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INFLUENCE OF SURFACE FINISHING BY GRINDING AND POLISHING ON THE RESIDUAL STRESSES IN S13CR STEEL

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Abstract. *Supermartensitic stainless steels, known as S13Cr steels, were developed as an improvement of martensitic stainless steels, such as AISI 410, having better mechanical and corrosion resistance properties than these steels, while presenting a lower production cost compared to superduplex stainless steels. The S13Cr steels have been widely used in the production of tubular components for the oil and gas industry, which are destined for services involving exposure to corrosive environment, in addition to mechanical and thermal loads. Under these conditions, the residual stresses generated in the manufacturing of these components, including machining-induced residual stresses, can significantly influence their performance. In machining processes, the workpiece is submitted to high deformation rates and high temperature gradients, giving rise to residual stresses that may be detrimental to the performance of the final product. This work presents a study on the influence of finishing by grinding and polishing on the residual stresses in the context of manufacturing S13Cr steel specimens for tensile testing. The residual stresses were measured by X-ray diffraction, using the* $sin^2\psi$ *technique and the study was complemented by analysis of magnetic Barkhausen noise and surface roughness. The results indicated that grinding was more effective in producing more compressive residual stresses. Polishing produced a slightly better surface finish when compared to grinding, although there was almost no significant difference.*

Keywords: *Residual stresses, S13Cr steel, Machining, X-Ray diffraction.*

1. INTRODUCTION

Supermartensitic stainless steels, commonly known as S13Cr or Super 13Cr steels, were developed as an improvement over conventional martensitic stainless steels and find extensive application in the oil and gas industry, mainly for the manufacturing of tubular components (Tavares et al., 2019). These steels exhibit enhanced toughness, superior corrosion resistance, and improved weldability compared to conventional martensitic stainless steels. Furthermore, their manufacturing cost is lower than that of duplex and superduplex stainless steels used for the same purposes, making them a favorable alternative (Tavares et al., 2018).

The machining-induced residual stresses play a significant role in determining the integrity and performance of machined components (Sarnobat and Raval, 2019). In machining processes, the workpiece material is submitted to non-uniform plastic deformations and uneven heating and cooling, inducing residual stresses which are greatly influencedby the cutting conditions (Lin et al., 2019; Wang et al., 2018). Furthermore, depending on their behavior, these residual stresses can produce either detrimental or beneficial effects on the service life of the machined components (Wang et al.,2018). Tensile residual stresses are known to adversely affect the fatigue and stress corrosion cracking resistance of a component, while compressive residual stresses generally enhance these properties (Martell et al., 2014; Salman et al., 2019).

One of the most common finishing processes in the metal-working industry is grinding, known to typically induce compressive residual stresses, which are beneficial to the finished component (Bianchi et al., 2003; Borchers et al., 2020; Capello and Semeraro, 2002; Ding et al., 2017; Li et al., 2018; Yao et al., 2013). Polishing is another widely used finishing process for components requiring fine surface finishing and it's also been reported in the literature as an effective process for inducing compressive residual stresses (Minguela et al., 2020; Tan et al., 2020; Quan et al., 2019).

This study presents an investigation on the behavior of residual stresses induced by grinding and polishing in the context of manufacturing S13Cr steel specimens for tensile testing. The work is complemented by analysis of magnetic Barkhausen noise and surface roughness.

2. MATERIALS AND METHODS

In this study, samples of a tube made of Super 13Cr steel were removed to produce 12 round specimens for tensile testing with reduced section diameter of 6.35 mm according to ASTM A370 standard. The dimensions of the specimens, as given by ASTM A370 standard, are illustrated in Figure 1.

