

# Supplementary Information for: Microstructural and fatigue characterization of 316L stainless steel subjected to flow drilling and tapping: comparison with machined threads.

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## S1. Hardness Measurements

Figure 1 shows how a specimen is cut to perform hardness measurements on holes 1 and 4 to determine if a series of drilling and tapping operations affects the hardness of the material. Tables 2 and 3 present the raw hardness data for the first and fourth cutting threads respectively. It can be observed that the hardness measured in the first hole is similar to the one in last hole. Tables 4 and 5 present the raw hardness data for the first and fourth flow processed threads. No difference is noted between the first and the last hole.

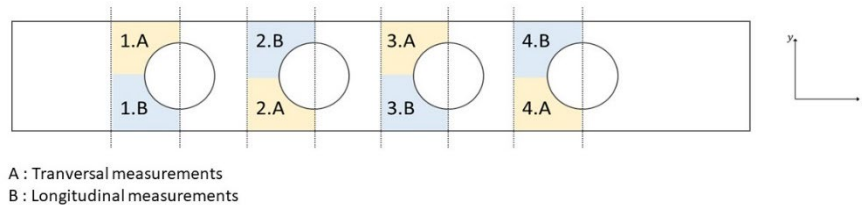


Figure 1. Cutting samples for hardness measurement from the threaded specimens

Table 1. Hardness measurements of conventional specimen, sample 1.A and 1.B

| 1.A                                |             | 1.B                                |             |
|------------------------------------|-------------|------------------------------------|-------------|
| Distance from the thread root (μm) | Hardness HV | Distance from the thread root (μm) | Hardness HV |
| 372,65                             | 190         | 393,55                             | 187         |
| 797,56                             | 185         | 803,31                             | 181         |
| 1177,53                            | 178         | 1163,41                            | 167         |
| 1115,33                            | 174         | 1566,37                            | 166         |
| 1356,27                            | 175         | 2044,04                            | 152         |
| 1571,08                            | 174         | 2375,92                            | 158         |
| 1809,93                            | 174         | 2792,47                            | 158         |
| 2048,78                            | 171         | 3233,58                            | 157         |
| 2284,49                            | 169         | 3648,04                            | 168         |
| 2523,86                            | 172         | 4063,55                            | 157         |
| 2802,95                            | 168         | 4485,33                            | 159         |
| 3048,07                            | 170         | 4870,00                            | 163         |
| 3282,74                            | 181         | 5272,96                            | 161         |
| 3522,64                            | 195         | 5662,86                            | 165         |
| 3760,44                            | 181         | 6081,50                            | 162         |
| 4039,01                            | 245         | 6472,44                            | 168         |
| 3926,64                            | 227         | 6862,86                            | 161         |
| 3922,46                            | 233         | 7265,82                            | 153         |
| 4290,40                            | 266         | 7669,83                            | 158         |
| 4526,11                            | 304         | 8061,29                            | 159         |
| 4759,21                            | 333         | 8465,30                            | 159         |
| 4866,84                            | 350         | 8856,76                            | 154         |
| 9,22                               | 519         | 9260,24                            | 162         |
| 53,40                              | 294         | 508,02                             | 165         |
| 120,55                             | 285         | 796,00                             | 165         |
| 203,14                             | 239         | 1098,61                            | 171         |
| 294,37                             | 243         | 1387,63                            | 169         |
| 324,08                             | 239         | 9,22                               | 519         |
| 414,53                             | 226         | 78,14                              | 291         |
|                                    |             | 150,00                             | 236         |
|                                    |             | 83,9                               | 282         |
|                                    |             | 178,14                             | 234         |
|                                    |             | 280,37                             | 230         |
|                                    |             | 364,79                             | 222         |
|                                    |             | 489,27                             | 220         |

Close to the surface  
(measurements using  
25 g mass)

Close to the surface  
(measurements using 25 g  
mass)

