Influence of machining on the microstructure, mechanical properties and corrosion behaviour of a low carbon martensitic stainless steel

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Abstract

The influence of cutting conditions of a low carbon martensitic stainless steel (15.5wt.% Cr, 4.8% Ni, 1% Mo, 0.9% Mn, 0.24% Si, 0.1% Cu, < 0.06% C and 77.46% Fe) on the microstructure is first studied using electron backscatter diffraction and transmission electron microscopy. The mechanical and corrosion behaviours of this stainless steel are then investigated. It was found that the microstructure is significantly affected near the machined surface. The formation of grain sub-boundaries or a refinement of the microstructure is observed depending on cutting conditions. Both lead to an increase of the hardness. In addition, the microstructure refinement yields to a huge increase of the average pit surface area. By contrast the average pit density is not affected by machining conditions.

Keywords: machining; stainless steel; corrosion; mechanical properties.
1. Introduction

Machining is used in numerous industrial sectors to produce workpieces with required shape, dimensions, and surface finish (surface characteristics such as roughness and subsurface characteristics such as texture, residual stresses and microstructure). One of the great challenges of modern machining is to optimise surface finish for the increase of the performance and lifetime of workpieces. Numerous experimental studies have quantified the influence of cutting parameters on the surface and sub-surface characteristics of metallic alloys [1,2].

By contrast, only a few experimental investigations have been carried out to study the performance of workpieces machined under different cutting conditions and it would be interesting to link both. This includes the mechanical behaviour [3], the resistance to crack initiation and propagation [4] under external loading and the corrosion behaviour [5,6].

Martensitic stainless steels (MMS) have a complex microstructure composed of martensite laths, austenite film between laths and ferrite islands. It is therefore interesting to quantify the influence of machining on the surface finish and the performance of this complex microstructure. The surface roughness produced by turning of MMS was already measured [7]. In a previous work [8], it was found that machined samples made of MSS can be classified into three categories based on the observable deformation: samples with severe observable deformation, noticeable observable deformation and no observable deformation. The observable deformation was qualitatively assessed from optical observations of cross-sections using ferrite islands as deformation indicators. It was also found [8] that severe observable deformation is generated under machining performed with the highest value of the feed rate, \( f \). By contrast, there is no observable deformation in two configurations: machining with the lowest value of \( f \) or machining with intermediary values of \( f \) and the lowest value of the cutting speed, \( V_c \).

In the present study, microstructural changes induced by machining of MSS are quantified by means of electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM). Samples representative of the first (severe observable deformation) and the third (no observable deformation) categories were selected. The corrosion behaviour of these two samples was then evaluated using the potentiostatic pulse technique (PPT). Obtained results were discussed considering microstructural changes determined previously and machining conditions (values of \( f \) and \( V_c \)).

2. Experimental

The studied material is a low carbon MSS. Its chemical composition is (wt.%): 15.5% Cr, 4.8% Ni, 1% Mo, 0.9% Mn, 0.24% Si, 0.1% Cu, < 0.06% C and 77.4% Fe. The material underwent a heat treatment at 1040°C, followed by an oil quenching, and a tempering treatment at 570°C.

Investigations were carried out on two machined samples extracted from the non-orthogonal design of experiments described in [8]: Sample #1 with no observable deformation (\( f = 0.1 \text{ mm/tr and } V_c = 73 \text{ m/min} \)) and Sample #2 with severe observable deformation (\( f = 0.3 \text{ mm/tr and } V_c = 182 \text{ m/min} \)). In both cases, the depth of cut was set at 4 mm and no lubricant was used.

The orientation of grains was determined on cross-section surfaces using the INCA Crystal EBSD System coupled with a field emission scanning electron microscope (JEOL JSM-6400F). EBSD measurements were performed with a step of 30 nm. The grain angle tolerance was set at 15°. Surfaces were ground (emery papers), smoothed (diamond pastes). A specific vibratory polishing was then carried out (VibroMet 2 vibratory polisher from Buehler).

FE-TEM investigations were carried out using a JEOL JEM-2100 microscope with a LaB6 source operating at 200 kV. For sample preparation, classical grinding, polishing and dimpling methods (Dimple Grinder Model 656 from Gatan) followed by ion beam milling (PIPS Model 691 from Gatan) were used on the opposite face to obtain a sample thickness that would be transparent to high energy electrons.

Corrosion tests were carried in 0.1M NaCl at 25°C using the PPT method [9]. It consists in applying a potential of 1 V vs. SCE for 3 s and then a potential of 0 V vs. SCE (passive behaviour) for 2 s (30 cycles). The specimen surface was cleaned in ethanol under ultrasonics and the zone of interest was observed by optical microscopy. Surface defects existing before machining were identified before the PPT test.

3. Results and discussion

3.1. Microstructural changes in MMS after machining

EBSD analysis was first performed on Sample #1 (no observable deformation). The IPF map (Fig. 1(a)) does not reveal any preferential orientation and any grain refinement in the close vicinity of the machined surface. By contrast, the
GOS/KAM maps (Fig. 1(b)) show that the density of grain sub-boundaries is significantly increased in a thin volume close to the surface. The thickness of the affected sublayer was estimated to be 2 µm. It can also be observed that some grains emerging at the surface are defined by an extremely high value of the GOS (values greater than 10°, corresponding to yellow, orange and red grains in Fig. 1(b)). These grains contain a high density of dislocations. By comparison, the GOS of grains in the bulk does not exceed 10° (green and blue grains in Fig. 1(b)). Although no observable deformation was observed (soft machining conditions), microstructural changes occur near the surface during machining.

