FINAL MACHINING EFFECTS ON THE CORROSION PROPERTIES OF AISI 304 AND AISI 321 AUSTENITIC STAINLESS STEELS

[1]Marek KUDLÁČ, [1]Mária DOMÁNKOVÁ, [1]Katarína BÁRTOVÁ, [1]Tomáš VOPÁT, [1]Matúš GAVALEC, [1]Dávid SLNEK

[1]Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Jána Bottu 2781/25, 917 24 Trnava, Slovakia EU, marek.kudlac@stuba.sk, maria.domankova@stuba.sk, katarina.bartova@stuba.sk, tomas.vopat@stuba.sk, matus.gavalec@stuba.sk, david.slnek@stuba.sk

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Abstract

Using final machining, as a finishing technology, components with specific precise dimensions are obtained. Despite the precise type of machining, the integrity of the surface is significantly affected, and the material acquires some negative surface properties that cause a decrease in corrosion resistance. Such properties are increased hardness of the surface layers (and therefore reduced toughness), roughness or tensile residual stresses. The combination of these parameters leads in many cases to susceptibility to stress corrosion cracking or other corrosion degradation phenomena. In this work, final turning was used as the machining process using a tool with a positive cutting geometry and a sharp cutting edge, while the cutting parameters – cutting speed (100 and 250 $m \cdot min^{-1}$) and feed (0.12, 0.2 and 0.3 mm) were combined. The depth of cut remained the same in all cases (0.8 mm). The studied and compared materials were austenitic stainless steels AISI 304 and AISI 321. After turning their surface properties such as roughness or hardness were analysed. The susceptibility to stress corrosion cracking was monitored using the ASTM G36 test, where the samples were exposed to a boiling magnesium chloride solution for up to 96 hours. The samples were observed using SEM, where the areal density of cracks was monitored, as well as the depth and length of cracks on cross-sections. As part of the influence of cutting parameters, increased values of areal density were found with an increase in feed but also with an increase in cutting speed, while the surface of austenitic steel AISI 304 was significantly affected compared to AISI 321 under the same conditions. In addition to the exposure method, an electrochemical method was also used, specifically the electrochemical potentiokinetic reactivation analysis, the double loop method (DL-EPR), where it was observed whether the final turning in any way affects the sensitivity to intergranular corrosion, or how the resulting roughness affects the measurement itself.

Keywords: Stress corrosion cracking, austenitic stainless steel, machining, turning, corrosion

1. INTRODUCTION

To obtain the necessary dimensions and shapes after rough machining, finishing technology is usually used, which also includes final machining (final turning or final milling). Despite the finer working with the prepared semi-finished product, during this technology the surface and surface layers of the material are affected [1,2]. Defects, roughness, increased hardness but also the formation of residual stresses are phenomena that appear during final machining. All these parameters largely affect corrosion resistance, especially susceptibility to stress corrosion cracking (SCC). In addition to the susceptibility to SCC, the passivation ability of materials is also affected, especially with significant surface roughness of the material. In articles that deal with the issue of SCC of austenitic stainless steels in chloride media, a boiling solution of magnesium chloride is most often used as a medium [2,3,4]. This solution causes SCC in these steels by both mechanisms, namely anodic dissolution and hydrogenation and it also causes localized corrosion by depassivation by chloride ions [2]. This work focuses on the effect of final turning of AISI 304 and AISI 321 on their susceptibility to SCC in a boiling

$MgCl_2$ solution according to ASTM G36. The density of surface cracks was monitored, as well as the length and depth of penetration. In addition, the microstructure and microhardness of the surface layers and the surface roughness after final turning were monitored. In addition to the exposure method for determining SCC susceptibility, the electrochemical method DL-EPR was used, which is primarily used to determine the degree of sensitisation to intergranular corrosion (DOS) [5] − in this case, it was also used to monitor the passivation ability of individual samples.

2. MATERIALS AND METHODS

Two types of austenitic stainless steels, AISI 304 and AISI 321, were used for the analysis. In **Table 1** and **Table 2** there are standard chemical compositions for both types of steel and the actual chemical composition of the prepared samples. AISI 304 is a typical and most widespread type of austenitic steel, while AISI 321, which is stabilized with titanium, is used especially in the chemical industry or nuclear energy sector.