Table 2 Hardness measurements of conventional specimen, sample 4.A and 4.B

| 4.A                                                       |                                    | 4.B                                |             |
|-----------------------------------------------------------|------------------------------------|------------------------------------|-------------|
|                                                           | Distance from the thread root (µm) | Distance from the thread root (µm) | Hardness HV |
|                                                           | 233,62                             | 230,49                             | 199         |
|                                                           | 451,56                             | 459,41                             | 175         |
|                                                           | 654,87                             | 689,90                             | 166         |
|                                                           | 894,92                             | 914,64                             | 169         |
|                                                           | 1152,59                            | 1180,67                            | 161         |
|                                                           | 1402,94                            | 1416,38                            | 165         |
|                                                           | 1617,23                            | 1664,64                            | 164         |
|                                                           | 1864,44                            | 1910,81                            | 168         |
|                                                           | 2118,97                            | 2163,35                            | 152         |
|                                                           | 2347,37                            | 2390,70                            | 154         |
|                                                           | 2613,4                             | 2646,27                            | 160         |
|                                                           | 2848,59                            | 2892,44                            | 167         |
|                                                           | 3055,04                            | 3131,29                            | 156         |
|                                                           | 3294,41                            | 3386,86                            | 168         |
|                                                           | 3537,44                            | 3636,16                            | 155         |
|                                                           | 3778,90                            | 3887,55                            | 160         |
|                                                           | 4024,02                            | 4148,36                            | 161         |
|                                                           | 4006,25                            | 4392,44                            | 159         |
|                                                           | 4257,12                            | 4650,11                            | 160         |
|                                                           | 4480,29                            | 4941,22                            | 157         |
|                                                           | 4780,26                            | 5181,52                            | 155         |
|                                                           | 3907,99                            | 5424,55                            | 157         |
|                                                           | 3666,53                            | 5730,30                            | 167         |
|                                                           | 9,22                               | 5973,33                            | 168         |
|                                                           | 62,43                              | 6237,27                            | 164         |
|                                                           | 134,55                             | 6463,58                            | 162         |
| Close to the surface<br>(measurements using<br>25 g mass) | 213,74                             | 6710,79                            | 160         |
|                                                           | 295,28                             | 6962,18                            | 161         |
|                                                           | 338,34                             | 7210,64                            | 156         |
|                                                           | 411,51                             | 7470,40                            | 162         |
|                                                           | 509,55                             | 7717,61                            | 159         |
|                                                           |                                    | 7981,55                            | 160         |
|                                                           |                                    | 8253,85                            | 161         |
|                                                           |                                    | 8497,93                            | 164         |
|                                                           |                                    | 9,22                               | 519         |
|                                                           |                                    | 67,15                              | 306         |
|                                                           |                                    | 157,6                              | 245         |
|                                                           |                                    | 197,26                             | 230         |
|                                                           |                                    | 220,43                             | 226         |
|                                                           |                                    | 315,06                             | 216         |
|                                                           |                                    | 461,26                             | 212         |
|                                                           |                                    | 424,61                             | 206         |

Table 3 Hardness measurements of flow processed specimen, sample 1.A and 1.B

| 1.A                                                       |                                    | 1.B                                |             |
|-----------------------------------------------------------|------------------------------------|------------------------------------|-------------|
|                                                           | Distance from the thread root (μm) | Distance from the thread root (μm) | Hardness HV |
|                                                           | 408,19                             | 270,73                             | 281         |
|                                                           | 796,52                             | 602,61                             | 258         |
|                                                           | 1255,93                            | 959,58                             | 243         |
|                                                           | 1035,37                            | 1243,38                            | 267         |
|                                                           | 1667,25                            | 1622,30                            | 241         |
|                                                           | 2011,68                            | 1924,91                            | 222         |
|                                                           | 2390,6                             | 2267,77                            | 185         |
|                                                           | 2684,85                            | 2540,07                            | 192         |
|                                                           | 3021,96                            | 2910,63                            | 182         |
|                                                           | 3389,38                            | 3282,76                            | 178         |
|                                                           | 3699,31                            | 3627,19                            | 191         |
|                                                           | 4033,80                            | 3980,71                            | 191         |
|                                                           | 10,62                              | 4353,36                            | 181         |
|                                                           | 49,74                              | 4738,55                            | 183         |
| Close to the surface<br>(measurements using<br>25 g mass) | 102,75                             | 10,62                              | 759         |
|                                                           | 152,23                             | 56,15                              | 388         |
|                                                           | 267,28                             | 143,98                             | 338         |
|                                                           | 333,12                             | 230,50                             | 342         |
|                                                           | 407,20                             | 276,7                              | 316         |
|                                                           | 461,52                             | 363,74                             | 291         |
|                                                           |                                    | 443,98                             | 265         |
|                                                           |                                    | 494,90                             | 303         |

