['Machining_Process'] == 'Starting', 'Machining_Process'] = 9

exp_df[['Machining_Process']]
```

```
Out[87]:
```

|       | Machining_Process |
|-------|-------------------|
| 0     | 0                 |
| 1     | 0                 |
| 2     | 0                 |
| 3     | 0                 |
| 4     | 0                 |
| ...   | ...               |
| 25281 | 8                 |
| 25282 | 8                 |
| 25283 | 8                 |
| 25284 | 8                 |
| 25285 | 8                 |

25286 rows × 1 columns

```
In [88]: exp_df['Machining_Process'].value_counts().sort_index()
```

```
Out[88]:
```

|   |      |
|---|------|
| 0 | 1796 |
| 1 | 4085 |
| 2 | 2655 |
| 3 | 3104 |
| 4 | 2528 |
| 5 | 2794 |
| 6 | 2354 |
| 7 | 3377 |
| 8 | 2593 |

Name: Machining\_Process, dtype: int64

```
In [89]: exp_df['Machining_Process'].value_counts().sort_index()
```

Out[89]:

|   |      |
|---|------|
| 0 | 1796 |
| 1 | 4085 |
| 2 | 2655 |
| 3 | 3104 |
| 4 | 2528 |
| 5 | 2794 |
| 6 | 2354 |
| 7 | 3377 |
| 8 | 2593 |

Name: Machining\_Process, dtype: int64

In [90]: `exp_df['Machining_Process']`

Out[90]:

|       |    |
|-------|----|
| 0     | 0  |
| 1     | 0  |
| 2     | 0  |
| 3     | 0  |
| 4     | 0  |
| ..    | .. |
| 25281 | 8  |
| 25282 | 8  |
| 25283 | 8  |
| 25284 | 8  |
| 25285 | 8  |

Name: Machining\_Process, Length: 25286, dtype: object

In [91]: `exp_df.describe()`

Out[91]:

|       | Unnamed: 0  | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | ... | S1_OutputCurrent | S1_OutputVoltage | S1_OutputPower | S1 |
|-------|-------------|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|-----|------------------|------------------|----------------|----|
| count | 25286.00000 | 25286.000000      | 25286.000000      | 25286.000000          | 25286.000000       | 25286.000000       | 25286.000000           | 25286.000000       | 2.528600e+04    | 25286.000000     | ... | 25286.000000     | 25286.000000     | 25286.000000   |    |
| mean  | 12642.50000 | 159.052045        | -0.288657         | 0.094264              | 159.050700         | -0.283076          | 0.253215               | -0.469714          | 6.603073e-02    | 326.945859       | ... | 322.784505       | 85.479195        | 0.127405       |    |
| std   | 7299.58379  | 19.330873         | 5.668260          | 93.877623             | 19.331144          | 5.664309           | 72.594951              | 4.220750           | 3.700384e-02    | 1.459937         | ... | 4.293571         | 52.531863        | 0.080753       |    |
| min   | 0.00000     | 141.000000        | -20.400000        | -1280.000000          | 141.000000         | -20.000000         | -1000.000000           | -23.400000         | 2.780000e-19    | 320.000000       | ... | 290.000000       | 0.000000         | -0.002960      |    |
| 25%   | 6321.25000  | 145.000000        | -2.050000         | -31.300000            | 145.000000         | -2.050000          | 0.000000               | -3.930000          | 4.150000e-02    | 326.000000       | ... | 320.000000       | 0.000000         | 0.000005       |    |
| 50%   | 12642.50000 | 153.000000        | 0.000000          | 0.000000              | 153.000000         | 0.000000           | 0.000000               | -0.666000          | 6.680000e-02    | 327.000000       | ... | 322.000000       | 117.000000       | 0.164000       |    |
| 75%   | 18963.75000 | 162.000000        | 0.200000          | 25.000000             | 162.000000         | 0.000000           | 0.000000               | 3.140000           | 9.130000e-02    | 327.000000       | ... | 327.000000       | 119.000000       | 0.183000       |    |
| max   | 25285.00000 | 198.000000        | 50.700000         | 1440.000000           | 198.000000         | 50.000000          | 1000.000000            | 27.100000          | 3.800000e-01    | 331.000000       | ... | 332.000000       | 130.000000       | 0.569000       |    |

8 rows × 51 columns

In [92]: `exp_result.groupby('class').count()`

Out[92]:

|        | exp_no | material | feedrate | clamp_pressure | tool_condition | machining_finalized | passed_visual_inspection |
|--------|--------|----------|----------|----------------|----------------|---------------------|--------------------------|
| class  |        |          |          |                |                |                     |                          |
| defect | 8      | 8        | 8        | 8              | 8              | 8                   | 8                        |
| pass   | 10     | 10       | 10       | 10             | 10             | 10                  | 10                       |

In [93]: `exp_df.groupby('class').count()`

Out[93]:

|       | Unnamed: 0 | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | ... | M1_CURRENT_PROGRAM_NUMBER | M1_sequence_number | M1_CURRENT |
|-------|------------|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|-----|---------------------------|--------------------|------------|
| class |            |                   |                   |                       |                    |                    |                        |                    |                 |                  |     |                           |                    |            |
| 0     | 19183      | 19183             | 19183             | 19183                 | 19183              | 19183              | 19183                  | 19183              | 19183           | 19183            | ... | 19183                     | 19183              |            |
| 1     | 6103       | 6103              | 6103              | 6103                  | 6103               | 6103               | 6103                   | 6103               | 6103            | 6103             | ... | 6103                      | 6103               |            |

2 rows × 55 columns

```
In [94]: exp_df['class'].value_counts().sort_index()
```

```
Out[94]: 0    19183
         1     6103
         Name: class, dtype: int64
```

## Feature Engineering

### Differential Features

- differences between Actual and Command position can indicate a sign of machining failure.

