EFFECT OF MACHINING PARAMETERS ON CUTTING FORCE OF THREE AUSTENITIC STAINLESS STEELS

Flávio Namura Macari
Polytechnic School – University of São Paulo. Av. Prof. Mello Moraes 2231 05508900 São Paulo S.P.
flavio.macari@poli.usp.br

Henrique Augusto Belizário Sanches
Polytechnic School – University of São Paulo. Av. Prof. Mello Moraes 2231 05508900 São Paulo S.P.
henrique.sanches@poli.usp.br

Izabel Fernanda Machado
Polytechnic School – University of São Paulo. Av. Prof. Mello Moraes 2231 05508900 São Paulo S.P.
machadoi@usp.br

Abstract. *Austenitic stainless steels are used in many areas of industry such as chemical and electronic. These steels do not have high strength, although they have high workhardening rate and low thermal conductivity. Therefore austenitic stainless steels machinability does not compare with low carbon steels. The main objective of this work is to study the effect of machining parameters (feed, cutting depth and cutting speed) on the cutting force of three austenitic stainelss steels during turning process. The three types of austenitic stainless steel studied were: AISI 303, 304 e 310. Two different feed (f) - cutting depth (d) relations were used. In the first set of tests the relation used was f/d<0.5 (plain state of strain) and in the second set of tests the relation used was 1< f/d<2 (plain state of tension). The effect of the cutting speed was also evaluated in the different set of tests, because of the built up edge formation during the machining of austenitic stainless steels is frequently observed. A surface profilometer was used to measure the finishing and the turned surface was also observed by using optical microscopy. The cutting force was measured by using a load cell connected to an acquisition board. The results showed differences in the three stainless steels studied turned using the same cutting conditions. The differences were observed mainly in the cutting forces as a result of dissimilar behavior of the austenitic stainless steels studied.*

Keywords: *Austenitic stainless steels, Cutting force, Roughness, Turning.*

1 Introduction

Stainless steels are iron-base alloys containing at least 12%wt of chromium. The austenitic stainless steel grade is most frequently used (Andrade et al., 2004). They are employed in many areas of industry such as chemical and electronic, because of their high corrosion resistance and nonmagnetism, respectively (Peckner et al., 1977).

Austenitic stainless steels have excellent ductility and toughness (Peckner et al., 1977). On the other hand, they have poor machinability as compared to other classes of steels (Lacombe et al., 1993; Jang et al.; 1996 and M'Saoubi et al., 1999). The problems related to the machining of austenitic stainless steels are: tool wear, poor finishing, long and stringy chips and low cutting speed (Fang et al., 1996, Jang et al.; 1996 and M'Saoubi et al., 1999). These problems are mainly caused by their high workhardening rate, low thermal conductivity and the tendency to strain-induced martensite formation (Tessler et al., 1992; Lacombe et al., 1993 and M'Saoubi et al., 1999, Padilha et al., 2002). The workhardening is introduced in the surface during the turning as a result of residual stresses due to plastic strain of the work material ahead of the tool cutting edge (Kulkarni et al., 2003). Plastic strain in the surface causes microstructural and mechanical modifications, which increase the cutting force among other points, and poorer finishing (Machado et al., 2003).

The chemical composition of steel also influences mechanical behavior as well as its machinability. There are wide ranges of chemical composition of austenitic stainless steels. The percentages of chromium can vary from 15 to 26 wt.% whereas the percentages of nickel can vary from 3.5 to 38wt. % (Peckner et al., 1977). Steels containing higher levels of alloying elements, particularly nickel, usually have a better corrosion, oxidation resistance and a steady austenite. The machinability of some austenitic stainless steels can be improved by sulphur addition. The resulfurization decreases the cutting forces. The sulphur addition propitiates the formation of manganese sulfide inclusions that make chip breaking easier. The sulphur also works as a lubricant (Lacombe, et.al, 1993). On the other hand, the resulfurization deteriorates the surface texture, especially at lower cutting speeds in dry cutting (Akasawa, et al., 2003).

In this study, three types of austenitic stainless steel were evaluated: AISI 303, 304 e 310. Two different feed (f) - cutting depth (d) relations were used in this study. In the first set of tests the relation used was f/d<0.5, which is nearly plain state of deformation, and in the second set of tests the relation used was 1<f/d<2, which is nearly plain state of tension. The effect of the cutting speed is also evaluated in different sets of tests, because the built up edge formation during the machining of austenitic stainless steels is frequently observed. A surface profilometer was used to measure the roughness (finishing). The turned surface was also observed by using optical microscopy. The cutting force was measured by using a load cell connected to an acquisition board. The results showed differences in the three stainless steels studied, which were turned in the same cutting conditions.