Table 4 Hardness measurements of flow processed specimen, sample 4.A and 4.B

| 4.A                                                       |                                                 |             | 4.B                                                       |                                                 |             |
|-----------------------------------------------------------|-------------------------------------------------|-------------|-----------------------------------------------------------|-------------------------------------------------|-------------|
|                                                           | Distance from the thread root ( $\mu\text{m}$ ) | Hardness HV |                                                           | Distance from the thread root ( $\mu\text{m}$ ) | Hardness HV |
|                                                           | 311                                             | 270         |                                                           | 240,42                                          | 282         |
|                                                           | 521                                             | 252         |                                                           | 511,67                                          | 240         |
|                                                           | 741                                             | 250         |                                                           | 765,15                                          | 251         |
|                                                           | 845                                             | 236         |                                                           | 1025,95                                         | 242         |
|                                                           | 1077                                            | 229         |                                                           | 1285,71                                         | 232         |
|                                                           | 1323                                            | 217         |                                                           | 1533,97                                         | 219         |
|                                                           | 1572                                            | 201         |                                                           | 1811,4                                          | 209         |
|                                                           | 1800                                            | 196         |                                                           | 2076,38                                         | 181         |
|                                                           | 2045                                            | 197         |                                                           | 2348,68                                         | 179         |
|                                                           | 2349                                            | 202         |                                                           | 2617,84                                         | 182         |
|                                                           | 2611                                            | 201         |                                                           | 2879,69                                         | 174         |
|                                                           | 2825                                            | 208         |                                                           | 3134,22                                         | 178         |
|                                                           | 3077                                            | 212         |                                                           | 3410,7                                          | 180         |
|                                                           | 3339                                            | 236         |                                                           | 3680,91                                         | 182         |
|                                                           | 3598                                            | 250         |                                                           | 3974,12                                         | 182         |
|                                                           | 3863                                            | 283         |                                                           | 4228,65                                         | 173         |
|                                                           | 4174                                            | 325         |                                                           | 4498,86                                         | 178         |
|                                                           | 10,62                                           | 759         |                                                           | 4743,98                                         | 181         |
|                                                           | 55,89                                           | 384         |                                                           | 10,62                                           | 759         |
|                                                           | 132,72                                          | 347         |                                                           | 63,22                                           | 384         |
| Close to the surface<br>(measurements using<br>25 g mass) | 156,41                                          | 330         | Close to the surface<br>(measurements using<br>25 g mass) | 153,67                                          | 327         |
|                                                           | 232,46                                          | 273         |                                                           | 239,93                                          | 297         |
|                                                           | 374,21                                          | 265         |                                                           | 332,47                                          | 291         |
|                                                           | 452,09                                          | 282         |                                                           | 383,91                                          | 265         |
|                                                           | 102,88                                          | 330         |                                                           | 465,98                                          | 250         |

## S2. Fatigue Tests Raw data

Table 5 shows the raw data from the fatigue tests conducted during this study. It is noted that 6 F specimens were tested with a maximum loading level of 700 N. It should be reminded that the tests were run at a stress ratio of 0.1 and the run-out is set at  $10^7$  cycles.