```
In [71]: for ax in ['X', 'Y', 'Z', 'S']:
         exp_df[f'{ax}1_Position_Diff'] = abs(exp_df[f'{ax}1_CommandPosition']-exp_df[f'{ax}1_ActualPosition'])
         exp_df[f'{ax}1_Velocity_Diff'] = abs(exp_df[f'{ax}1_CommandVelocity']-exp_df[f'{ax}1_ActualVelocity'])
         exp_df[f'{ax}1_Acceleration_Diff'] = abs(exp_df[f'{ax}1_CommandAcceleration']-exp_df[f'{ax}1_ActualAcceleration'])
```

### FFT Features

it is thought that highest frequency and amplitude can be good information to detect machining failures.

```
In [72]: from scipy import signal

         for col in ['ActualPosition', 'ActualVelocity', 'ActualAcceleration', 'CurrentFeedback', 'DCBusVoltage', 'OutputCurrent', 'OutputVoltage', 'OutputPower']:
             dt = 0.1
             for i in range(1,19):
                 for ax in ['X', 'Y', 'Z', 'S']:
                     try:
                         f = df[df['exp_no']==i].reset_index()[f'{ax}1_{col}']
                     except:
                         continue

                     N = len(f)
                     t = np.arange(0, N*dt, dt)
                     freq = np.linspace(0, 1.0/dt, N)
                     F = np.fft.fft(f)
                     F_abs = np.abs(F) / (N/2)
                     F_abs[0] = F_abs[0] / 2
                     maximal_idx = signal.argrelemax(F_abs, order=1)[0]

                     high_amp = np.max(F_abs[maximal_idx]) if len(maximal_idx) > 0 else 0
                     high_freq = freq[maximal_idx][np.argmax(F_abs[maximal_idx])] if len(maximal_idx) > 0 else 0

                     exp_df.loc[exp_df['exp_no']==i, f'{ax}1_{col}_High_Amp'] = high_amp
                     exp_df.loc[exp_df['exp_no']==i, f'{ax}1_{col}_High_Freq'] = high_freq
                     exp_df.loc[exp_df['exp_no']==i, f'{ax}1_{col}_High_Amp_Freq'] = high_amp * high_freq
```



DataFrame is highly fragmented. This is usually the result of calling `frame.insert` many times, which has poor performance. Consider joining all columns at once using `pd.concat(axis=1)` instead. To get a de-fragmented frame, use `newframe = frame.copy()`

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In [73]:

```
from sklearn.preprocessing import StandardScaler, LabelEncoder

# label encoding & drop unnecessary columns
feature_df = df.copy()
feature_df['Machining_Process'] = LabelEncoder().fit_transform(feature_df['Machining_Process']).astype(np.int8)
feature_df['tool_condition'] = LabelEncoder().fit_transform(feature_df['tool_condition']).astype(np.int8)
feature_df['machining_finalized'] = LabelEncoder().fit_transform(feature_df['machining_finalized']).astype(np.int8)
feature_df['passed_visual_inspection'] = LabelEncoder().fit_transform(feature_df['passed_visual_inspection']).astype(np.int8)
feature_df.drop(['material', 'exp_no'], axis=1, inplace=True)
feature_df.head(3)
```

Out[73]:

|   | X1_ActualPosition | X1_ActualVelocity | X1_ActualAcceleration | X1_CommandPosition | X1_CommandVelocity | X1_CommandAcceleration | X1_CurrentFeedback | X1_DCBusVoltage | X1_OutputCurrent | X1_OutputVoltage | ... | M1_CURRENT_PROGRAM_NUMBER | M1_sequence_number | M1_CURI |
|---|-------------------|-------------------|-----------------------|--------------------|--------------------|------------------------|--------------------|-----------------|------------------|------------------|-----|---------------------------|--------------------|---------|
| 0 | 198.0             | 0.0               | 0.00                  | 198.0              | 0.0                | 0.000000               | 0.18               | 0.0207          | 329.0            | 2.77             | ... | 1.0                       | 0.0                |         |
| 1 | 198.0             | -10.8             | -350.00               | 198.0              | -13.6              | -358.000000            | -10.90             | 0.1860          | 328.0            | 23.30            | ... | 1.0                       | 4.0                |         |
| 2 | 196.0             | -17.8             | -6.25                 | 196.0              | -17.9              | -0.000095              | -8.59              | 0.1400          | 328.0            | 30.60            | ... | 1.0                       | 7.0                |         |

3 rows × 54 columns

In [74]:

```
feature_df = feature_df.drop(columns = ['class'])
```

## Case1 : Tool Condition

In [75]:

```
y_series = feature_df['tool_condition']
x_df = feature_df.drop(['tool_condition', 'machining_finalized', 'passed_visual_inspection'], axis=1)
X_train, X_valid, Y_train, Y_valid = train_test_split(x_df, y_series, test_size=0.2, random_state=0, stratify=y_series)

lgb_train = lgb.Dataset(X_train, Y_train)
lgb_valid = lgb.Dataset(X_valid, Y_valid, reference=lgb_train)
```

In [76]:

```
import lightgbm as lgb

params = {
    'task' : 'train',
    'boosting' : 'gbdt',
    'objective': 'binary',
```

```
'metric': 'l2',  
'num_leaves': 200,  
'feature_fraction': 1.0,  
'bagging_fraction': 1.0,  
'bagging_freq': 0,  
'min_child_samples': 5  
}  
gbm_tool_wear = lgb.train(params,  
    lgb_train,  
    num_boost_round=100,  
    valid_sets=lgb_valid,  
    early_stopping_rounds=100)
```

```
[LightGBM] [Info] Number of positive: 10646, number of negative: 9582
[LightGBM] [Warning] Auto-choosing col-wise multi-threading, the overhead of testing was 0.003153 seconds.
You can set 'force_col_wise=true' to remove the overhead.
[LightGBM] [Info] Total Bins 7226
[LightGBM] [Info] Number of data points in the train set: 20228, number of used features: 45
[LightGBM] [Info] [binary:BoostFromScore]: pavg=0.526300 -> initscore=0.105298
[LightGBM] [Info] Start training from score 0.105298
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[1]    valid_0's l2: 0.203471
Training until validation scores don't improve for 100 rounds
[2]    valid_0's l2: 0.166717
[3]    valid_0's l2: 0.136749
[4]    valid_0's l2: 0.112511
[5]    valid_0's l2: 0.0929087
[6]    valid_0's l2: 0.0768045
[7]    valid_0's l2: 0.0638497
[8]    valid_0's l2: 0.0532614
[9]    valid_0's l2: 0.0446534
[10]   valid_0's l2: 0.0376186
[11]   valid_0's l2: 0.0318281
[12]   valid_0's l2: 0.0271606
[13]   valid_0's l2: 0.023302
[14]   valid_0's l2: 0.0202183
[15]   valid_0's l2: 0.0174369
[16]   valid_0's l2: 0.0151209
[17]   valid_0's l2: 0.0132292
[18]   valid_0's l2: 0.0116673
[19]   valid_0's l2: 0.0103524
[20]   valid_0's l2: 0.00924293
[21]   valid_0's l2: 0.00837016
[22]   valid_0's l2: 0.00766329
[23]   valid_0's l2: 0.00702296
[24]   valid_0's l2: 0.00654439
[25]   valid_0's l2: 0.00610943
[26]   valid_0's l2: 0.00573864
[27]   valid_0's l2: 0.00544579
[28]   valid_0's l2: 0.0052072
[29]   valid_0's l2: 0.00501323
[30]   valid_0's l2: 0.00484795
[31]   valid_0's l2: 0.00473727
[32]   valid_0's l2: 0.00465215
[33]   valid_0's l2: 0.00460009
[34]   valid_0's l2: 0.00453435
[35]   valid_0's l2: 0.00444635
[36]   valid_0's l2: 0.00438391
[37]   valid_0's l2: 0.00437146
[38]   valid_0's l2: 0.00426328
[39]   valid_0's l2: 0.00417064
[40]   valid_0's l2: 0.00414718
[41]   valid_0's l2: 0.00411675
[42]   valid_0's l2: 0.00406027
[43]   valid_0's l2: 0.00400784
[44]   valid_0's l2: 0.00396881
[45]   valid_0's l2: 0.00392189
[46]   valid_0's l2: 0.00386941
[47]   valid_0's l2: 0.00384198
[48]   valid_0's l2: 0.0038432
[49]   valid_0's l2: 0.00382277
[50]   valid_0's l2: 0.00381387
[51]   valid_0's l2: 0.00377727
[52]   valid_0's l2: 0.00376789
[53]   valid_0's l2: 0.0037184
[54]   valid_0's l2: 0.00370367
[55]   valid_0's l2: 0.00371757
[56]   valid_0's l2: 0.00372994
[57]   valid_0's l2: 0.00373073
[58]   valid_0's l2: 0.00371942
[59]   valid_0's l2: 0.00372255
[60]   valid_0's l2: 0.00370136
[61]   valid_0's l2: 0.00370245
[62]   valid_0's l2: 0.00366973
[63]   valid_0's l2: 0.00367636
[64]   valid_0's l2: 0.00368937
```