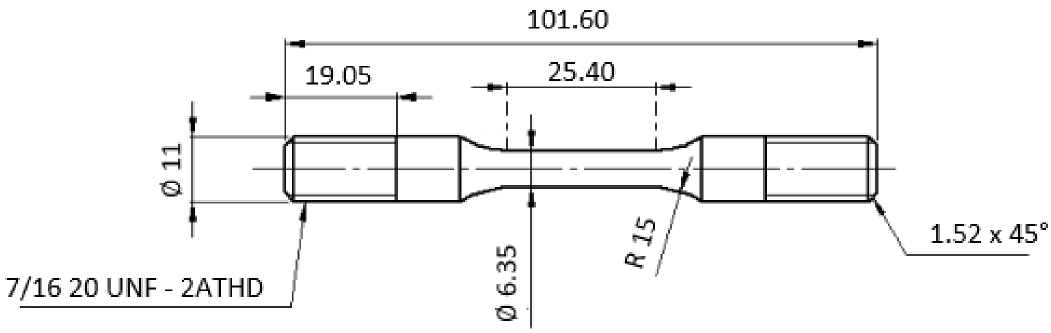

Figure 1. Dimensions of the tensile testing specimens (mm).

The chemical composition of the Super 13Cr steel and its mechanical properties are given in Table 1 and Table 2, respectively.

Table 1. Chemical composition of Super 13Cr steel (%wt.) (Manufacturer).

C	Mn	P	S	Si	Ni	Cr
0.013	0.44	0.018	0.001	0.24	5.82	12.3
Mo	Al	Cu	V	Nb	Ti	N
2.11	0.005	0.1	0.027	0.01	0.073	0.0116

Table 2. Mechanical properties of Super 13Cr steel (Manufacturer).

Tensile Yield Strength (MPa)	Ultimate Yield Strength (MPa)	Hardness (HRC)
841	887	25.4

The 12 specimens were divided in two groups of 6 specimens and each group was submitted to a different finishing treatment. All the specimens were ground on a NC Toyoda cylindrical grinder, using the same cutting conditions. The grinding process was conducted in wet condition, using a synthetic cutting fluid for grinding diluted in water in a proportion of 5%. An aluminum oxide (Al2O3) grinding wheel was applied and the wheel was dressed before grinding of each specimen. After grinding, 6 specimens were hand polished. Polishing was conducted in 3 steps, using 3 different aluminum oxide sandpapers. Diamond paste was applied in each step. The two groups of 6 specimens each were labeled G (ground specimens) and P (polished specimens). The parameters of the grinding and polishing processes are given in Table 3 and Table 4, respectively.

Table 3. Parameters of the grinding process.

Parameter	Value
Workpiece speed V_w (m/min)	8
Cutting speed V_c (m/min)	3845
Depth of cut a_e (µm)	200
Wheel diameter (mm)	510
Wheel thickness (mm)	41
Abrasive grit size	180
Wheel hardness	Medium (K)

Table 4. Polishing parameters.

Step	Abrasive grit size (FEPA)
1	600
2	1200
3	2500

The manufacturing of the specimens was followed by analysis of residual stresses, magnetic Barkhausen noise and surface roughness. The residual stresses were analyzed by X-diffraction technique, using the $\sin^2\psi$ method. Measurements were carried out with a Stresstech Xstress 3000 analyzer, using a 1.0 mm diameter collimator and the stress calculation was performed by the software Xtronic V1-0 Standard. Measurement parameters are given in Table 5.

Table 5. Parameters used for X-ray residual stress analysis.

Diffraction plane (hkl)	(211)
Radiation	CrKα
Radiation wavelength λ (Å)	2.29092
Inclination angles ψ (º)	0, 18, 27, 33 and 45
Exposure time (s)	10

Surface residual stresses were analyzed in the longitudinal direction in one point located at the center of each specimen. The setup used for the residual stresses analysis is shown in Figure 2.