*Table 5. Fatigue test raw data*

| Load Max (N) | Maximum bending moment (N.m) | Number of cycle |          |
|--------------|------------------------------|-----------------|----------|
|              |                              | C               | F        |
| 1125         | 16,875                       | 1,03E+05        | 1,14E+05 |
|              |                              | 1,75E+05        | 1,01E+05 |
|              |                              | 1,35E+05        | 1,12E+05 |
|              |                              | 3,52E+05        | 1,68E+05 |
|              |                              | 1,69E+05        | 1,12E+05 |
| 900          | 13,5                         | 3,70E+05        | 2,55E+05 |
|              |                              | 3,90E+05        | 1,73E+05 |
|              |                              | 3,98E+05        | 4,94E+05 |
|              |                              | 4,59E+05        | 3,29E+05 |
|              |                              | 3,58E+05        | 7,96E+05 |
| 700          | 11,25                        | 1,00E+07        | 1,00E+07 |
|              |                              | 1,00E+07        | 4,93E+05 |
|              |                              | 9,07E+05        | 7,04E+05 |
|              |                              | 1,04E+06        | 2,21E+05 |
|              |                              | 1,00E+07        | 2,63E+05 |
|              |                              |                 | 7,63E+05 |

### S3. Material analysis

The following figures present an analysis conducted using an SEM on samples from a test specimen related to the project that have not undergone any testing. The samples were polished up to the OPS stage to reveal the microstructure at the thread's root (Figure 2), crest (Figure 3), and in the bulk material (Figure 4) where the influence of flow drilling and flow tapping is no longer present. These microstructure images are accompanied by EDS analyses performed in the three mentioned zones. The chemical composition does not vary across the sample. The microstructure near the surface of the threads (both crest and root) is very fine owing to : the work hardening induced by flow drilling and flow tapping, the heating of the material during flow drilling and the air cooling. The grain orientation induced by the material flow during flow drilling and flow tapping is also visible at the root and crest of the thread. As shown by the Figure 5, the increase in hardness observed is consistent with the reduction of the grain size.