```

[65] valid_0's l2: 0.00368747
[66] valid_0's l2: 0.00368483
[67] valid_0's l2: 0.00371579
[68] valid_0's l2: 0.00370253
[69] valid_0's l2: 0.00370807
[70] valid_0's l2: 0.00369657
[71] valid_0's l2: 0.00370153
[72] valid_0's l2: 0.00371384
[73] valid_0's l2: 0.00367677
[74] valid_0's l2: 0.00364911
[75] valid_0's l2: 0.00363861
[76] valid_0's l2: 0.00360785
[77] valid_0's l2: 0.00357761
[78] valid_0's l2: 0.00357706
[79] valid_0's l2: 0.00353199
[80] valid_0's l2: 0.00348967
[81] valid_0's l2: 0.00343981
[82] valid_0's l2: 0.00340329
[83] valid_0's l2: 0.00337703
[84] valid_0's l2: 0.00335217
[85] valid_0's l2: 0.00331589
[86] valid_0's l2: 0.00331388
[87] valid_0's l2: 0.00328813
[88] valid_0's l2: 0.00326204
[89] valid_0's l2: 0.00323271
[90] valid_0's l2: 0.00321646
[91] valid_0's l2: 0.00321215
[92] valid_0's l2: 0.0032033
[93] valid_0's l2: 0.00319567
[94] valid_0's l2: 0.00319971
[95] valid_0's l2: 0.00317759
[96] valid_0's l2: 0.00316564
[97] valid_0's l2: 0.0031382
[98] valid_0's l2: 0.00312796
[99] valid_0's l2: 0.00311631
[100] valid_0's l2: 0.0031043
Did not meet early stopping. Best iteration is:
[100] valid_0's l2: 0.0031043

```

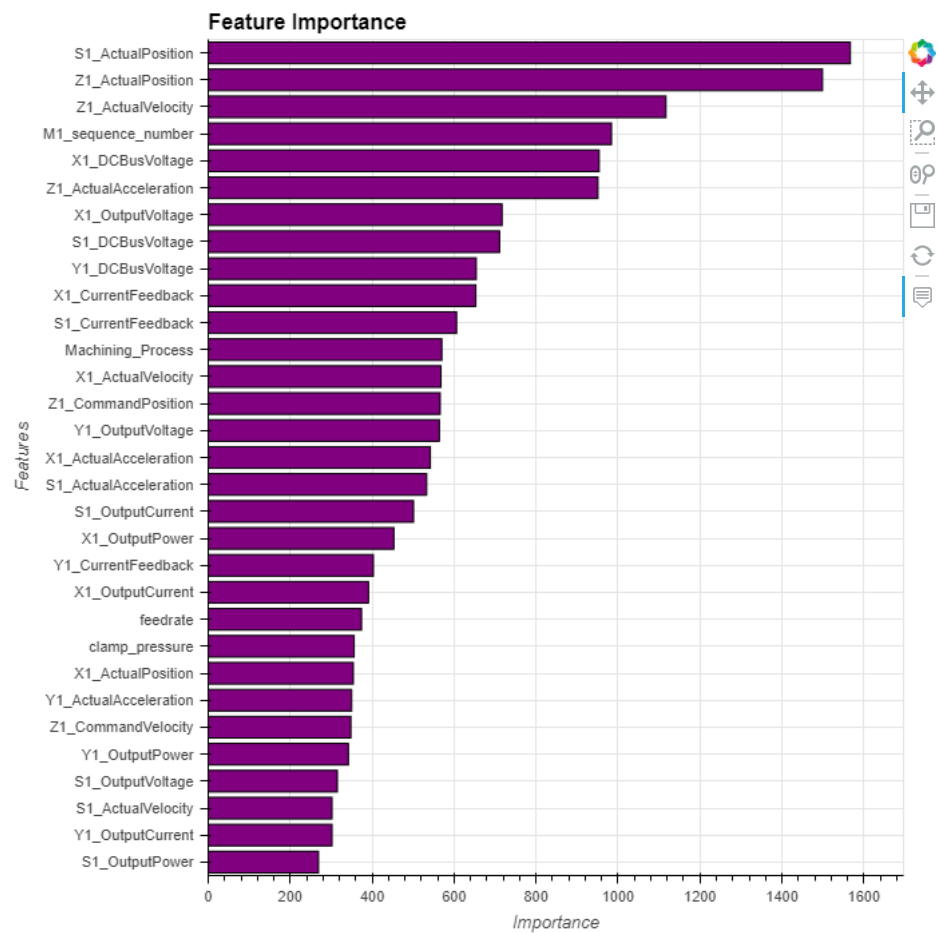
In [77]:

```

feature_imp = pd.DataFrame()
feature_imp['feature'] = gbm_tool_wear.feature_name()
feature_imp['importance'] = gbm_tool_wear.feature_importance()
hv.Bars(feature_imp.sort_values(by='importance', ascending=False)[0:31][::-1]).opts(title="Feature Importance", color="purple", xlabel="Features", ylabel="Importance")
    .opts(opts.Bars(width=700, height=700, tools=['hover'], show_grid=True))

```

Out[77]:



```
In [78]: #t = lgb.plot_tree(gbm_tool_wear, figsize=(20, 20), precision=3, tree_index=1, show_info=['split_gain'])
#plt.title('Visualization of Tree in Tool Condition')
#plt.show()
```

## Case2 : Machining Finalized

```
In [79]: y_series = feature_df['machining_finalized']
x_df = feature_df.drop(['tool_condition', 'machining_finalized', 'passed_visual_inspection'], axis=1)
X_train, X_valid, Y_train, Y_valid = train_test_split(x_df, y_series, test_size=0.2, random_state=0, stratify=y_series)

lgb_train = lgb.Dataset(X_train, Y_train)
lgb_valid = lgb.Dataset(X_valid, Y_valid, reference=lgb_train)
```

```
In [80]: params = {
    'task' : 'train',
    'boosting' : 'gbdt',
    'objective': 'binary',
```

```
'metric': 'l2',  
'num_leaves': 200,  
'feature_fraction': 1.0,  
'bagging_fraction': 1.0,  
'bagging_freq': 0,  
'min_child_samples': 5  
}  
gbm_machining_finalized = lgb.train(params,  
    lgb_train,  
    num_boost_round=100,  
    valid_sets=lgb_valid,  
    early_stopping_rounds=100)
```