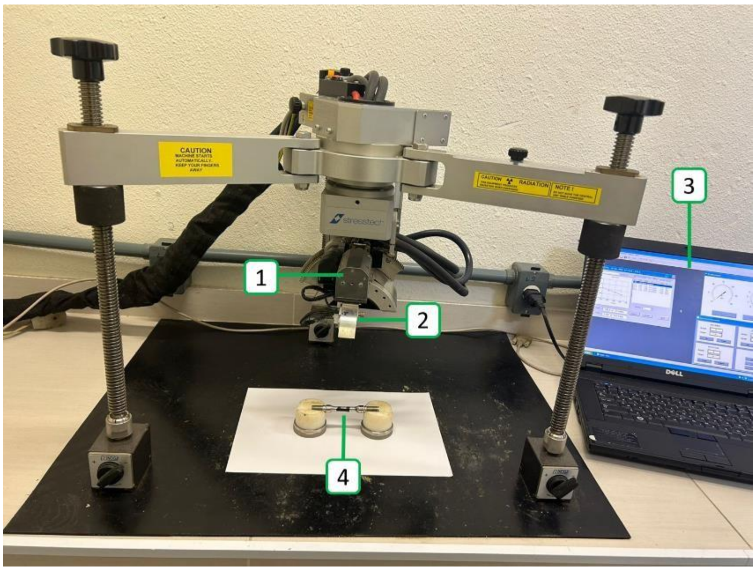

Figure 2. Residual stresses analysis setup: 1) X-ray tube; 2) collimator; 3) Xtronic V1-0 Standard software; 4) specimen.

Magnetic Barkhausen noise (MBN) analysis was carried out with a non-commercial equipment Barktech. This technique was used for a qualitative analysis of the results and comparison with the residual stress measurements by X-ray diffraction technique. The parameter adopted for the MBN analysis was the RMSMBN values of the electric signals measured when exciting the specimens by applied magnetic field generated with an exciting frequency of 10 Hz. Surface roughness analysis was carried out with a Mitutoyo surface roughness tester. The parameter adopted to evaluate the surface roughness was the arithmetical mean height Ra. Analysis of variance (ANOVA) was used to verify the significance of the experimental results of residual stresses and surface roughness.

3. RESULTS AND DISCUSSION

3.1 Residual stresses

The results of the residual stress analysis are shown in Figure 3.

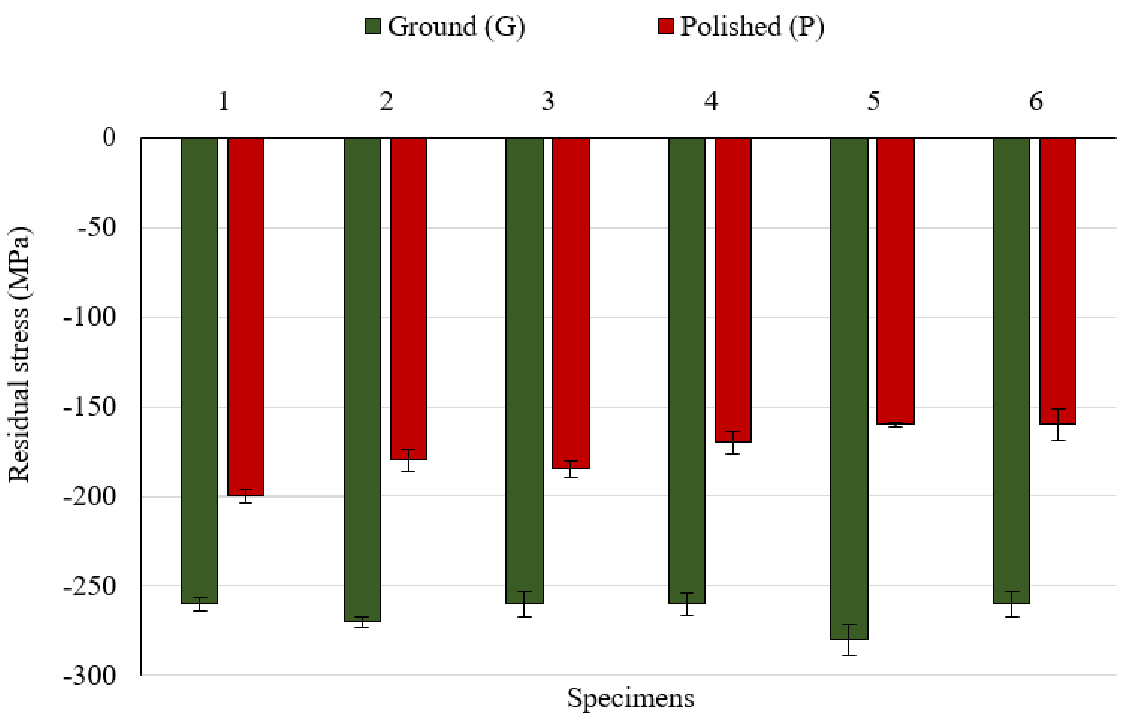

Figure 3. Residual stresses after grinding and polishing.