Table 1 Chemical composition of material of samples and standard chemical composition of AISI 304

Type of steel/norm	C (wt%)	Si (wt%)	Mn (wt%)	Cu (wt%)	Cr (wt%)	Ni (wt%)	Mo (wt%)	S (wt%)	P (wt%)
Material of samples	0.026	0.33	1.78	0.45	18.40	8.01	0.28	0.025	0.044
AISI 304 Standard	≤ 0.07	≤ 1.0	≤ 2.0	–	17.5–19.5	9.0–11.0	–	≤ 0.03	≤ 0.035

Table 2 Chemical composition of material of samples and standard chemical composition of AISI 321

Type of steel/norm	C (wt%)	Si (wt%)	Mn (wt%)	Cu (wt%)	Cr (wt%)	Ni (wt%)	Ti (wt%)	S (wt%)	P (wt%)
Material of samples	0.064	0.83	1.44	0.66	17.50	9.89	0.47	0.025	0.026
AISI 321 standard	≤ 0.08	≤ 0.8	≤ 2.0	–	17.0–19.0	9.0–11.0	≥ 5·C ≤ 0.70	≤ 0.020	≤ 0.035

2.1 Preparation and metallographic analysis of samples

Bars of austenitic steel AISI 304 and AISI 321 were turned with a tool with a positive cutting geometry (positive rake angle), a sharp cutting edge and a tip radius r_ε of 0.4 mm. The cutting parameters were as follows: the feed was set to 0.12, 0.2 and 0.3 $mm \cdot rev^{-1}$, the cutting speed – 100 and 250 $m \cdot min^{-1}$ and the depth of cut remained constant at 0.8 mm. With this combination of parameters, 6 samples of AISI 304 and 6 samples of AISI 321 were prepared. Finally, the bars were cut into cylinders and those into quarters, with each quarter of the individual samples being used in a different experiment. First, the microstructure of metallographically prepared cross sections (ground, polished and electrolytically etched in 10% oxalic acid solution) was monitored using light optical microscopy. At the same time the microhardness HV 0.05 was monitored. The roughness was measured using a Mitutoyo SJ 210 roughness meter. Other quarters were used for corrosion experiments.

2.2 ASTM G36

The apparatus was prepared based on ASTM G36 (**Figure 1a**), consisting of an Erlenmeyer flask, a condenser, and a heating element. 500 g of magnesium chloride hexahydrate and 12 cm^3 of demineralized water were weighed into the flask. Heating was started until the solution temperature reached 155 °C. Subsequently, after reaching the specified temperature, the samples were placed in solution and exposed for 96 hours. The samples were placed in the edge parts of the flask to avoid direct contact with the heating plate. After this time, the samples were removed from the solution, cleaned in demineralized water, and cleaned in

ultrasound in ethyl alcohol. After cleaning, the turned surface was observed in SEM, where images of cracks were taken to evaluate their density. 5 images were taken on each sample at a magnification of 500x. The samples were then cross-cut and the length (sum of the lengths of the primary and lateral secondary cracks) and depth (distance from the surface to the deepest point where the crack penetrated) of the cracks penetrating the sample were evaluated. ImageJ software was used for evaluation. Subsequently, the crack depths and lengths were divided into size classes and graphs of distribution were prepared for both steels.

2.3 DL-EPR analysis

Electrochemical potentiokinetic reactivation analysis, the double loop method, is an electrochemical method used to determine the degree of sensitization to intergranular corrosion. It can also be used to monitor the passivation ability of stainless steel. Therefore, this method was also used in this case, where it was used to determine the sensitivity (especially for AISI 304), but also to monitor the ability to passivate at different levels of roughness caused by turning. A flat corrosion cell connected to a three-electrode system was used for electrochemical tests (**Figure 1b**). An Ag/AgCl electrode was used as a reference electrode and a platinum mesh was used as an auxiliary electrode. A mixture of 2 M H_2SO_4 + 0.05 M KSCN was used as a solution. Initially, the open circuit potential was measured for 30 minutes and then the DL-EPR measurement itself was performed, where a scanning rate of 1.67 mV·s^{-1} was used in the range from −750 mV to 500 mV and back.