2 Materials and experimental procedure.

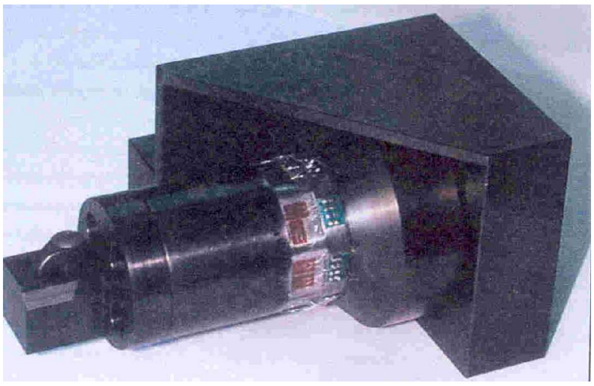
The materials utilized in this study were AISI 303, 304 and 310 austenitic stainless steels rolling bars of about 25 mm in diameter. The chemical composition of the steels is showed in table 1. The samples used in the tests were 120 mm in length and of about 25 mm in diameter.

Table 1 – Chemical compositions (wt%) of AISI 303, 304 and 310 austenitic stainless steels and Mn/S ratio.

Steel	%Cr	%Ni	%C	%Mn	%Si	%S	%P	Mn/S
303	17.2	8.21	0.050	1.88	0.48	0.200	0.036	10
304	18.1	8.54	0.055	1.80	0.58	0.030	0.037	60
310	24.2	19.6	0.069	2.00	0.62	0.019	0.036	105

The samples were turned in different conditions. Feeds utilized in the tests were 0.104 and 0.327 mm/rotation. Two different feed (f) - cutting depth (d) relations were used in this study. In the first set of tests the relation used was $f/d<0.5$, which is nearly plain state of strain, and in the second set of tests the relation used was $1<f/d<2$, which is nearly plain state of tension.

A universal lathe was used in turning of the steels samples. The toolholder equipped with a load cell (figure 1(a)) made possible to measure the cutting forces. The samples were placed in three-jaw chucks without using tailstock. The tool utilized was TCMT160304 type, TiN coated. The side cutting edge angle utilized was 0^o, the rake angle used was $+4^o$ and relief angle was 7^o. The cutting speeds of the tests were 85 m/min and 20 m/min, respectively. No cutting fluid was used. The experimental equipment is shown in figure 1(b).



(a)

(b)

Figure 1. (a) The toolholder equipped with a load cell and (b) experimental equipment used to measure cutting forces during turning: Lathe, acquisition system and a microcomputer.

The Vickers microhardness was measured the use of 2kg load (HV 2) in all the austenitic stainless steels studied.

A surface profilometer Mitutoyo SJ-201P was used to measure the roughness of the turned surfaces. The cut-off (λc) utilized was the one recommended in ASTM 95 (0.8 mm or 2.5 mm selected based on arithmetic mean roughness value (Ra)). The roughness was measured twice in each turned sample to confirm the results. Only one measure of each sample was chosen to be shown in this work. The turned surface was also observed by using optical microscopy.

During the turning, the cutting force was evaluated. The cutting force was measured by using a load cell connected to an acquisition board with a power source, an amplifier and a low pass filter. The load cell was calibrated by applying force in a spindle linked to a mechanical dynamometer. A calibration constant was obtained to set the tests. During turning test, the sample rate utilized was 5000Hz. The results were acquired during 60s test.

3 Results and discussion

The results and discussion will be presented in different sections as follows: 3.1 Vickers microhardness, 3.2 Roughness, and surface finishing and 3.3 Specific cutting pressure.

3.1 Vickers microhardness

Vickers microhardness of AISI 303, 304 and 310 austenitic stainless steels studied are displayed in table 2. The microhardness of the different steels are similar.

Table 2 - Vickers microhardness of AISI 303, 304 and 310 austenitic stainless steels studied.

Steel	Microhardness (HV)
303	177
304	170
310	156

3.2 Roughness and surface finishing.

The roughness of the surface can be determined by geometrical aspects, which depend on the feed and the tool nose radius. The roughness is also influenced by tool wear, vibrations and plastic strain that occurs due to the chip formation. The geometrical values of roughness were previously calculated. The feed of 0.104 resulted in 3.38 μm and the feed of 0.327 resulted in 33.42 μm. Table 3 shows the roughness (Ra and Rt) of the machined surface of the steels studied as a function of the cutting speed, the feed and the f/d relation (f represents the feed and d represents the cutting depth). The relation f/d<0.5 causes a plane state of strain in the cutting areas. The relation 1<f/d<2 causes a plain state of tension in the cutting areas.

Table 3 – Roughness of machined surface of different steels as a function of the cutting speed, the feed and the f/d relation (f represents the feed and d represents the cutting depth).

Steel	**f/d<0.5 f=0.104 mm/rot**	**f/d<0.5 f=0.327 mm/rot**	**1<f/d<2 f=0.104 mm/rot**	**1<f/d<2 f=0.327 mm/rot**
303 85m/min	Ra 0.79 Rt 5.95	Ra 8.2 Rt 32.74	Ra 1.46 Rt 8.32	Ra 8.32 Rt 34.75
303 20m/min	Ra 3.1 Rt 23.94	Ra 9.01 Rt 43.42	Ra 2.16 Rt 12.29	Ra 8.11 Rt 41.62
304 85m/min	Ra 1.08 Rt 6.54	Ra 9.48 Rt 45.95	Ra 1.24 Rt 7.34	Ra 1.14 Rt 7.52
304 20m/min	Ra 1.2 Rt 8.12	Ra 9.35 Rt 43.05	Ra 1.14 Rt 7.52	Ra 8.41 Rt 37.18
310 85m/min	Ra 1.55 Rt 10.75	Ra 9.48 Rt 41.85	Ra 8.5 Rt 37.01	Ra 8.71 Rt 35.74
310 20m/min	Ra 1.41 Rt 10.78	Ra 9.83 Rt 46.17	Ra 2.58 Rt 18.35	Ra 7.73 Rt 29.92

The roughness measured was different from the geometrical roughness. The significant difference was observed when the lowest feed (0.104 mm/rot) was used. The reason is connected to high normal stress in the material at the trailing edge of the tool, which causes material flow to alleviate the stress when low feeds where used. In this case, the undeformed chip thickness gradually went to zero (Shaw, 1986). The material flow and the high strain in the chip can affect the amount of the local strain in surface and roughness. Therefore the roughness could be determined by other factors, such as surface deformation due to chip formation. The relation 1<f/d<2 (plain state of tension) certainly increased these differences.

The arithmetic mean roughness (Ra) measured was not strongly influenced by the material, the cutting speed or the f/d relation. The exceptions were the AISI 304 (1<f/d<2, f=0.327 mm/ rotation and cutting speed of 85 m/min) and mainly the AISI 310 steel, which were considerably influenced by the state of tension. The roughness (maximum peak-to-valley hight - Rt) of AISI 303 steel also showed a considerable difference in only one cutting condition (cutting speed of 85m/min, f/d<0.5 and f=0.104 mm/rotation).

The finish surfaces characterization obtained by using optical microscopy and the surfaces profiles of the three austenitic steels studied are shown in figure 2. The feed of 0.104 mm/rotation caused the poorest quality in finishing observed in the samples turned. The profile of the surfaces machined showed irregularities mainly in AISI 303 steel as can be observed in figure 2 (a) and (b).

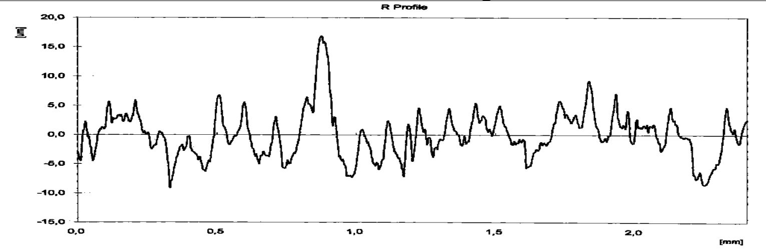
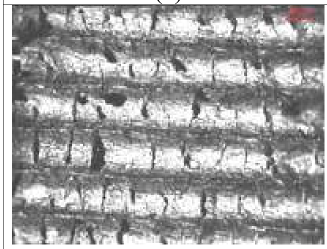
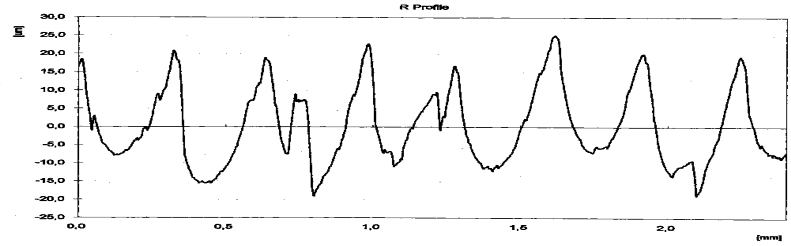
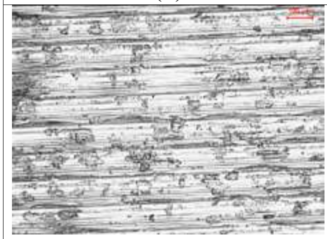
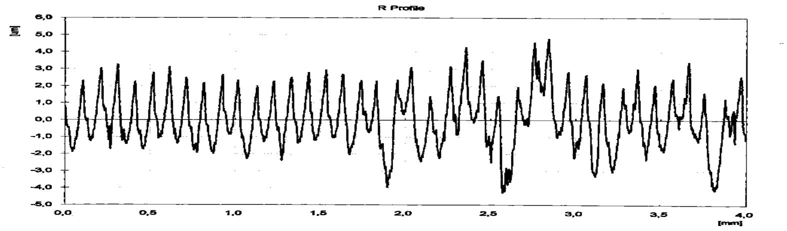
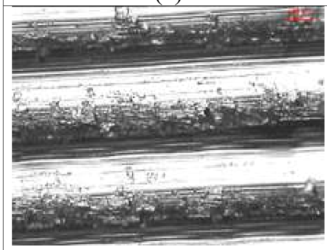
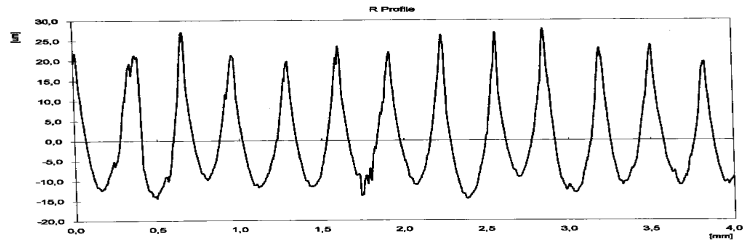
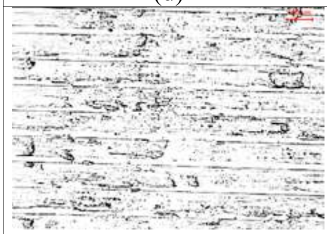
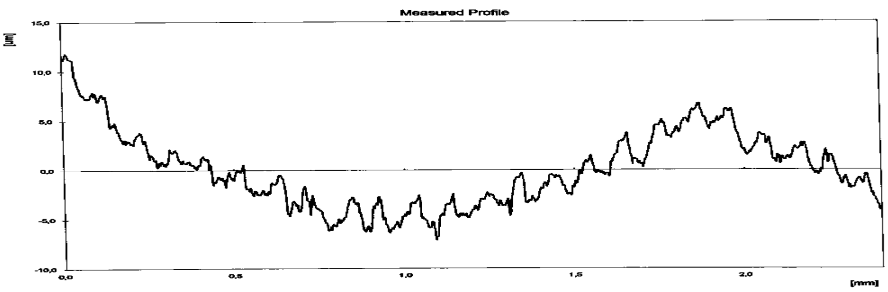
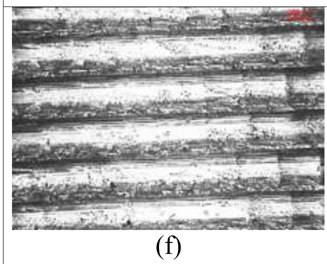
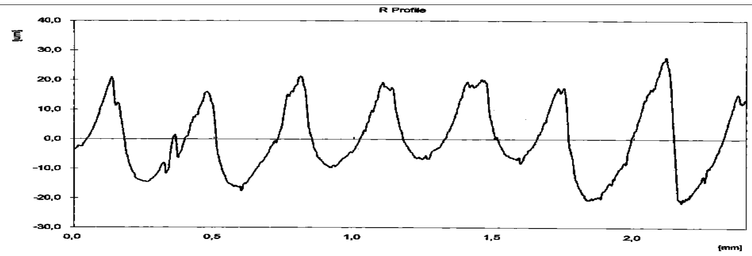
Optical Microcopy	Profile of surface - Roughness
 (a)	
 (b)	
 (c)	
 (d)	
 (e)	
 (f)	

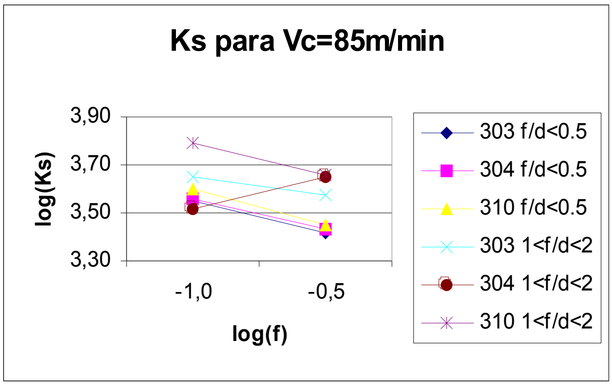
Figure 2 – Surface finishing (optical microscopy) and roughness profile of samples turned with cutting speed of 20 m/min and the relation f/d<0.5 (plain strain of deformation). (a) AISI 303 steel, 0.104 mm/rotation; (b) AISI 303 steel, 0.327 mm/rotation; (c) AISI 304 steel, 0.104 mm/rotation; (d) AISI 304steel, 0.327 mm/rotation; (e) AISI 310 steel, 0.104 mm/rotation; (f) AISI 310steel, 0.327 mm/rotation.

3.3 Specific cutting pressure.

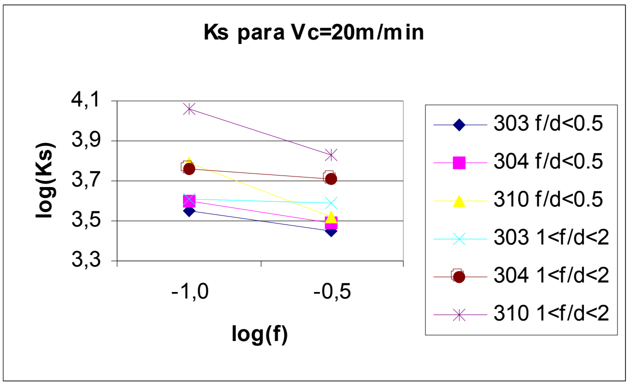
The specific cutting pressure (ks) value is more representative than the cutting force. In addition to this, a better correlation between the machining parameters and the cutting force can be obtained. The specific cutting pressure is calculated through dividing cutting force by the chip section area (feed multiplied by cutting depth) (Ferraresi, 1977). The results of ks are shown in table 4. Figure 3 shows the results of ks (specific cutting pressure) versus feed (f).

Table 4 - Specific cutting pressure - ks - (N/mm^2) as a function of the cutting speed, the feed and the f/d relation (f represents the feed and d represents the cutting depth).

Steel	**f/d<0.5 f=0.104 mm/rot ks**	**f/d<0.5 f=0.327 mm/rot ks**	**1<f/d<2 f=0.104 mm/rot ks**	**1<f/d<2 f=0.327 mm/rot ks**
303 85m/min	3521	2602	4487	3779
303 20m/min	3570	2883	4114	3857
304 85m/min	3604	2692	3260	4430
304 20m/min	3958	3096	5754	5088
310 85m/min	3988	2821	6137	4541
310 20m/min	6122	3349	11404	6699



(a)



(b)

Figure 3. Log (ks) (ks, N/mm^2) versus log (f) (mm/rot), ks means specific cutting pressure and f indicates feed. (a) Cutting speed of 85 m/min and (b) 20 m/min.

The AISI 310 showed the highest values of specific cutting pressure. This behavior can be associated to the high workhardening of this material. On the other hand, the AISI 303 steel showed the lowest specific cutting pressure. This austenitic stainless steel is known for its better machinability, which is linked to the existence of MnS inclusions, improving chip breaking. The AISI 304 has lower contents of alloying elements than AISI 310. Therefore the intermediate values of specific cutting pressure were expected. The relationship between the specific cutting pressure and the three austenitic steels studied showed the same pattern of previous work (Machado et al., 2005). The results of this work confirm the effect of the mechanical behavior of materials on the cutting force or, more precisely, on the specific cutting pressure.

The effect of cutting speed was also evaluated. Generally, the highest value of specific cutting pressure was measured when the lowest cutting speed was used (20 m/min). Therefore, the decrease in workhardening rate, which is related to cutting speed, caused an increase in specific cutting pressure. These results are probably due to the built up edge formation.

The AISI 310 has no tendency to strain-induced martensite formation. Neither on machined sample nor in the chip is magnetism verified. Apart from that, in the extreme conditions of feed, f/d and cutting speed, the specific cutting pressure almost tripled. On the other hand, the formation of strain-induced martensite is observed in the AISI 303 and 304. This phase transformation is usually undesirable. However, the formation of strain-induced martensite could cause the chip broking in the AISI 304 steel and, indirectly, decrease the specific cutting pressure.

The specific cutting pressure had an opposite behavior from the feed in the materials studied. The decrease in the feed caused an increase in the specific cutting pressure. Figure 3 showed the behavior of steels studied (cutting force versus feed).

The steels studied showed almost the same behavior. The only exception was the AISI 304 in the plain state of tension during cutting. An increase in the specific cutting pressure was observed in the plain state of tension ($1<f/d<2$). The plain state of deformation is probably more representative of the machinability and of the behavior during machining of the material.

4 Conclusions

The following conclusions are based on the results presented in this study:

1. The roughness was considerably influenced by feed. The influence of the other cutting parameters did not follow a pattern.

2. The specific cutting pressure was related to materials and machining parameters. The specific cutting pressure generally rises with the decrease in the cutting speed, the feed and in the plain state of tension ($1<f/d<2$). The highest value of specific cutting pressure was obtained for AISI 310 steel and the lowest for the AISI 303 steel.

5 Acknowledgments

The authors are grateful to FAPESP for their financial support (FAPESP 03/05490), to LFS (Laboratório de Fenômenos de Superfície, Mechanical Department of Polytechnic School of University of São Paulo) for the equipment used and for Sandvik Coromant S.A, Mr. Aldeci Vieira dos Santos, who kindly provided the tools for the experiments.

6 References

Andrade, M. S. et al., 2004, "Formability evaluation of two austenitic stainless steels. Mechanical Sciences and Engineering", Vol. 26, n. 1, pp. 47-55.

Fang, X. D.; Zhang, D., 1996, "An investigation of adhering layer formation during tool wear progression in turning of free-cutting stainless steels", Wear, Vol. 197, pp. 169-178.

Ferraresi, D., 1977, "Fundamentos da Usinagem dos Metais", Edgard Blücher ltda, São Paulo.

Jang, D. Y.; Choi, Y.Gu; Kim, H-Gil; Hsio, 1996, "A. Study of the correlation between surface roughness and cutting vibrations to develop on line roughness measuring technique in hard turning", International Journal of Machine Tools & Manufacturing, Vol. 36, pp. 453-464.

Lacombe, P.; Baroux, B.; Beranger, G., 1993, "Stainless Steels"., Les Editions de Physique Les Ulis, France.

Machado, I. F.; Marcicano, J. P.; Driemeier. L.; Dias, C. A. N. An investigation of the effect of machining parameters on the strain induced martensite formatiom during turning in an austenitic stainless steel In: 17 th International Congress of Mechanical Engineering, 2003, São Paulo. 17 th International Congress of Mechanical Engineering: COBEM 2003 - São Paulo, 2003.

Machado, I. F.; Marcicano, J. P. P.;Souza, L.; Hassui; A. Relação existente entre a microestrutura de alguns aços inoxidáveis austeníticos, formação de cavaco, força de corte e o acabamento superficial no processo de torneamento In: 3º Congresso Brasileiro de Engenharia de Fabricação, 2005, Joinville. 3º Congresso Brasileiro de Engenharia de Fabricação: COBEF 2005 – Joinville, 2005.

M´Saoubi, R.; Outeiro, J. C.; Changeoux, B.; Lebrun, J. L.; Mourao Dias, A., 1990, "Residual stress analysis in orthogonal machining of standard and resulfurized AISI 316L steel", Journal of Materials Processing Technology, Vol. 96, pp. 225-233.

Peckener, D.; Bernstein, I.M. Handbook of Stainless Steels. USA. McGraw Hill, 1977.

Shaw , M. C., 1984, "Metal Cutting Principles", Clarendon Press, Great Britain.

Tessler, M. B.; Barbosa, C. A., 1992, "A usinabilidade dos aços inoxidáveis". In: INOX'96 (Seminário Brasileiro do Aço Inoxidável), 3., São Paulo, São Paulo, Núcleo Inox, pp. 151-167.

7. Responsibility notice.

The authors are the only responsible for the printed material included in this paper.