Both grinding and polishing processes induced compressive residual stresses only, however, the residual stresses induced by grinding were higher in magnitude than those induced by polishing, for all the specimens. Moreover, the lowest and the highest compressive residual stresses observed on the ground specimens were -260 MPa and -280 MPa, respectively, corresponding to a difference of 7.69%, while for the polished specimens the lowest and highest stresses were -160 MPa and -200 MPa, corresponding to a difference of 25%. Quan et al. (2019) studied the effects of combining milling, grinding and polishing on the surface integrity of blades and also observed that both grinding and polishing induced compressive residual stresses, although grinding followed by polishing resulted in residual stresses of higher magnitudes, which is the opposite of what was observed in this work. However, the grinding and polishing experiments conducted by the authors were both carried out on a NC machine. The results obtained in this work can be explained by highlighting major differences between the finishing processes.

First, grinding was carried out on a NC machine, while polishing was performed manually. NC machines provide better control of the cutting process, in terms of both stability of the tooling system and more uniform contact between the tool and the workpiece, which may explain why the residual stresses were more stable on the ground specimens, when compared to the polished specimens. Also, higher contact pressure between the tool and the workpiece can be achieved with a CNC machine, when compared to manual working. This may have contributed to produce higher and more uniform plastic deformations on the ground specimens, when compared to the manually polished specimens and these deformations are the main source of compressive residual stresses. Furthermore, grinding was conducted in wet condition, minimizing the thermal effects which are the main source of tensile residual stresses.

Another major difference between the finishing processes is the material removal rate, which is expressively higher for grinding. With higher material removal rate more heat can be evacuated by the chips, further minimizing the thermal effects responsible for tensile residual stresses. When compared to grinding, manual polishing involves almost neglectable material removal rate and contact pressure between the sandpaper and the workpiece. Hence the effect of attrition predominates over the evacuation of heat by the chip and plastic deformation by pressing the sandpaper against the workpiece surface. In this way, heat is accumulated on the surface of the workpiece and very low plastic deformations are produced, which may have contributed to the generation of less compressive residual stresses.

Analysis of variance (ANOVA) was used to verify the significance of the experimental measurements, providing support to the discussion. The results are shown in Table 6.

Table 6. ANOVA for residual stresses.

Source of Variation	SS	df	MS	F	**P-value**	F_{crit}
Between Groups	23852.08	1	23852.08333	151.8435013	**2.27571E-07**	4.964602744
Within Groups	1570.833	10	157.0833333			
Total	25422.92	11				

Considering a significance level of 0.05 it can be seen that there was a significant difference between the experimental results, since the p-value was almost zero. This supports the observation that the different finishing processes resulted in expressively different behaviors of residual stresses. The effect of the surface treatments can be further exploited by observing the ANOVA main effects plot shown in Figure 4. The residual stresses were plotted in absolute values, corresponding to compressive residual stresses.

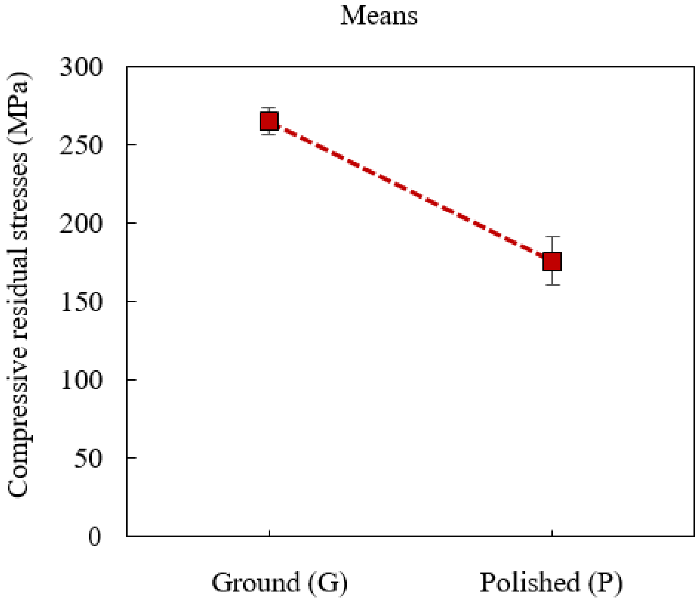

Figure 4. Main effects of grinding and polishing on residual stresses.