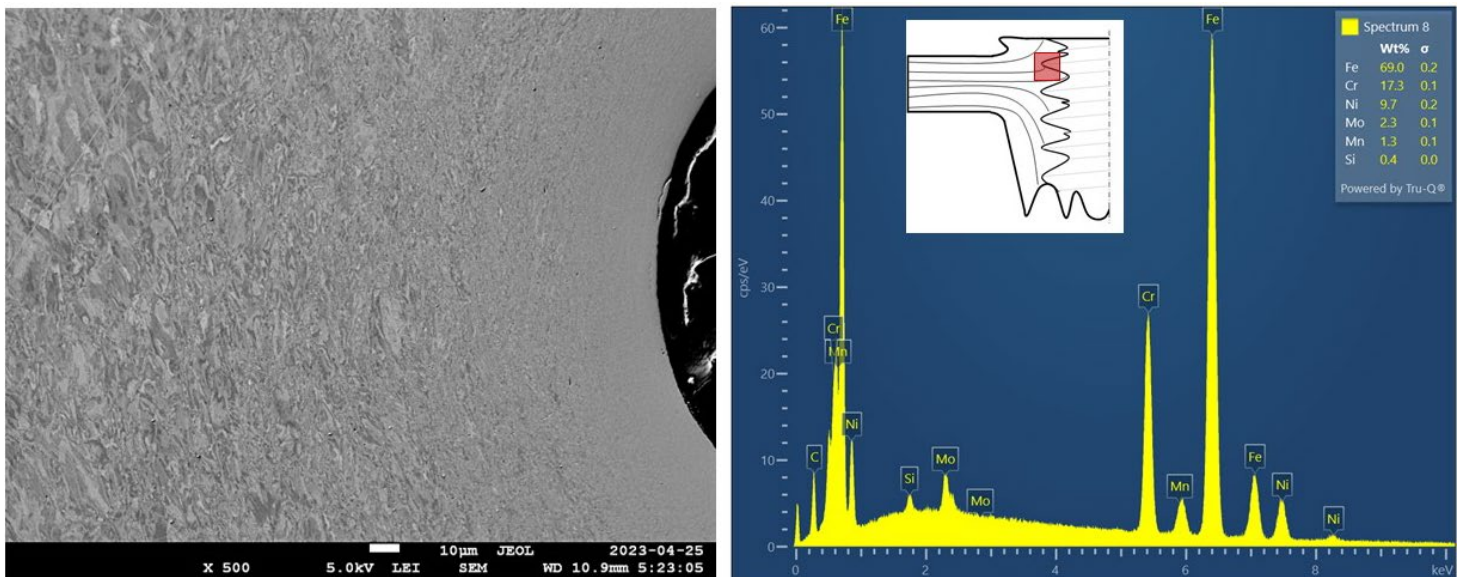


Figure 2. Microstructure and EDS analysis at the thread's root

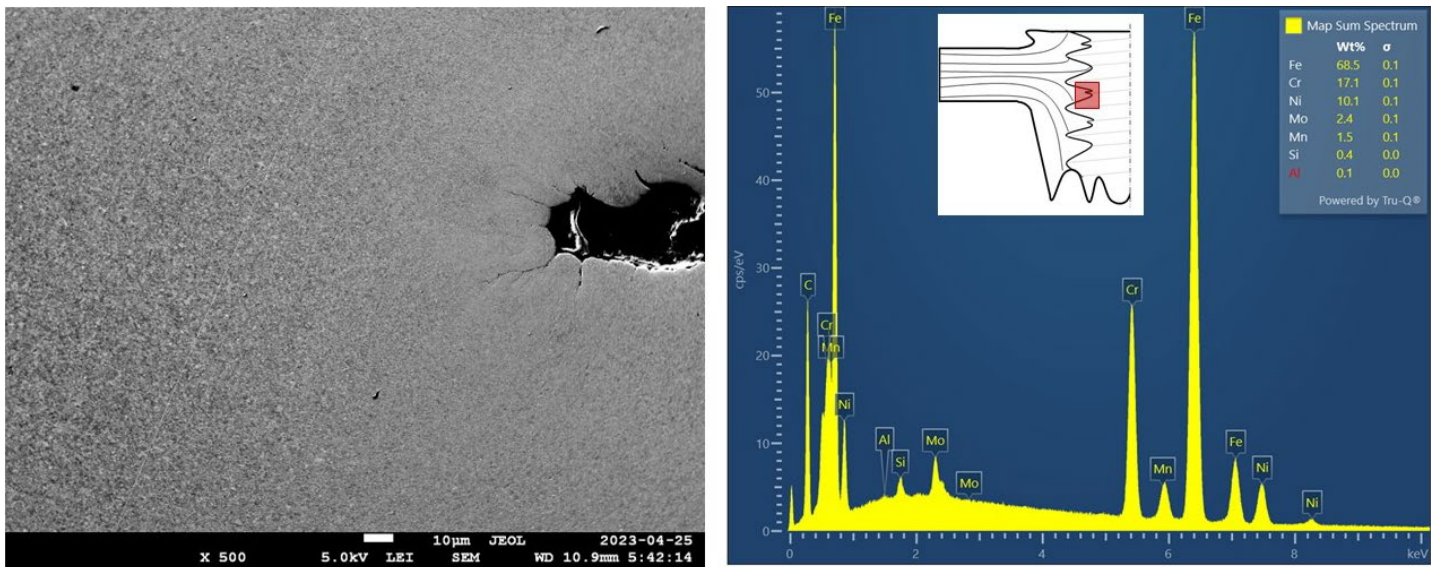


Figure 3. Microstructure and EDS analysis at the thread's crest

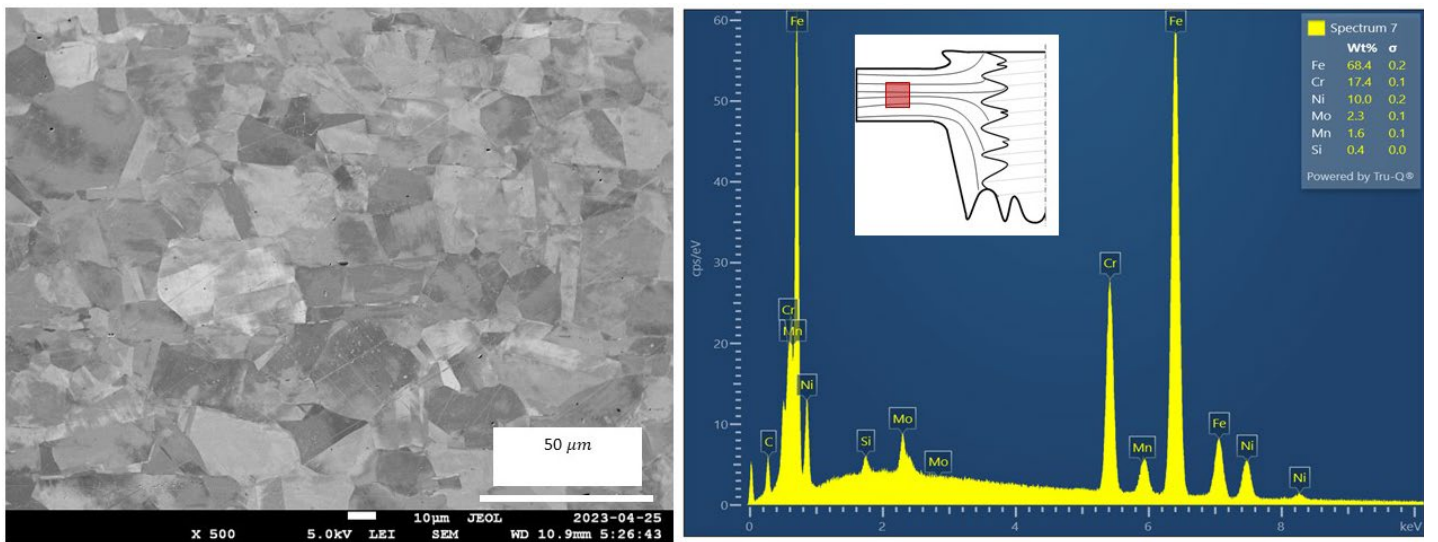


Figure 4. Microstructure and EDS analysis of the bulk material

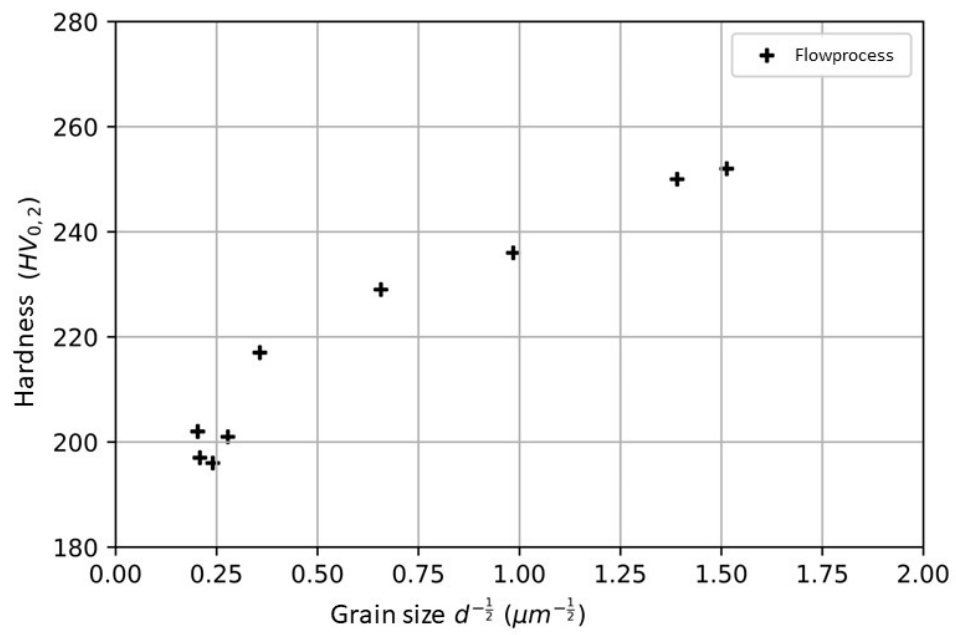