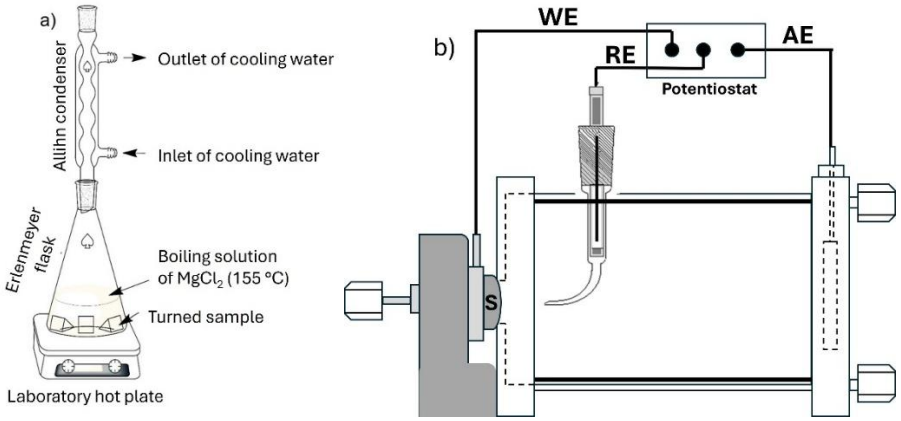

Figure 1 Exposure test apparatus according to ASTM G36 a) apparatus for DL-EPR – three-electrode system, b) WE – working electrode, RE – reference electrode, AE – auxiliary electrode, S - sample)

3. RESULTS AND DISCUSSION

The initial part of work was metallographic analysis of turned samples, measuring the microhardness of the surface layers as well as roughness. This was followed by the evaluation of the ASTM G36 test itself and finally DL-EPR analysis, which monitored the passivation ability of the turned surface as well as the DOS.

3.1 Metallographic analysis

The microstructure of the turned surfaces consisted of deformed grains containing deformation twins and slip bands (**Figure 2a**). Gradually, with increasing depth, the material was already composed of polyhedral austenitic grains. The microhardness HV 0.05 was also measured on the surface, where the principle is shown in (**Figure 2b**). The increase in microhardness was in AISI 304 mainly in samples turned with a lower cutting speed, on the contrary, in AISI 321 it was precisely the higher cutting speed at which higher hardnesses were measured. A slight increase was also visible in terms of increasing tool feed, which had a more significant effect on the surface roughness R_a. Measured values of roughness and microhardness are in **Table 2**.

3.2 Crack analysis

The surface of both turned AISI 304 and AISI 321 samples was covered with homogeneously branching cracks (**Figure 2c**). An increase in crack density was observed for samples turned at a cutting speed of 250 m·min^{-1}, while an increase was also observed with tool feed. The highest crack densities were for samples just turned at a cutting speed of 250 m·min^{-1} and a feed of 0.3 mm·rev^{-1}. On the contrary, the lowest feed and cutting speed were ideal in terms of crack density (**Table 3**). A comparison of both types of steels shows that AISI 321 is more resistant to SCC than AISI 304, where sample 7 had the lowest crack density (53.8 mm·mm^{-2}).

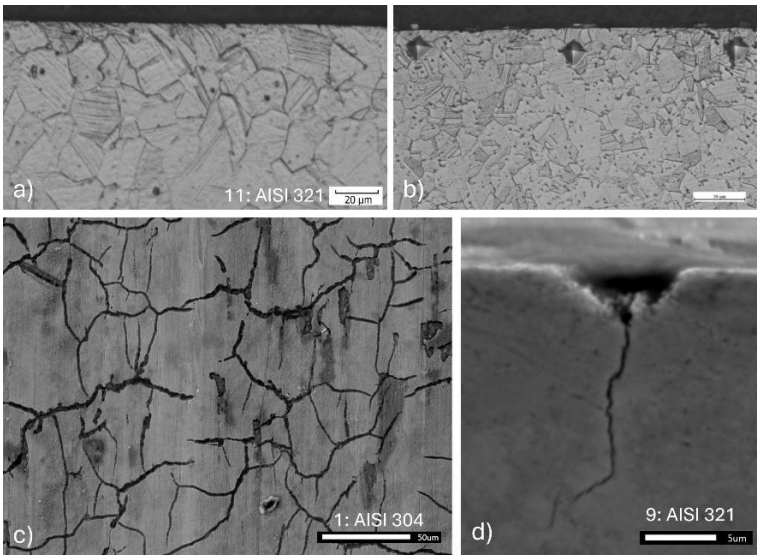

Figure 2 Surface grains after final turning of sample 11 (a) principle of microhardness measurement (b) surface cracks created after ASTM G36 in sample 1 (c) SEM image of crack penetrating the sample 9 which was initiated from corrosion pit (d)

Table 3 Machining parameters and measured values of roughness, microhardness HV 0.05 of surface zone and summary of crack density measurement results on the surface of samples of AISI 304 and AISI 321