The result shown in Figure 4 supports the hypothesis that compared to manually polishing, grinding is a better choice as the last finishing process, in terms of enhancing the residual stress state, that is, inducing surface compressive residual stresses, which are beneficial to the finished component.

3.2 Magnetic Barkhausen noise

The results of Magnetic Barkhausen noise (MBN) analysis are shown in Figure 5.

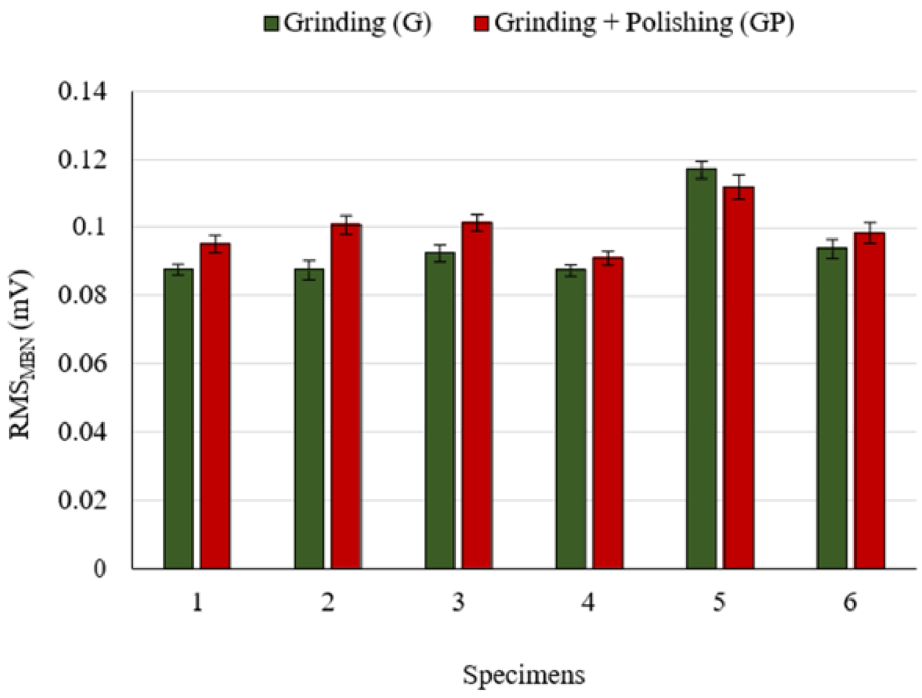

Figure 5. RMSMBN values after grinding and polishing.

The results of MBN analysis show that the RMSMBN values were higher on the polished specimens, with exception for specimen P5. Higher RMSMBN values can be associated to tensile or less compressive stresses, corresponding to the behavior observed for the residual stresses, shown in Figure 3. However, the difference between the results for ground specimens and polished specimens is not expressive. The MBN technique is sensitive not only to residual stresses, but also microstructure and hardness, which may have influenced the analysis made in this work.

3.3 Surface roughness

The results of surface roughness analysis are shown in Figure 6.