```
[LightGBM] [Info] Number of positive: 18499, number of negative: 1729
[LightGBM] [Warning] Auto-choosing col-wise multi-threading, the overhead of testing was 0.003083 seconds.
You can set 'force_col_wise=true' to remove the overhead.
[LightGBM] [Info] Total Bins 7241
[LightGBM] [Info] Number of data points in the train set: 20228, number of used features: 45
[LightGBM] [Info] [binary:BoostFromScore]: pavg=0.914524 -> initscore=2.370173
[LightGBM] [Info] Start training from score 2.370173
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[1]   valid_0's l2: 0.056175
Training until validation scores don't improve for 100 rounds
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[2]   valid_0's l2: 0.0445993
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[3]   valid_0's l2: 0.0358616
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[4]   valid_0's l2: 0.0290024
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[5]   valid_0's l2: 0.0235434
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[6]   valid_0's l2: 0.0191494
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[7]   valid_0's l2: 0.0156034
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[8]   valid_0's l2: 0.0127417
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[9]   valid_0's l2: 0.0104147
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[10]  valid_0's l2: 0.00851808
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[11]  valid_0's l2: 0.00698037
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[12]  valid_0's l2: 0.00571645
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[13]  valid_0's l2: 0.00468446
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[14]  valid_0's l2: 0.00384359
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[15]  valid_0's l2: 0.00315204
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[16]  valid_0's l2: 0.00258942
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[17]  valid_0's l2: 0.00212467
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[18]  valid_0's l2: 0.00174391
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[19]  valid_0's l2: 0.00143256
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[20]  valid_0's l2: 0.00117676
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[21]  valid_0's l2: 0.000969162
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[22]  valid_0's l2: 0.0007972
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[23]  valid_0's l2: 0.000654116
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[24]  valid_0's l2: 0.000536683
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[25]  valid_0's l2: 0.000440264
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[26]  valid_0's l2: 0.000361144
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[27]  valid_0's l2: 0.000296214
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[28]  valid_0's l2: 0.000242935
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[29]  valid_0's l2: 0.000199226
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[30]  valid_0's l2: 0.000163365
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[31]  valid_0's l2: 0.000133942
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[32]  valid_0's l2: 0.000109811
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
```

[33] valid\_0's l2: 9.0017e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[34] valid\_0's l2: 7.37854e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[35] valid\_0's l2: 6.04746e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[36] valid\_0's l2: 4.95616e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[37] valid\_0's l2: 4.06634e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[38] valid\_0's l2: 3.33188e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[39] valid\_0's l2: 2.72988e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[40] valid\_0's l2: 2.23653e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[41] valid\_0's l2: 1.83222e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[42] valid\_0's l2: 1.50093e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[43] valid\_0's l2: 1.22949e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[44] valid\_0's l2: 1.00709e-05  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[45] valid\_0's l2: 8.24881e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[46] valid\_0's l2: 6.75617e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[47] valid\_0's l2: 5.53344e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[48] valid\_0's l2: 4.53185e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[49] valid\_0's l2: 3.71145e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[50] valid\_0's l2: 3.03948e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[51] valid\_0's l2: 2.48912e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[52] valid\_0's l2: 2.03836e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[53] valid\_0's l2: 1.6692e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[54] valid\_0's l2: 1.36687e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[55] valid\_0's l2: 1.11929e-06  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[56] valid\_0's l2: 9.1653e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[57] valid\_0's l2: 7.50493e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[58] valid\_0's l2: 6.14527e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[59] valid\_0's l2: 5.03188e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[60] valid\_0's l2: 4.12017e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[61] valid\_0's l2: 3.37361e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[62] valid\_0's l2: 2.76231e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[63] valid\_0's l2: 2.26176e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[64] valid\_0's l2: 1.8519e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[65] valid\_0's l2: 1.5163e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[66] valid\_0's l2: 1.24151e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[67] valid\_0's l2: 1.01651e-07  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[68] valid\_0's l2: 8.32288e-08  
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf  
[69] valid\_0's l2: 6.81448e-08



```

[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[70] valid_0's l2: 5.57943e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[71] valid_0's l2: 4.5682e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[72] valid_0's l2: 3.74025e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[73] valid_0's l2: 3.06234e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[74] valid_0's l2: 2.50878e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[75] valid_0's l2: 2.05558e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[76] valid_0's l2: 1.69462e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[77] valid_0's l2: 1.40328e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[78] valid_0's l2: 1.15008e-08
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[79] valid_0's l2: 9.42846e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[80] valid_0's l2: 7.84405e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[81] valid_0's l2: 6.43273e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[82] valid_0's l2: 5.27762e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[83] valid_0's l2: 4.42875e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[84] valid_0's l2: 3.62781e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[85] valid_0's l2: 3.05551e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[86] valid_0's l2: 2.55509e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[87] valid_0's l2: 2.0931e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[88] valid_0's l2: 1.71484e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[89] valid_0's l2: 1.40657e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[90] valid_0's l2: 1.18513e-09
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[91] valid_0's l2: 9.79416e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[92] valid_0's l2: 8.30387e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[93] valid_0's l2: 7.11673e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[94] valid_0's l2: 6.14902e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[95] valid_0's l2: 5.34427e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[96] valid_0's l2: 4.46405e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[97] valid_0's l2: 3.7369e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[98] valid_0's l2: 3.29757e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[99] valid_0's l2: 2.78894e-10
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[100] valid_0's l2: 2.3818e-10
Did not meet early stopping. Best iteration is:
[100] valid_0's l2: 2.3818e-10