The Vickers hardness was then determined on the machined surface. The penetration depth of the indenter was first calculated from geometrical considerations. It was estimated to 1.2 µm. The penetration depth is then roughly twice lower than the thickness of the affected layer (of about 2 µm). The hardness values derived from these measurements were then representative of the affected sublayer. A hardness value of 423 ± 10 HV0.01 was found (instead of 390 ± 10 HV0.01 in the bulk). The slight increase of hardness in the sublayer is mainly attributed to the increase of the grain sub-boundaries observed by means of EBSD (Fig. 1(b)). These results show that even though no deformation was observed by optical microscopy (soft machining conditions with the lowest value of f) microstructural changes may occur. Previous results [8] indicate that the increase of hardness induces a decrease of the pitting potential of the machined surface.

EBSD analysis of Sample #2 (severe observable deformation) shows that the martensite laths are highly elongated in the direction of machining (Fig. 2). A very fine microstructure with a high density of grain boundaries is then present near the surface. The thickness of the affected sublayer is at least 10 µm. The quality of EBSD maps was lower than in the previous case, confirming that large deformation occurred. The hardness value obtained on this machined surface was 498 ± 10 HV0.01. This value is significantly greater than that measured on Sample #1 and in the bulk. It was associated with the grain refinement observable in Fig. 2.

The presence of ferrite islands in the sublayer affects significantly the deformation process. Upstream of the island, laths are highly elongated (site A in Fig. 3(a)). When the thickness of the affected sublayer between the machined surface and the ferrite island becomes very low, laths are destroyed. Grains with a globular shape and an equivalent diameter in the sub-micrometer range are then formed (Fig. 3(b)). This indicates that strain concentrations certainly exist at this location during machining. Downstream of the ferrite island, laths are not highly elongated (site B in Fig. 3(a)). It seems that the ferrite undergoes deformation instead of laths. Indeed, numerous grain sub-boundaries are formed in the ferrite and orientation gradients developed (Fig. 3(a)-(b)).

These results show that severe machining conditions can lead to significant microstructural changes and significant increase of the hardness. Note that DSC results (not shown here) demonstrate that no phase transformation occurs during machining of MSS (under these selected conditions). The corrosion resistance of the machined surface is then significantly decreased [8].

TEM investigations were then performed in the bulk (no machining) and in Sample #2, as shown in Fig. 4(a) and 4(b) respectively. In both cases, the width of 50 laths was measured. In the bulk, the width of laths extends from 0.4 µm over several micrometers. By contrast, the width of laths in Sample #2 is in the range of 40-600 nm (Fig. 5). The average width is 0.24 µm. Therefore, TEM results confirm that significantly elongation of laths occurred during machining.

Machining performed with the lowest value of f or the intermediary value of f and the lowest value of Vc yields the formation of grain sub-boundaries in a 2 µm-thick sublayer and a slight increase of the hardness. By contrast, machining performed with the highest value of f yields microstructure refinement in a thick sublayer (thickness of about 10 µm) and significant increase of hardness. So we can affirm that the feed rate f has an important impact on the microstructure of the final workpiece, and as a consequence on the corrosion behavior of the machined surface.

3.2. Corrosion behaviour of machined samples

After PPT, optical images of the specimen surface were recorded using a Nikon Eclipse LV150A upright metallurgical microscopy (soft machining conditions with the lowest value of f).
microscope. These optical images were then assembled to produce a two-dimensional reconstruction of the machined surface. Obtained pictures were treated using the Photoshop software package. The distribution of the pit surface areas at the mouth was then determined for the two samples (Fig. 6).

The pit surface area is the range of 30-240 µm² for Sample #1 (Fig. 6(a)) and 20-560 µm² for Sample #2 (Fig. 6(b)). Pits can be significantly larger in Sample #2 (machined with the highest value of f). The average values of the pit surface area are reported in Table 1. These values are compared to that obtained for the bulk material (no machining) which was previously polished using diamond pastes (down to 1 µm). Formation of numerous grain sub-boundaries (Sample #1) yields to slight increase of this parameter (increase of about 50% vs. the bulk material). By contrast, the microstructure refinement observed in Sample #2 yields to huge increase of this parameter, of about 260% vs. the bulk material. Therefore machining conditions (even for low values of f and Vc) affect significantly the average pit surface area.

The average pit density is also reported in Table 1. Roughly the same value was found for both machined samples. This shows that the average pit density is not affected by machining conditions. It can also be seen that this parameter is significantly lower after machining than on the bulk material. The difference is of about 80%. This may be explained by the fact that machined surfaces may be under compression. It is well known that compressive stresses have beneficial effects on pitting corrosion.

4. Conclusions

Microstructural changes were found in MMS after machining: formation of grain sub-boundaries in a thin affected sublayer for soft machining conditions "lowest value of f" and refinement of the microstructure for severe machining conditions "highest value of f".

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**Table 1. Numerical values derived from PPT test**

<table>
<thead>
<tr>
<th></th>
<th>Average pit surface area (µm²)</th>
<th>Average pit density (pit/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample #1</td>
<td>94</td>
<td>15</td>
</tr>
<tr>
<td>Sample #2</td>
<td>224</td>
<td>13</td>
</tr>
<tr>
<td>Bulk material</td>
<td>62</td>
<td>67</td>
</tr>
</tbody>
</table>
In both cases, the hardness was significantly increased. The highest values of hardness was found when the microstructure refinement occurs. The corrosion behaviour of the surface was also affected by machining. The average pit density is not affected by machining conditions. By contrast, the microstructure refinement (highest value of $f$) yields to a huge increase of the average pit surface area.

These results show that machining conditions play a significant role in the surface integrity and corrosion behaviour of MMS.

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6. References