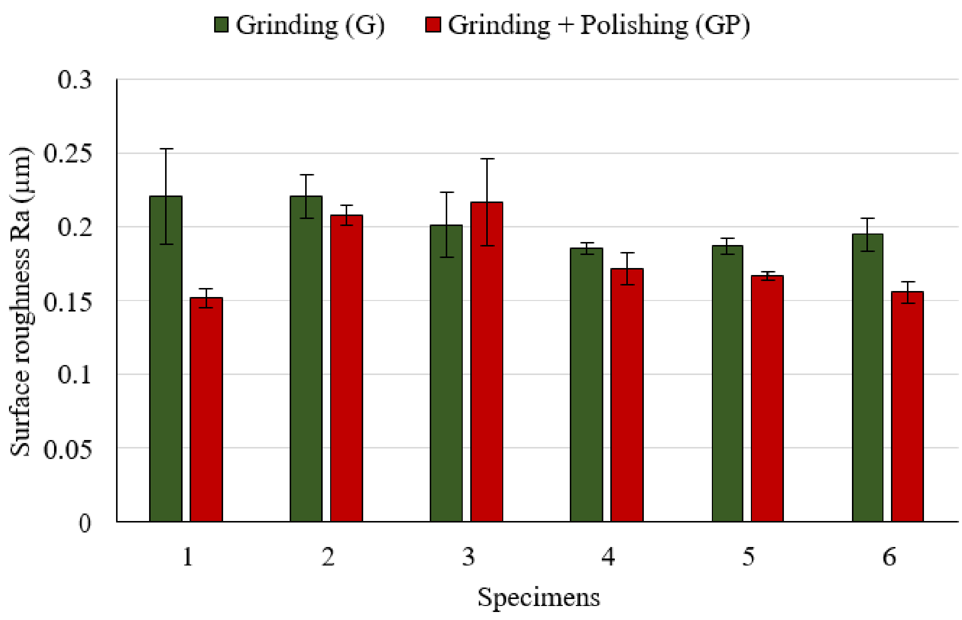

Figure 6. Surface roughness Ra after grinding and polishing.

The results show that, in general, polishing produced a better surface finish (lower Ra values), except for specimen P3. Moreover, the difference between the surface finish produced in specimens G1 and P1 was more expressive, when compared to the other specimens. It can also be seen that the results for polishing vary more expressively when compared to the results for grinding. This can be explained by the fact that polishing was conducted manually. The significance of the different treatments was evaluated by ANOVA. The results are shown in Table 7.

Table 7. ANOVA for surface roughness.

Source of Variation	SS	df	MS	F	**P-value**	F_{crit}
Between Groups	0.002395	1	0.002395	6.004153	**0.039916**	5.317655
Within Groups	0.003191	8	0.000399			
Total	0.005586	9				

The result of the ANOVA show that the difference between the treatments was statistically significative, however, the p-value of approximately 0.04 indicates that the difference between the effects of the treatments may not be expressive. Figure 7 show the main effect plot for this analysis.

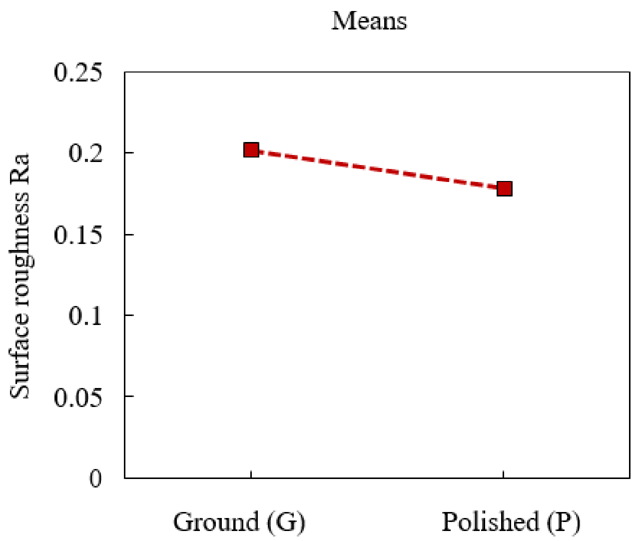

Figure 7. Main effects of grinding and polishing on surface roughness Ra.

It can be seen by Figure 7 that there was no expressive difference between the means of the results for surface roughness Ra obtained by grinding and polishing. This does not indicate that both finishing processes were equally efficient, since lower Ra values were observed on the polished specimens. However, hand polishing involves much less control of the finishing operation and the results may have been influenced by this factor.

4. CONCLUSIONS

In the present work the residual stresses and surface finish generated on supermartensitic stainless steel by grinding and polishing were experimentally investigated. Based on the analysis of the experimental results the following conclusions can be summarized:

1) NC grinding provided a better control of the finishing operation when compared to hand polishing, which may have contributed to the formation of compressive residual stresses of higher magnitudes.

2) The magnetic Barkhausen noise technique worked as a qualitative support for the residual stresses measured by X-ray diffraction in most specimens.

3) Hand polishing in 3 steps using finer abrasive in each step resulted in a better surface finishing than that obtained by NC grinding.

5. ACKNOWLEDGEMENTS

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