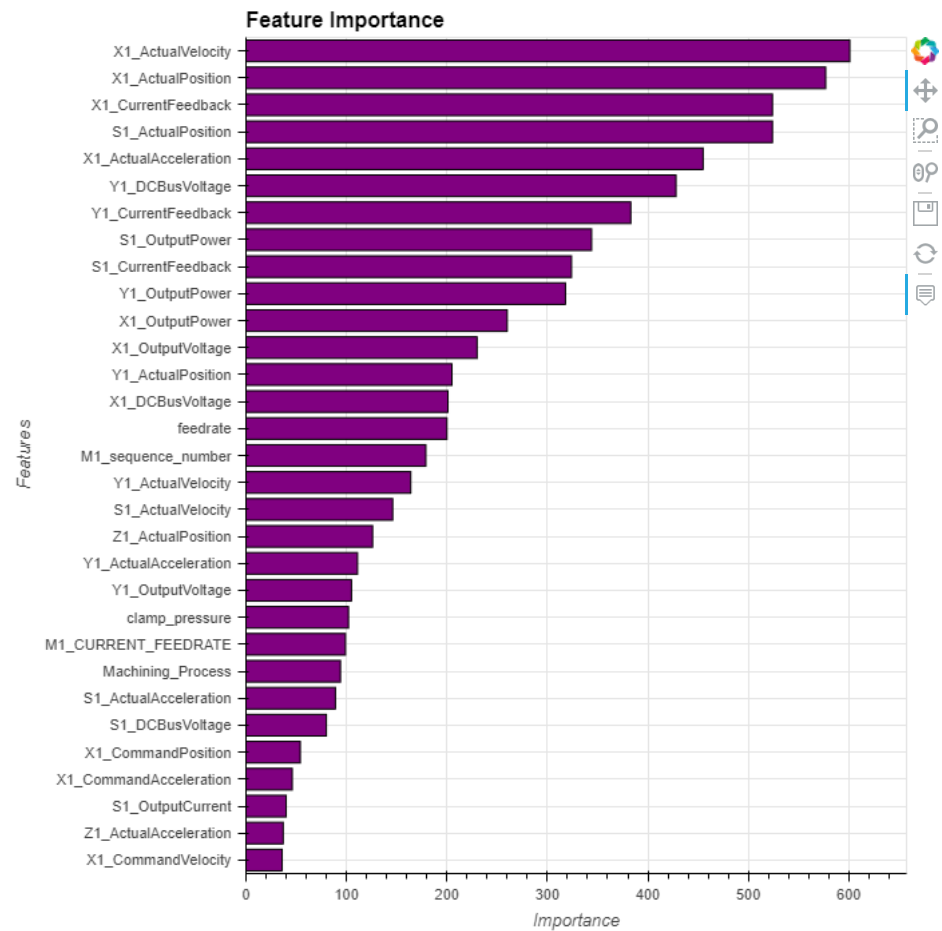
```

```

In [81]: feature_imp = pd.DataFrame()
feature_imp['feature'] = gbm_machining_finalized.feature_name()
feature_imp['importance'] = gbm_machining_finalized.feature_importance()
hv.Bars(feature_imp.sort_values(by='importance', ascending=False)[0:31][::-1]).opts(title="Feature Importance", color="purple", xlabel="Features", ylabel="Importance",
        .opts(opts.Bars(width=700, height=700, tools=['hover'], show_grid=True))

```

Out[81]:



```
In [82]: #t = lgb.plot_tree(gbm_machining_finalized, figsize=(20, 20), precision=3, tree_index=1, show_info=['split_gain'])
#plt.title('Visulalization of Tree in Machining Finalized')
#plt.show()
```

## Case3 : Passed Visual Inspection

```
In [83]: y_series = feature_df['passed_visual_inspection']
x_df = feature_df.drop(['tool_condition', 'machining_finalized', 'passed_visual_inspection'], axis=1)
X_train, X_valid, Y_train, Y_valid = train_test_split(x_df, y_series, test_size=0.2, random_state=0, stratify=y_series)

lgb_train = lgb.Dataset(X_train, Y_train)
lgb_valid = lgb.Dataset(X_valid, Y_valid, reference=lgb_train)
```

```
In [84]: params = {
    'task' : 'train',
    'boosting' : 'gbdt',
```

```
    'objective': 'binary',  
    'metric': 'l2',  
    'num_leaves': 200,  
    'feature_fraction': 1.0,  
    'bagging_fraction': 1.0,  
    'bagging_freq': 0,  
    'min_child_samples': 5  
}  
gbm_passed_vis_inspection = lgb.train(params,  
    lgb_train,  
    num_boost_round=100,  
    valid_sets=lgb_valid,  
    early_stopping_rounds=100)
```