Figure 5. Hardness measurement related to grain size

#### S4. Evolution of the temperature during a flow drilling sequence

The flow-drilling tool was instrumented with a thermocouple placed at its center. The temperature was measured during a drilling operation. Figure 6 shows the temperature reached by 316L during a flow-drilling operation with the operating parameters used during this study. As can be seen, the material does not reach its melting temperature; at most, it reached 85% of its melting temperature.

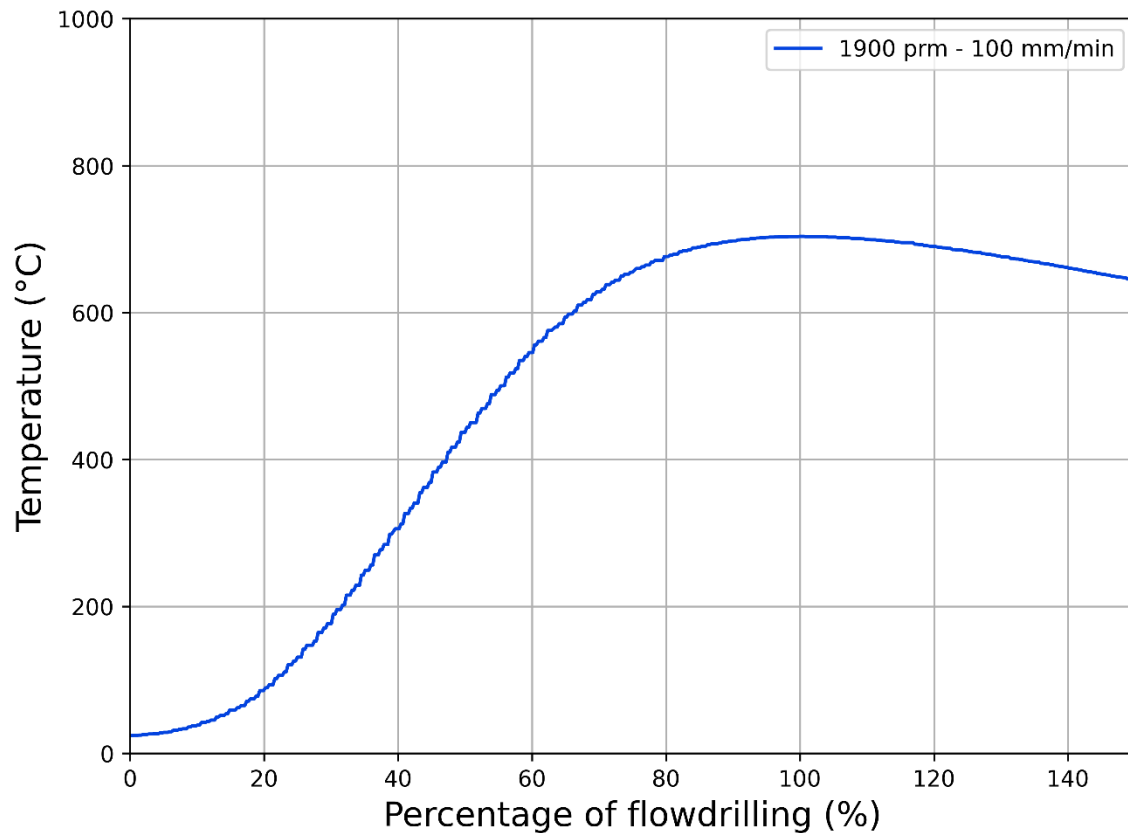


Figure 6. Evolution of the temperature at the tip of the flow drilling tool during a flow drilling sequence