Material of samples	Sample marking	Tool feed f (mm·rev^{-1})	Cutting speed v_c (m·min^{-1})	Roughness R_a (µm)	Microhardness HV 0.05 (-)	Crack density (mm·mm^{-2})
AISI 304	1	0.12	100	1.385	340 ± 18	81.1 ± 7.8
	2	0.12	250	1.217	324 ± 18	115.3 ± 8.2
	3	0.20	100	2.474	378 ± 19	100.6 ± 8.6
	4	0.20	250	2.698	325 ± 18	125.6 ± 11.6
	5	0.30	100	7.398	385 ± 11	87.3 ± 11.8
	6	0.30	250	6.854	354 ± 23	147.2 ± 11.5
AISI 321	7	0.12	100	1.429	329 ± 19	53.8 ± 7.9
	8	0.12	250	1.377	341 ± 18	90.0 ± 1.0
	9	0.20	100	2.661	335 ± 12	71.2 ± 14.3
	10	0.20	250	2.879	263 ± 19	104.2 ± 10.8
	11	0.30	100	7.151	337 ± 14	72.5 ± 7.1
	12	0.30	250	7.062	376 ± 13	120.4 ± 14.1

Cracks were observed on cross-sections using SEM. They had different morphology and size – from branched to simple unbranched magisterial cracks penetrating deep into the material. Corrosion points were often observed that initiated the formation of such cracks (**Figure 2d**). From the point of view of the penetration of cracks into the material, the length and depth of these cracks were monitored. **Figure 3** shows graphs of the distribution of crack length and depth for AISI 304 steel (up) and AISI 321 (down). It turns out that in AISI 304 the cracks penetrated to greater depths and had larger dimensions compared to AISI 321, which could be caused by many factors such as the influence of individual elements on the microstructure (e.g. TiC formation in AISI 321) or the distribution and penetration of residual stresses into the material. However, what they had in common was the trend of increasing crack lengths and depths with increasing feed and cutting speed.

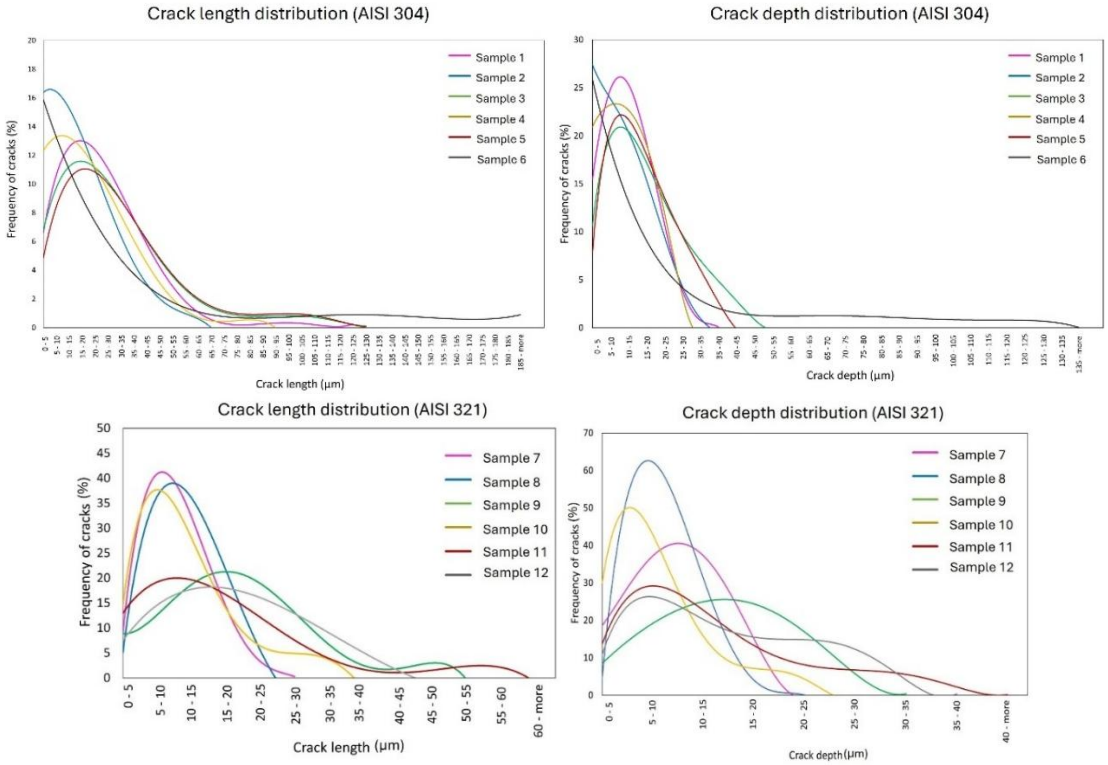

Figure 3 Crack length and depth distribution for AISI 304 (up) and AISI 321 (down)

In AISI 304 steel, this is visible at a cutting speed of 250 mm·min^{-1}, where the occurrence of larger cracks gradually increased, with sample 6 containing the longest and deepest cracks (in some cases exceeded 200 µm in length and 130 µm in depth). The lowest and shortest cracks were in samples 2 and 4. However, shallow cracks were also present in sample 1. Austenitic steel AISI 321 had the longest cracks in sample 11, with a gradual increase with feed. Here, however, they did not exceed a length of 60 µm and a depth of 40 µm. The combination of the lowest feed and both cutting speeds caused the formation of the shortest and shallowest cracks (samples 7 and 8). The same was for the combination of feed 0.2 mm·rev^{-1} and higher cutting speed – sample 10 (similar to AISI 304).

3.3 DL-EPR

DL-EPR analysis noted that in both cases the materials were not sensitized. However, an increase of the maximum current density during reactivation and DOS with increasing roughness was observed – visible especially in AISI 304 samples from 1 to 4, when the DOS increased from 0.05% to 0.09%. In AISI 321 samples, DOS was determined only in samples 7 and 8, which were at the level of 0.03%. With increasing roughness, it was no longer possible to determine the reactivation maximum, and therefore DOS was not

determined in samples 5 and 6 for AISI 304 and samples 9 to 12 for AISI 321. A significant increase in the current density in the passive state was visible in these samples (especially in 11 and 12 for AISI 321, (**Figure 4**), which may be a consequence of the impaired passivation ability at such roughness. In the case of AISI 304, an increase in current density in the passivity region was also observed at higher roughness, but it was not as pronounced - probably due to the larger amount of Cr, passivation was more complete.

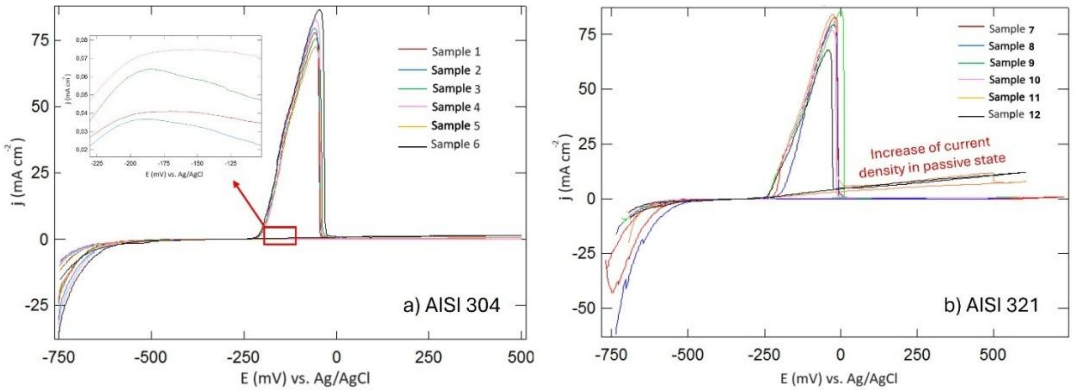

Figure 4 DL-EPR scans of AISI 304 (a) and AISI 321 (b)

4. CONCLUSION

The work investigated the effect of final turning on the corrosion resistance of austenitic stainless steels AISI 304 and AISI 321 and found that:

- Final turning affected the surface properties and microstructure of surface areas (roughness, hardness, presence of deformation twins and slip bands). Individual turning parameters affected the susceptibility to SCC. Higher cutting speed caused an increase in crack density, while AISI 321 being more resistant compared to AISI 304. On the other hand, the cutting speed but especially the feed affected the length and depth of cracks penetrating the material, where samples turned with a feed of 0.12 mm·rev^{-1} containing the shortest and shallowest cracks and at lower cutting speed samples had the lowest crack density.
- DL-EPR analysis confirmed that the samples were non-sensitized and observed an increase in current density in the passive region and in the reactivation peak with increasing roughness.

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REFERENCES

[1] GOSH, S. et al. Role of residual stresses induced by industrial fabrication on stress corrosion cracking susceptibility of austenitic stainless steel. *Materials and Design*. 2011, vol. 32, pp. 3823-3831.

[2] LYNCH, S. Mechanistic and fractographic aspects of stress corrosion cracking. *Corrosion Reviews*. 2012, vol. 30, pp. 63-104.

[3] PEDEFERRI, P. *Corrosion Science and Engineering*. Cham: Springer, 2018

[4] ASTM G36-00: *Standard Practice for Evaluating Stress-Corrosion-Cracking Resistance of Metals and Alloys in a Boiling Magnesium Chloride Solution*. West Conshohocken, PA, USA: ASTM International, 2000.

[5] BS EN ISO 12732:2008. *Corrosion of metals and alloys. Electrochemical potentiokinetic reactivation measurement using double loop method (based on Cihal's method)*, United Kingdom: BSI, 2008.