```
[LightGBM] [Info] Number of positive: 15346, number of negative: 4882
[LightGBM] [Warning] Auto-choosing col-wise multi-threading, the overhead of testing was 0.003431 seconds.
You can set `force_col_wise=true` to remove the overhead.
[LightGBM] [Info] Total Bins 7225
[LightGBM] [Info] Number of data points in the train set: 20228, number of used features: 45
[LightGBM] [Info] [binary:BoostFromScore]: pavg=0.758651 -> initscore=1.145300
[LightGBM] [Info] Start training from score 1.145300
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[1]    valid_0's l2: 0.146727
Training until validation scores don't improve for 100 rounds
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[2]    valid_0's l2: 0.118647
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[3]    valid_0's l2: 0.0964902
[4]    valid_0's l2: 0.0787066
[5]    valid_0's l2: 0.0644084
[6]    valid_0's l2: 0.0528745
[7]    valid_0's l2: 0.0434695
[8]    valid_0's l2: 0.035869
[9]    valid_0's l2: 0.0295953
[10]   valid_0's l2: 0.0244943
[11]   valid_0's l2: 0.0203593
[12]   valid_0's l2: 0.0169702
[13]   valid_0's l2: 0.0142211
[14]   valid_0's l2: 0.011991
[15]   valid_0's l2: 0.0101437
[16]   valid_0's l2: 0.00866674
[17]   valid_0's l2: 0.007418
[18]   valid_0's l2: 0.00643691
[19]   valid_0's l2: 0.00563921
[20]   valid_0's l2: 0.0049583
[21]   valid_0's l2: 0.00439412
[22]   valid_0's l2: 0.00391479
[23]   valid_0's l2: 0.00352767
[24]   valid_0's l2: 0.00320357
[25]   valid_0's l2: 0.00293919
[26]   valid_0's l2: 0.00272154
[27]   valid_0's l2: 0.00254611
[28]   valid_0's l2: 0.00238961
[29]   valid_0's l2: 0.00226634
[30]   valid_0's l2: 0.00217077
[31]   valid_0's l2: 0.00208356
[32]   valid_0's l2: 0.00201288
[33]   valid_0's l2: 0.00195193
[34]   valid_0's l2: 0.00189608
[35]   valid_0's l2: 0.00185398
[36]   valid_0's l2: 0.00180459
[37]   valid_0's l2: 0.00176323
[38]   valid_0's l2: 0.00172553
[39]   valid_0's l2: 0.00169333
[40]   valid_0's l2: 0.00166601
[41]   valid_0's l2: 0.00164015
[42]   valid_0's l2: 0.00161838
[43]   valid_0's l2: 0.00159954
[44]   valid_0's l2: 0.00158329
[45]   valid_0's l2: 0.00156298
[46]   valid_0's l2: 0.00154914
[47]   valid_0's l2: 0.00153765
[48]   valid_0's l2: 0.00151881
[49]   valid_0's l2: 0.00150857
[50]   valid_0's l2: 0.00149987
[51]   valid_0's l2: 0.00149269
[52]   valid_0's l2: 0.00148687
[53]   valid_0's l2: 0.00147103
[54]   valid_0's l2: 0.00145198
[55]   valid_0's l2: 0.00143852
[56]   valid_0's l2: 0.00142149
[57]   valid_0's l2: 0.00141051
[58]   valid_0's l2: 0.00140088
[59]   valid_0's l2: 0.00139262
[60]   valid_0's l2: 0.00138569
[61]   valid_0's l2: 0.00138011
[62]   valid_0's l2: 0.00137581
```

```

[63]    valid_0's l2: 0.00137274
[64]    valid_0's l2: 0.00135146
[65]    valid_0's l2: 0.00134307
[66]    valid_0's l2: 0.00133593
[67]    valid_0's l2: 0.00133
[68]    valid_0's l2: 0.00133177
[69]    valid_0's l2: 0.00133719
[70]    valid_0's l2: 0.001342
[71]    valid_0's l2: 0.0013493
[72]    valid_0's l2: 0.00135759
[73]    valid_0's l2: 0.00136688
[74]    valid_0's l2: 0.00137171
[75]    valid_0's l2: 0.00137551
[76]    valid_0's l2: 0.00138023
[77]    valid_0's l2: 0.00138588
[78]    valid_0's l2: 0.00139761
[79]    valid_0's l2: 0.00140601
[80]    valid_0's l2: 0.00140769
[81]    valid_0's l2: 0.00141662
[82]    valid_0's l2: 0.0014264
[83]    valid_0's l2: 0.00143953
[84]    valid_0's l2: 0.00144875
[85]    valid_0's l2: 0.00146559
[86]    valid_0's l2: 0.00148308
[87]    valid_0's l2: 0.00149922
[88]    valid_0's l2: 0.00151638
[89]    valid_0's l2: 0.00153442
[90]    valid_0's l2: 0.00154217
[91]    valid_0's l2: 0.00155144
[92]    valid_0's l2: 0.00156384
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[93]    valid_0's l2: 0.00157501
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[94]    valid_0's l2: 0.00158933
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[95]    valid_0's l2: 0.0015939
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[96]    valid_0's l2: 0.00159879
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[97]    valid_0's l2: 0.00160233
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[98]    valid_0's l2: 0.0016107
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[99]    valid_0's l2: 0.0016232
[LightGBM] [Warning] No further splits with positive gain, best gain: -inf
[100]    valid_0's l2: 0.00162009
Did not meet early stopping. Best iteration is:
[67]    valid_0's l2: 0.00133

```

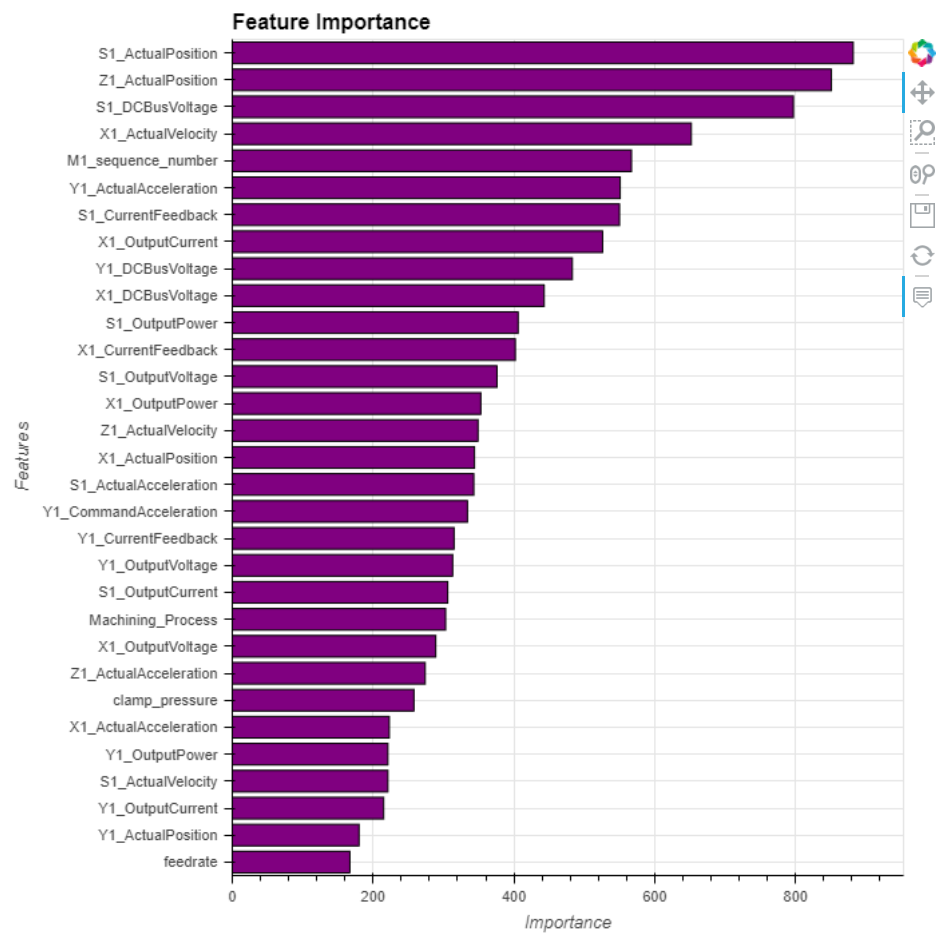
In [85]:

```

feature_imp = pd.DataFrame()
feature_imp['feature'] = gbm_passed_vis_inspection.feature_name()
feature_imp['importance'] = gbm_passed_vis_inspection.feature_importance()
hv.Bars(feature_imp.sort_values(by='importance', ascending=False)[0:31][::-1]).opts(title="Feature Importance", color="purple", xlabel="Features", ylabel="Importance",
                                             .opts(opts.Bars(width=700, height=700, tools=['hover'], show_grid=True)))

```

Out[85]:



```
In [87]: #t = lgb.plot_tree(gbm_passed_vis_inspection, figsize=(20, 20), precision=3, tree_index=1, show_info=['split_gain'])
#plt.title('Visualization of Tree in Passed Visual Inspection')
#plt.show()
```

In [ ]:

## 7. Insight (결론)

### 1) 공구마모

X축과 S축 데이터는 공구 마모에 큰 영향을 미치며 X축과 S축 움직임은 공구 마모에 나쁜 영향을 미칠 수 있으며, 속도와 전압은 수집된 데이터에 큰 영향을 미칩니다. FFT에 의해 생성된 특정 수의 피쳐도 피쳐 중요도의 최상위에 포함되며, 특정 주파수 범위에서 공구 마모가 진폭을 증가시킨 것으로 간주됩니다.

### 2) Machining Finalized

X축과 Y축 데이터는 공구 마모에 큰 영향을 미치며, X축과 Y축의 움직임은 가공 공정에 나쁜 영향을 미칠 수 있음 위치와 전압은 수집된 데이터에 큰 영향을 미침.

### 3) Passed Visual Inspection

X축 및 Y축 데이터는 공구 마모에 큰 영향을 미치며 X축 및 Y축 이동은 가공 공정에 나쁜 영향을 미칠 수 있음. 속도와 전압은 수집된 데이터에 큰 영향을 미침. Machining Finalized 케이스에 비해 FFT로 생성된 형상의 중요성이 높아졌음. 특정 주파수 범위에 대한 공구 마모의 영향은 인간이 감지할 수 있는 외부 처리 결과와 관련이 있는 것으로 간주.

4) Others

모든 실험을 통해 Z축 데이터는 거의 중요하지 않으며, 차등 특징은 전반에 걸쳐 이상 검출에 큰 영향을 미치지 않으며, 대부분의 경우 공구 마모 및 가공 공정에서 명령과 실제 위치의 차가 무시할 정도로 > 작았던 것으로 보임.

보다 자세한 분석을 진행하기 위해서는 가공 기계의 작동 원리에 대한 이해가 필수적으로 필요함

Feature Importance top-20

- 1. X1\_ActualVelocity
- 2. X1\_CurrentFeedback
- 3. X1\_ActualPosition
- 4. X1\_DCBusVoltage
- 5. X1\_ActualAcceleration
- 6. X1\_OutputVoltage
- 7. X1\_ActualVelocity\_High\_Amp
- 8. Y1\_CurrentFeedback
- 9. Z1\_ActualPosition\_High\_Amp
- 10. X1\_CommandAcceleration
- 11. Y1\_OutputVoltage
- 12. X1\_CommandVelocity
- 13. X1\_OutputPower
- 14. Y1\_DCBusVoltage
- 15. S1\_ActualAcceleration
- 16. S1\_ActualPosition
- 17. Y1\_ActualVelocity
- 18. S1\_OutputPower
- 19. Y1\_CommandVelocity
- 20. Y1\_OutputPower

In [ ]: