STUDY OF RESIDUAL STRESS IN A SUPER DUPLEX STAINLESS STEEL AFTER TURNING

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Abstract. *The purpose of this paper was to study the main effects of the turning in the residual stress generation of the duplex stainless steel ASTM A890-Gr6A. The focus of the work was the finishing operations and a complete factorial planning was used, with 2 levels and 5 factors. The tests were conducted on a turning center with carbide tools and the main entrances variables were: tool material class, feed rate, cutting depth, and cutting speed. The residual stress measurements were conducted by x-ray diffraction technique. The results correlated the residual stress with the cutting parameters and its better combination was founded for it's best generation. The smaller feed rate (0.1 mm/v), smaller cutting speed (110 m/min) and the greater cutting depth (0.5 mm) provided the smaller values for the tensile residual stress. The paper contribute for the study of the super duplex stainless steel, considering that no one researches was founded for the studied topics in this material in witch presents different behavior in machining when compared with another stainless steels.*

Keywords: *Manufacturing and processing, machining, turning, super duplex stainless steel and residual stress.*

1. INTRODUCTION

The super-duplex stainless steel presents characteristics of the ferritic and austenitic stainless steels in just one material and in this form it has greater mechanic and corrosion resistance than the conventional austenitic stainless steel. It's characterized by a mixture structure in approximately equal parts of austenite and ferrite. The DSS with relationship to the austenitic steels stainless steel, presents several advantages, being the mayor ones: larger resistance to the corrosion under clorets tension, larger resistance to the pitting corrosion and in general twice strength limit than an austenitic, with just half of the amount of nickel present in the austenitics, being less sensitive at the high cost of this element (Davidson et al., 1986).

The machining of stainless steels is in general different, when compared with other steels. It's mainly characterized for: high strain rates that induce mechanical modifications and heterogeneous behavior in the generated surfaces, and that take to the unstable chip formation and vibrations (Saoubi et al., 1999); Low thermal conductivity (Dolinsek, 2003) because the conduction of heat corresponds approximately ¼ of the value found in the machining of a common steel, and in this way the heat is less transferred for the work material or the chip and it's concentrated more on the tool edges; High fracture resistance, resulting in high temperatures, difficult chip break and consequently low superficial quality (Jang et al., 1996); High values of mechanical resistance and ductibility (Chang et al., 2003); BUE formation, and in a different way from the conventional steels, it can appear in higher speeds; High wear of the tools, due to the high cutting forces, and frequently small material pieces are removed from the tool, due to the high adhesion in the rake surface; High thermal dilation coefficient, what difficult the maintenance of small tolerances and high friction coefficient, that has as consequence, the increase of the cutting forces and of the generated heat.

In spite of the main characteristics presented, it's noted that the machining of stainless steels cannot be totally generalized. Due to the great variety, the machining can be worse, or better, in agreement with the microstructure, hardness and league content of elements, being known that the microstructure affects the machining in larger scale than the hardness. As example, Bletton et al. (1990) mention that the two-phase structure of the duplex stainless steels, contribute to induce vibrations during the its cutting, increasing the problems mentioned until the moment and contributing to the decrease of the tool life.

The difficulties in the machining of super duplex stainless steel tend to increase, therefore the machining of this material frequently is compared with its PRE (Pitting resistance equivalent) (Jiang et al., 1996). Due to the great amount of austenite, nitrogen and alloy elements, the machining of this material tends to decrease quickly. Another factor that contributes to the difficulties in the machining and in the study of this material, is the fact that, it's biphasic, as previously mentioned. Each phase is random distributed, and contains different characteristics and properties, and each one contributes in a different way to the chip formation and material cutting during the machining.

The demand for the products production of high quality has its attention in the pieces surface properties, especially in the residual stress of the machined surfaces, due to its effects in the acting of the components, longevity and reliability (Jang et al., 1996 and Saoubi et al., 1999). Many fails produced by fatigue, creep and stress corrosion cracking, invariably begin in the surface of the components and depend largely on the quality of it. Therefore it is of extreme importance to characterize the influence of the machining conditions in the surface of the pieces (Sauvage et al. 2003). Besides, the residual stress can cause deformations, accelerate phase transformations and corrosion processes and its one of the crucial factors in the superficial quality determination.

To accomplish the established objectives of this work, some tests were made buy a factorial design and the residual stress was measured by x-ray difractometer. The objective of this work is to characterize the main effects caused in the residual stress material surface by the machining through the turning operation and to establish correlations between the cutting parameters and it's consequences, since the adequate choice of the cutting parameters is basic to get products with the superficial qualities required (Thomas et al., 2003 and Lee et al., 2000).

2. THE RESIDUAL STREES

The residual stress is defined as the stress that exists in an elastic body after all the external loads are removed. Machining generally involves a large amount of plastic deformation with extremely high strain and strains rate (Jang et al., 1996).

The residual stress can be of tension or compression. Compressive residual stress generally increases the piece life, by the reduction of the work tensile stress and consequently the fissures nucleation. The tensile residual stress increase the work tensile stress and can lead the components to premature fails.

Sigwart e Fessenmeyer (1995 apud EL-Axir, 2002) shows that to pieces of DIN 42CrMo4 steel with compressive residual stress greater than 600MPa, the fatigue limit life increase 30%.

By Capello et al. (1999), the main influence factors for the residual stress formation in the turning process are the cutting speeds and the primary rake angle, that are directly connects to the thermal phenomenon and the deformation ranges, respectively. Liu and Barash (1976) show that the main influence factors are: cutting depth and flank wear.

The thermal tension in the case of the duplex stainless steel become the study more complicated by the different thermal expansion factor from each material phase. Johansson et al, (1999), studied the residual stress in each material phase after heating and mechanical deformation, and the results showed predominantly tensile and compressive values in the austenitic and ferritic phases respectively.

Jang et al. (1996) during austenitic AISI 304 stainless steel turning, concluded that the sharpness of the tool influences more in the residual stress than the cutting parameters, even so lower feed rate (0,08mm/v), great cutting depth (1mm) and lowers cutting speed (<180 rpm = 30m/min) produced pieces with the smallest values of tensile residual stress.

Bouzid Saï et al., (2001) accomplished some milling experiments, in order to begin the study of the surface integrity of a 1020 carbon steel and a duplex stainless steel, even so they didn't make measurements of residual stress for the stainless steel. The results showed that with the increase of the feed rate and cutting speed (considering the group and not the factors individually) an increase of the tensile residual stress was noted in the two directions of the machined material.

Shaw (2005) during orthogonal cutting of a low carbon steel, found perpendicular values of tensile residual stress to the cutting direction in all the bodies tests. Larger values of tensile residual stress were obtained with low cutting speeds and low cutting depths.

Brinksmeier et al. (1982) mention that the increase of the cutting temperature, favors the increase of the tensile residual stress.

Saoubi et al. (1999) during orthogonal cutting experiments in cylindrical pieces of AISI 316L, concluded that the residual stress increases around 20% with the increase of the cutting speed (working in values from 100 to 200m/min). The authors also found significant changes in the residual stress values when different coating were tested for the inserts and they concluded that the decrease of the friction due to the used coating decreased the temperature in the cutting area and they appeared when the smaller values of tensile residual stress were reached. They still mention that the thermal effects caused by this change in the friction were the variable that more contributed to the characterization of the surface during the tests. The authors still concluded that the feed rate didn't have significant influence in the residual stress, but that its increase makes the increases in the tensile residual stress layer grows as well as the compressive residual stress below the surface.

Capello et al. (1999) studied the influence of the cutting parameters in the residual stress of two hardened materials in the turning process. The authors mention that, due to the low heating in the work piece during the turning, it is waited that the thermal effect alleviates the residual stress generated by the deformation fields and, therefore, the factors that more influence the formation of the residual stress are those that more affects the deformation and the temperature during the process. The cutting speed and the primary rake angle are the factors that more influence the residual stress, according to the revision accomplished by the authors, even so the experiments showed that, the most influential factors were the feed rate and the radius point of the tool. The cutting speed and the rake angle had secondary relevance. The increase of the cutting speed, the decrease of the feed rate, the decrease of the radius point ray, and the positive increase of the rake angle produced pieces with smaller tensile residual stress.

Already the results obtained by Delijaicov (2004), showed that the increase of the cutting speed, the decrease of the feed rate and the increase of the radius point decrease the compressive residual stress. It means that for almost same works, the results just converge for the radius point, considering that the same ones were accomplished with hardened materials.

As can bee notes the residual stress analysis is so complicated and cannot be generalized, because some small changes in the cutting process makes greats differences in the final results. No one references was founded for the residual stress analysis of a super duplex stainless steel after machining.

3. EXPERIMENTAL PROCEDURE

The tests were conducted in a turning center OKUMA LB300, and the used cutting fluid was the Castrol PS04002 with 6% of emulsion in water in abundance.

The material was the super duplex stainless steel ASTM A890GR6A (0.02 C, 24.8 Cr, 7.49 Ni, 0.65 Mn, 0.8 Si, 3.37 Mo, 0.006 S, 0.025 P, 0.8 Cu, 0.059 Zr, 0.79 W, 0.24 N, <0.001 Nb, <0.001 Al, 0.044 Co, 0.03 V, 0.006 Ti, 0.0009 Pb, 0.082 Sn, Fe).

After the casting made especially for this work with dimensions ∅90x400mm, the material was annealed.

Each part of the specimens (approximately 15mm and separated by a groove) were machined by different cutting parameters, as will be showed at next.

The used design of experiments was the complete factorial, with 2 levels and 5 factors and 2 replicates. This design was used because it’s the unique that can study the interactions between the factors (Calado et al., 2003 and Montgomery, 1976). The used cutting parameters were: cutting speed (110 and 150 m/min), feed rate (0.1 and 0.2 mm/r) and cutting depth (0.25 and 0.5 mm).

Every one of the used insert carbide tools doesn’t have been utilized for more than 2 segments of the specimen and in this way, no wear was observed, and was considered that only new tools were used on the work. The inserts carbides used were: VNMG 160404-MF–1025 with PVD TiAlN coating and VNMG 160404-MF–2015 with CVD TiCN-Al2O3-TiN coating.

The residual stress measurements were made by x-ray difractometer RIGAKU – DMAX Rint 2000. The method used was sen² ψ from –60° to +60°, of 10 in 10°. The CrKα rays were irradiated on the crystallographic plans (2 1 1). The results were relative to the circumferential residual stress and the axial values weren’t measured.

4. RESULTS AND DISCUSSIONS

The Table 1 shows the founded values for the residual stress.

Table 1. Founded values of residual stress measurements

Test	Cutting speed (m/min)	Feed rate (mm/r)	Cutting depth (mm)	Insert class	Residual stress (MPa)
1	110	0,1	0,25	2015	484,5
2	150	0,1	0,25	2015	417
3	110	0,2	0,25	2015	434,5
4	150	0,2	0,25	2015	222,5
5	110	0,1	0,5	2015	654
6	150	0,1	0,5	2015	299,5
7	110	0,2	0,5	2015	345,5
8	150	0,2	0,5	2015	572
9	110	0,1	0,25	1025	354,3
10	150	0,1	0,25	1025	326,4
11	110	0,2	0,25	1025	560
12	150	0,2	0,25	1025	492,5
13	110	0,1	0,5	1025	281,5
14	150	0,1	0,5	1025	329,5
15	110	0,2	0,5	1025	326
16	150	0,2	0,5	1025	406

As can be noted, all the residual stresses generated during the machining were tensile. The residual stresses are generated during machining by mechanical and thermal effects, and in the most cases predominantly mechanical than thermal (Brinksmeier et al., 1982). All the cutting parameters have effects in the residual stress formation, because all of then make changes or in the temperature or in the mechanical deformation. In this case, was noted during the data interactions analysis, that the cutting speed and the insert class presented interactions with all the other factors.

Just to be compared with the existent results, one piece was machined without cutting fluid utilization and another one was machined with bigger cutting speed (600 m/min). The specimen machined with the higher speed obtained 225 MPa, and the cutting parameters were the same as the test number 10 and 11, from Table 1, except the cutting speed, that means the tensile residual stress value dropped. The specimen machined without cutting fluid obtained 512 MPa, and the cutting parameters were the same as the used in test number 1, from Table 1, that means, an augment in the tensile residual stress.

The Fig. 1 shows the influence of the cutting parameters on the tensile residual stress.

It is noticed that the variable with smaller influence is the cutting depth, when the averages are studied. The increase of the cutting speed contributed to smaller found values of tensile residual stress, and these results were still more pronounced in the body test where cutting speed increased abruptly, as exposed previously. The smaller feed rate also contributed to the decrease of the tensile residual stress, as well as the machining with the insert class GC1025 and the increase of the cutting depth, in spite of having smaller influence.

Great values of compression residual stress provides longer life fatigue to the pieces in service, and for the tensile residual stress, how minor is it's values, it's better for the pieces lives. The carbide insert class 1025 provides smaller values of residual stress, as previously saw in Fig. 1. In some previous analysis including cutting force measurements, surface roughness analysis and micro-hardness measurements, it was noted that this tool class always provide the better answers, so from this point of the work, only the 1025 insert class will be analyzed.

The Fig. 2 shows the main effects plot for the 1025 class. As can bee noted the smaller feed rate and the bigger cutting depth provide the best results for residual stress analysis. In this case, as the same as presented in the Fig. 1, bigger values of deformation imposed by the feed rate provides the augment in the residual stress values. The augment in the cutting depth also provides same results, once a bigger part of main edge was in contact with the material and it provides a better cutting witch attenuates some deformation cutting area.

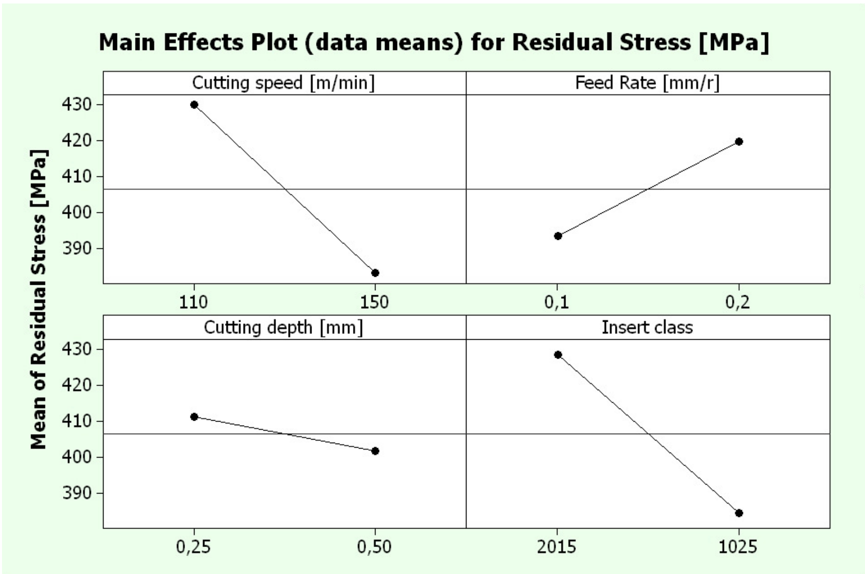

Figure 1. Factorial analysis for tensile residual stress

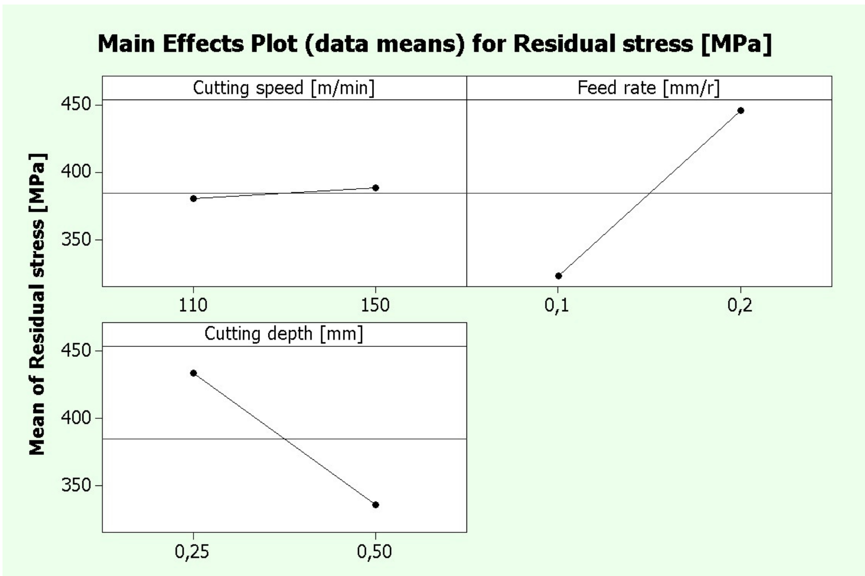

Figure 2. Factorial analysis for tensile residual stress for 1025 tool class

The Fig. 3 and 4, shows the contour plots for the 1025 class, for the low and high values respectively.

It is noticed in the Fig. 4 in the graph “feed rate x cutting speed” that with the feed rate 0,1mm/r used with this tool class (1025), even varying the cutting speed, the values of the tensile residual stress were the smallest ones (around 300-350 MPa). In the Fig. 3, to reach the smallest value of tensile residual stress, the graph “cutting depth x cutting speed” must be observed, where almost the same situation is showed. These two graphs shows the same results as illustrated in Fig. 2, that shows the importance of cutting depth and the speed in the residual stress generation. With this graphs analysis, can be noted that for the tool class 1025, the best machining condition for the residual stress generation was obtained with the use of the smallest feed rate and the bigger cutting depth, and the cutting speed has a secondary importance.

With this graphics it's possible to establish correlations between the cutting parameters used and residual stress measurements.

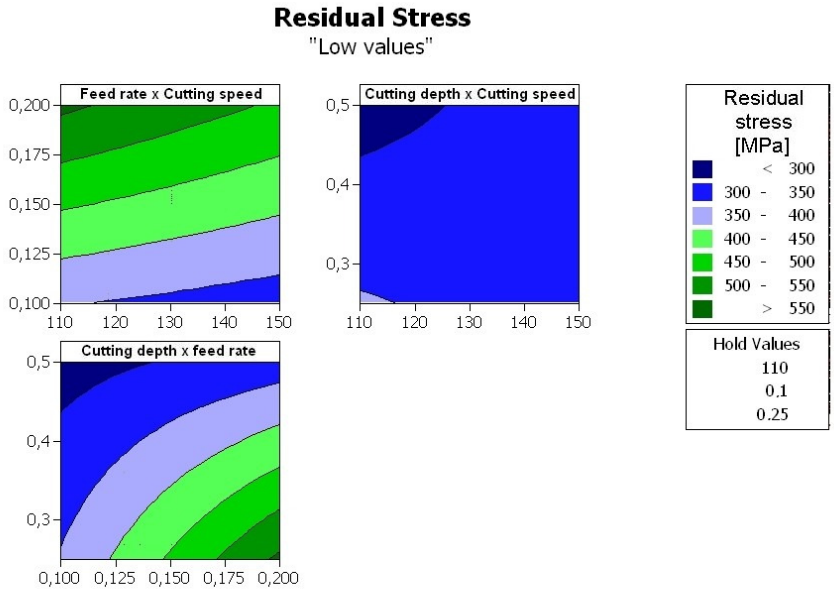

Figure 3. Contour plot for residual stress (low values)

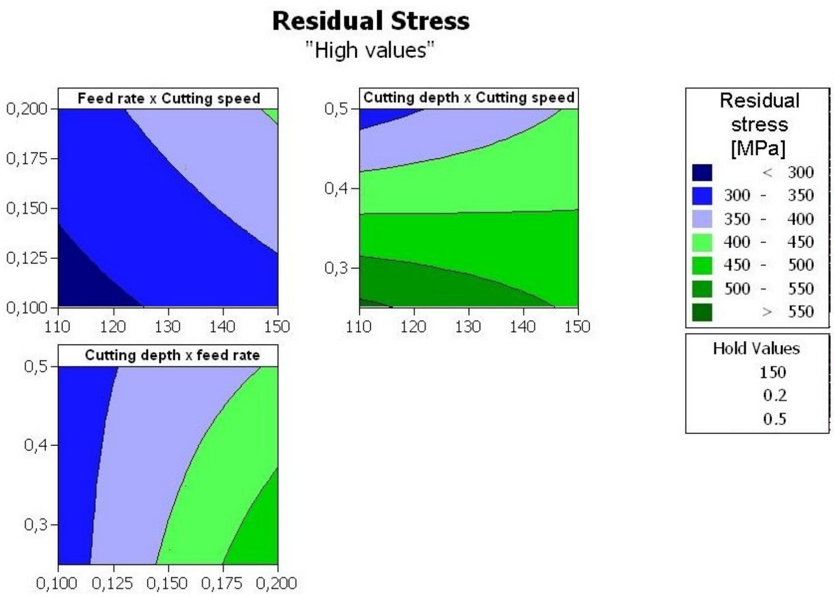

Figure 4. Contour plot for residual stress (high values)

An empirical model was designed to correlate the cutting parameters with the residual stress, by linear regression, for the 1025 tool class, as showed in the Equation (1).

$$\sigma_{res} = 320 + 0{,}20V_c + 1232f - 390a_p \quad (1)$$

The maximum difference between the measured and calculated values was 15%, in according with Table 2. These values seems reasonable, since this material presents more difficult to analyze, because it's two present phases, that each one of that contributes in different way to the chip formation.

Table 2. Differences between the residual stress measurements and the calculated

Vc [m/min]	f [mm/r]	ap [mm]	Residual stress measurements [MPa]	Residual stress by model [MPa]	Difference in%
110	0,1	0,25	354,3	367,7	-3,78
150	0,1	0,25	326,4	375,7	-15,10
110	0,2	0,25	560	490,9	-12,34
150	0,2	0,25	492,5	498,9	-1,30
110	0,1	0,5	281,5	270,2	4,01
150	0,1	0,5	329,5	278,2	15,57
110	0,2	0,5	346	393,4	-13,70
150	0,2	0,5	406	401,4	1,13

5. CONCLUSIONS

- ✓ The founded range between the residual stress measurements was around 400MPa;
- ✓ The smaller cutting speed, the tool class 1025, the smaller feed rate and the bigger cutting depth provides the smaller residual stress, where the feed rate and the cutting depth were the most important parameters;
- ✓ The dry cutting, showed a tendency to increase the tension residual stress;
- ✓ Contours graphs were generated which was possible to find the best cutting parameters combinations to the residual stress generation;
- ✓ An empirical model was founded to correlate the residual stress values with the cutting parameters that presents maximum error around 15%;

Acknowledgements

The authors would like to thank the Sandvik Coromant, the Sulzer Pumps and the Mauá Institute of Technology for the great help during this work.

REFERENCES

Berglund, G., Wilhelmsson, P., 1986. Fabrication and Practical Experience of Duplex Stainless Steels. Proceedings of "UK Corrosion '86", Birmingham.

Bletton, O., Duet, R., Heritier, B., 1990. Usinabilité des aciers inoxydables. In: P. LACOMBE, P. ; BAROUX, B. ; BERANGER, G. (Eds.) Les Aciers Inoxydables, Les Editions de Physique, chap.21, pp. 759-794.

Bouzid Saï, W., Ben Salah N., Lebrun, J. L., 2001. Influence of machining by finishing milling on surface characteristics. International Journal of Machine Tools & Manufacture, v.41, pp. 443-450.

Brinksmeier, E., Cammett, J. T., König, W., Leskovar, P., Peters, J., Tönshoff, H. K., 1982. Residual stresses – Measurement and causes in machining processes. Annals of the CIRP, v.31, pp. 491-510.

Calado, V., Montgomery, D. C., 2003. Experimental-planing using the Statistica. Rio de Janeiro, E-papers Serviços Editoriais Ltda.

Capello, E., Davoli, P., Bassanini, G., Bisi, A., 1999. Residual stresses and surface roughness in turning. Transactions of the ASME, v.121, pp.346-351.

Chang, C., Tsai, G., 2003. A force model of turning stainless steel with worn tools having nose radius. Journal of Materials Processing Technology, v. 142, pp. 112-130.

Davidson, R. M., Redmond, J. D., 1991. A guide to use duplex stainless steels. Materials & Design, v. 12, n. 4, pp. 187-192.

DELIJAICOV, S., 2004. Residual stress modeling in the turning process of a hardened steel DIN 100 CrMn6 and it's correlations with the cutting forces. São Paulo, Tese (Doutorado) – Escola Politécnica da Universidade de São Paulo, 176p, 2004.

Dolinsek, S., 2003. Work-hardening in the drilling of austenitic stainless steels. Journal of Materials Processing Technology, , v.133, pp. 63-70.

El-AXIR, M. H., 2002. A method of modeling residual stress distribution in turning for different materials. International Journal of Machine Tools & Manufacture, v.41, pp.1055-1063.

Jang, D. Y., Watkins, T. R., Kozaczek, K. J., Hubbard, C. R., Cavin, O. B., 1996. Surface residual stresses in machined austenitic stainless steel. Wear, v.194, pp. 168-173.

Jiang, L., Paro, J., Hänninen, H., Kauppinen, V., Oraskari, R., 1996. Comparison of grindability of IPED austenitic 316L, duplex 2205 and super duplex 2507 and as-cast 304 stainless steels using alumina wheels. Journal of Materials Processing Technology, v. 62, pp. 1-9.

Joahnsson, J., Odén, M., Zeng, X. H., 1999. Evolution of the residual stress state in a duplex stainless steel during loading. Acta Metallurgica Inc., n.9, pp. 2669-2684.

Lee, B. Y., Tarng, Y. S., 2000. Cutting-parameter selection for maximizing production rate or minimizing production cost in multistage turning operations. Journal of Materials Processing Technology, v.105, pp. 61-66.

Liu, C. R., Barash, M. M., 1976. The mechanical state of the sublayer of a surface generated by chip-removal process, Part2: Cutting with a tool with flank wear. Transactions of ASME, pp. 1202-1208.

Montgomery, D. C., 1976. Design and analysis of experiments. 3.ed. New york, John Wiley & Sons, Inc.

Saoubi, R. M.; Outeiro, J. C., Changeux, B., Lebrun, J. L. Dias, A. M., 1999. Residual stress analysis in orthogonal machining of standard and resulfurized AISI 316L steels. Journal of materials processing technology, v.96, pp. 225-233.

Sauvage, X., Le Breton, J. M., Guillet, A., Meyer, A., Teillet, J., 2003. Phase transformation in surface layers of machined steels investigated by X-ray diffraction and Mössbauer spectrometry. Materials Science and Engineering, v.A362, pp. 181-186.

Shaw, M. C., 2005. Metal cutting principles. 2.ed. New York, Oxford series on advanced manufacturing.

Thomas, M., Beauchamp, Y., 2003. Statistical investigation of modal parameters of cutting tools in dry turning. International Journal of Machine Tools & Manufacture, v.43, pp. 1093-1106.