27th INTERNATIONAL CONGRESS OF MECHANICAL ENGINEERING
COBEM 2023

ABCM
Brazilian Society of Mechanical Sciences and Engineering
27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0164
INFLUENCE OF INCREMENTAL SHEET FORMING PARAMETERS ON SURFACE ROUGHNESS OF DUPLEX AISI 2205 AND AUSTENITIC AISI 304 STAINLESS STEELS

João Victor Marzinetti Cunha
Estefany de Almeida Freitas
Guilherme Lobo Rocha
Sara Silva Ferreira de Dafé
Departamento de Engenharia Mecânica, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, MG, Brasil
joaovmarzinetti@gmail.com

Abstract. *Incremental stamping has been studied as an alternative to conventional fabrication methods. It allows the production of custom made parts at low cost, ideal characteristics to the production of prototypes. Duplex stainless steels present high corrosion resistance, good stampability and mechanical strength after forming, in part due to the transformation of the austenite phase into martensite during the cold forming process. The objective in this study is to analyze the effects different parameters have in the surface roughness of parts made using incremental sheet forming. The effects of wall angle and tool rotation speed were chosen. Roughness was measured using a Surtronic S128 rugosimeter, with a 0,8 cutoff according to ABNT 6405 standard. The mean roughness results were analyzed using the ANOVA statistical technique. An increase in wall angle caused a reduction in surface roughness, while the increase in tool rotation speed caused an increase in surface roughness. The duplex 2205 steel demonstrated an overall lower surface roughness in comparison to the 304 steel.*

Keywords: *Incremental sheet forming, Stainless steel, Duplex, Surface Roughness.*

1. INTRODUCTION

Duplex stainless steels represent an important class of stainless steels. Their use has expanded into structural applications for the chemical, petrochemical, nuclear and marine industries. This is due to the microstructure of duplex stainless steel having a mixture of austenitic (γ) and ferritic (α) phase properties (Michalska and Sozańska, 2006).

The properties of duplex stainless steels depend on the ratio between the ferrite and austenite phases. Phase formation depends on the chemical composition of the steel and the heat treatment of the final product. Therefore, it is necessary to control fraction volumes, morphologies and phase distribution patterns (Fedorov et al.,2021).

The austenitic phase in duplex stainless steels tends to be metastable, being able to transform into martensite through the process of martensitic transformation induced by deformation, as proven in the studies by Breda et al. (2015) and Rodrigues et al. (2019).

The choice of material for stamping processes must be made balancing the strength and deformability of the material, very resistant materials cannot be stamped in deep and complex geometries. Thus, the transformation of austenite into martensite during the stamping process may be desirable for the mechanical performance of the finished part.

Single point incremental sheet forming is a relatively recent technique that allows solving several problems of conventional stamping, such as the high cost of the die and the difficulty of customizing the parts. Single point incremental forming is a dieless forming process suitable for producing small batches of parts and has shown great potential for forming parts with complex geometries using simple low-cost tools. Potential areas of application include the aerospace industry, biomedical applications, rapid prototyping and metal forming for the automotive industry (Dakhli et al.,2019).

The first patent for a dieless incremental forming system was filed in the United States in 1967. The process consisted of the deformation of a cup-shaped part by a tool that moved only in the X and Z axes, while the sheet rotated. The popularization of CNC systems and CAD software enabled the manufacture of non-symmetrical parts, starting a new wave of studies for the incremental stamping technique. Japan was a pioneer in this segment, where in 1993 Iseki and his collaborators presented a computer-controlled incremental stamping system, enabling the manufacture of more complex geometries and capable of conforming carbon steel, stainless steel and titanium plates of up to 0.7 *mm.* of thickness (Emmens et al.,2010).

The forming parameters directly affect the surface properties. Dwivedy and Kalluri (2019) studied the effects of the parameters of sheet thickness, feed speed, tool diameter, rotational speed and vertical increment depth (Table 1) on incremental stamping forces in steel sheets for deep drawing.

Table 1. Incremental sheet forming parameters. Adapted from Dwivedy and Kalluri (2019)

	Level 1	Level 2	Level 3
Tool diameter (mm)	10	12	14
Sheet thickness (mm)	0,6	1,0	1,2
Feed speed (mm/min)	1300	1400	1500
Tool rotation speed (RPM)	700	800	900
Step (mm)	0,2	0,3	0,4

The ANOVA results (Table 2) demonstrated that sheet thickness was the main factor in stamping force, followed by vertical increment depth and tool diameter.

Table 2. Axial forces ANOVA results. Adapted from Dwivedy and Kalluri (2019)

Source	F-value	P-value
Tool diameter (mm)	25,58	0,005
Sheet thickness (mm)	74,52	0,001
Feed speed (mm/min)	1,98	0,252
Tool rotation speed (RPM)	0,36	0,716
Step (mm)	61,54	0,001

Sales (2018) studied the effects of incremental forming parameters on the surface finish of the formed part. The effects of lubricant choice, feed rate, and tool rotation speed on roughness were studied. The increase in feed speed caused an increase in roughness, but at lower speeds it was not possible to complete the stamping due to the formation of cracks. Mean roughness (Ra) and maximum roughness (Rz) increased with increasing rotation, as can be seen in Figure 1.

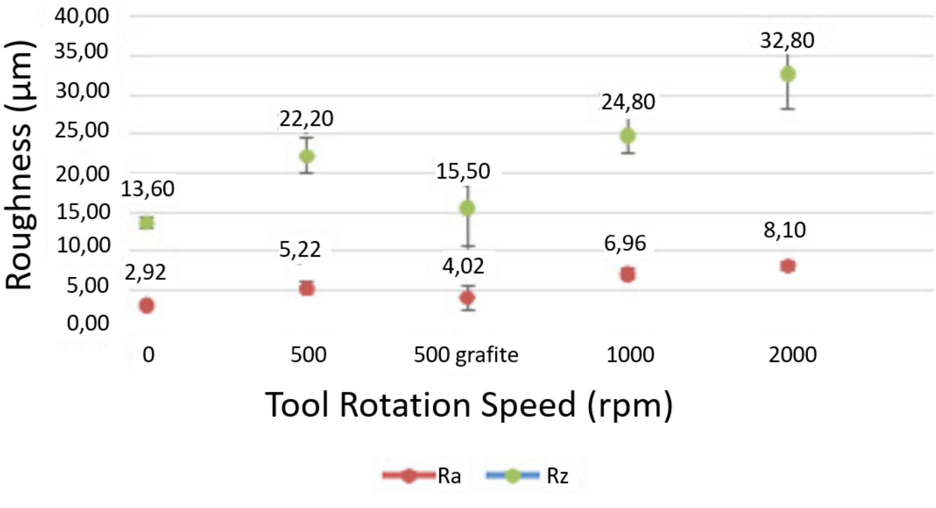

Figure 1. Roughness as a function of rotation. Adapted from Sales (2018)

There is an evident scarcity of studies that explore the use of duplex stainless steels in conjunction with the incremental sheet forming process. In this sense, this article aims to analyze the effects of feed speed, tool rotation speed and wall angle parameters in the surface roughness of parts made from duplex stainless steel using incremental sheet forming.

2. EXPERIMENTAL

The selected geometry was a truncated cone (Figure 2), with wall angles of 55°, 40° and 25°.

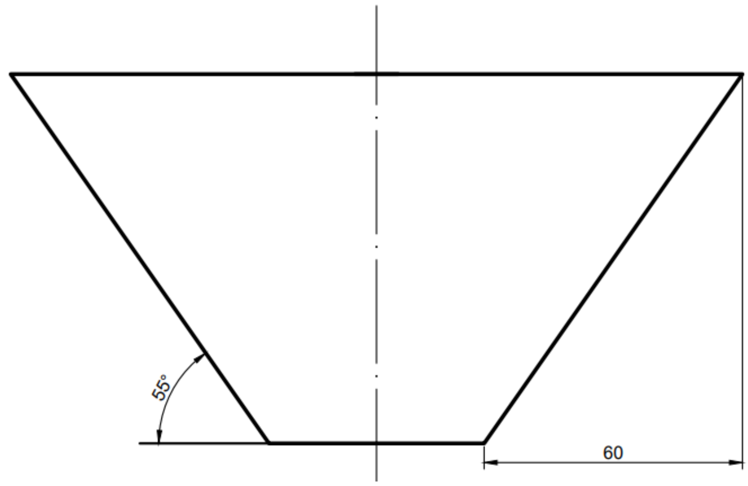

Figure 2. Geometry sketch with 55° angle

For all tests, a step of 0.3 mm, helical path, fixed hemispherical tool with a diameter of 10 mm and 10 ml of Quimatic 1 lubricant were used. The maximum forming angle was measured using the truncated cone method proposed by Hussain and Gao (2007). For feed speeds of 250 and 500 mm/min, the maximum forming angles were 64° and 72.5°, respectively. The difference in the maximum stamping angle due to the increase in feed speed was also observed in the study by Sales (2018), where at lower speeds it was not possible to complete the stamping due to the formation of cracks. Although it was below the predicted value, preliminary stamping tests using an angle of 60° pointed to the rupture of the cone, for this reason a maximum angle of 55° was adopted. The difference between the angle predicted by the truncated cone method and the actual maximum forming angle is due to the distribution of forces applied by the forming tool. As shown in Figure 3, in the truncated cone (a), the force acts only on the LN segment, while for the cone with a constant wall angle (b), the force acts on the entire MN segment, weakening the segment and facilitating breakage.

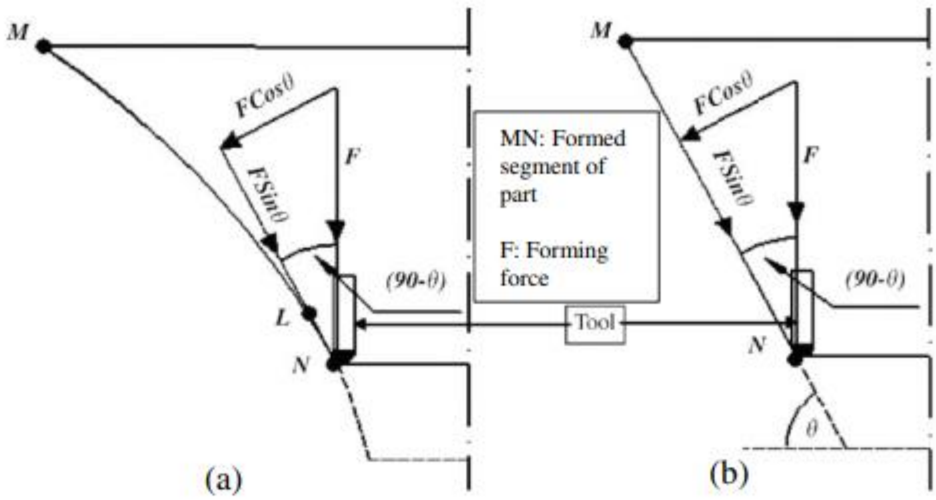

Figure 3. Forming forces for a truncated cone (a) and a straight Cone (b). Adapted from Hussain and Gao (2007).

The selected parameters and levels are shown in Table 3

Table 3. Incremental sheet forming parameters and levels

	Level 1	Level 2	Level 3
Wall angle (°)	25	40	55
Feed speed (*mm/min*)	250	500	750
Tool rotation speed (*RPM*)	30	120	-

2.1 Results

The materials as received were characterized through tensile strength tests, optical microscopy and Energy Dispersive Spectroscopy (EDS).

Results for the tensile strength tests can be seen in Figure 4 and Table 4.

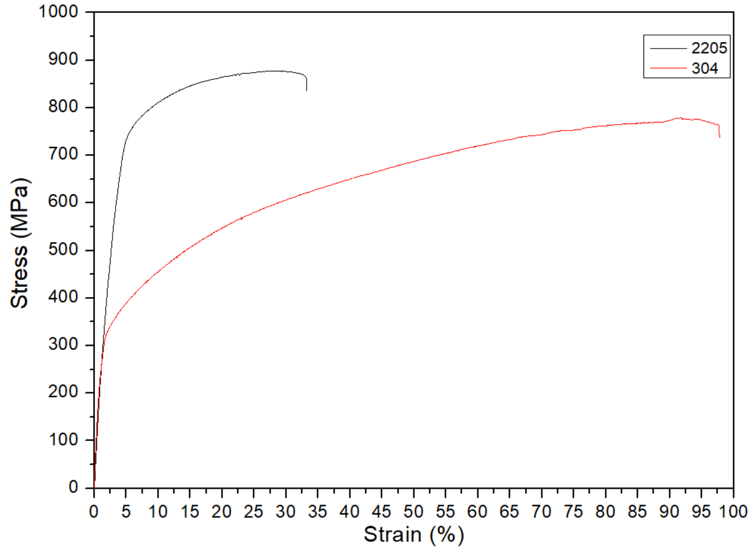

Figure 4. Stress–strain curve for 2205 and 304 stainless steels

Table 4. Mechanical properties for 2205 and 304 stainless steels

		Yield strength (MPa)	Ultimate strength (MPa)	Strain to fracture (%)
2205	Average	692	871,9	31,6
	σ	35	4,5	1,0
304	Average	297,7	780,4	98,6
	σ	3,2	1,8	0,8

Duplex steel 2205 has a yield strength of 692 MPa, much higher than the yield of 297 MPa presented by 304. The strength limit of both steels was closer, being 871 MPa for 2205 steel and 780 MPa for 304. The maximum deformation also presented values similar to those in the literature, with the austenitic steel reaching maximum elongation 3.12 times higher than the duplex steel.

Utilizing a selective electrolytic etch it is possible to etch the ferritic phase while not affecting the austenitic phase, as can be seen in Figure 5.

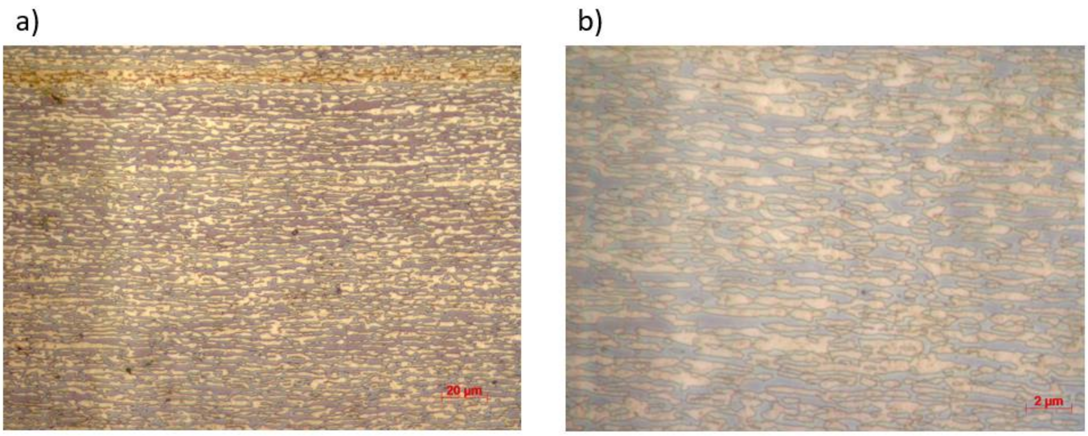

Figure 5. Micrograph using NaOH solution of AISI 2205 steel as received. Bluish ferrite and slightly brown austenite, magnification 500X (a), and 1000X (b)

We can see elongated grains of austenite in a ferritic matrix. Using the ImageJ software, the metallographs were processed in order to separate the etched ferrite and the austenite. The fraction of austenite observed was 45.7%, and that of ferrite 54.3%.

The austenitic 304 steel presented equiaxed grain structure and much larger average grain size, as seen in Figure 6.

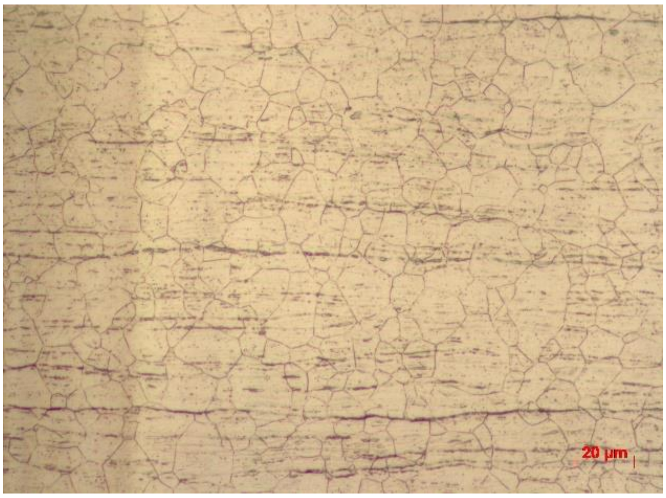

Figure 6. AISI 304 steel micrograph using HNO_3 solution, 500X magnification

The chemical composition of both steels were gauged using energy-dispersive spectroscopy (EDS), and displayed in Table 5.

Table 5. Chemical composition of 2205 and 304 stainless steels

	Cr	Ni	Mo	Mn	Si
2205	22.1	5.5	3.1	1.4	0.5
304	18.7	7.8	-	1.1	0.4

Surface roughness results were compiled and are displayed in Figure 7.

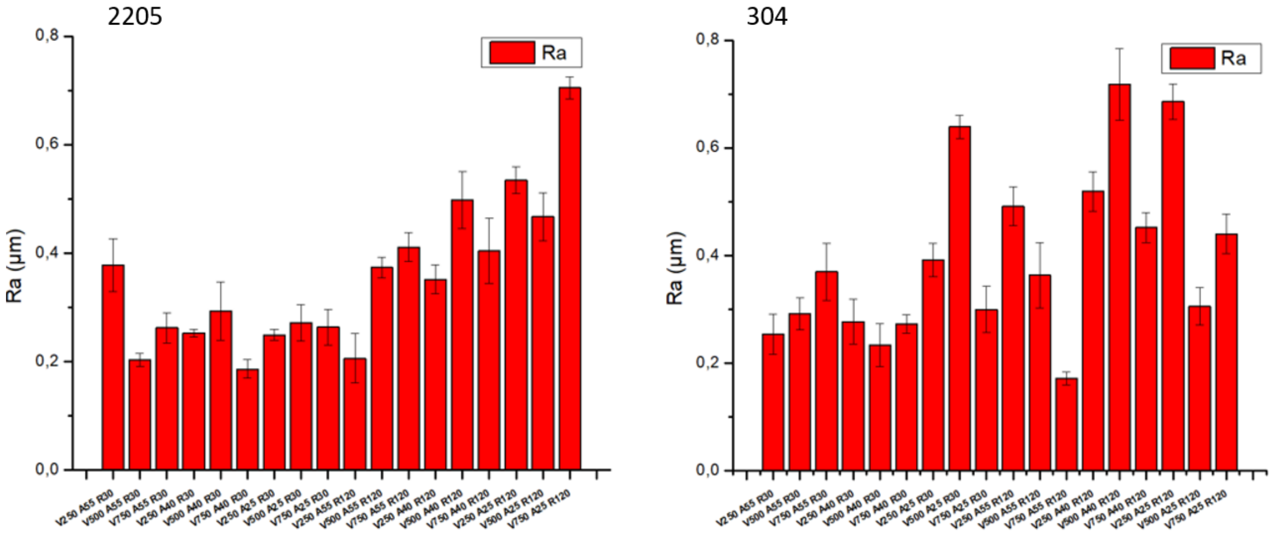

Figure 7. Surface roughness results

As predicted by the study by Sales (2018), the increase in tool rotation caused an increase in the roughness of the part. In the 2205 samples manufactured at 120 RPM, it was possible to observe a tendency towards an increase in roughness due to the reduction in the wall angle.
The analysis of variance, shown in Tables 6 and 7, and Figures 8 and 9, performed using the Minitab software and the data in Figure 7, makes it possible to observe the individual interaction of the stamping parameters and the roughness of the stamped parts.

Table 6. ANOVA roughness (Ra) 2205 steel

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Feed speed (mm/min)	2	0,005650	0,002825	0,26	0,776
Wall angle (°)	2	0,039346	0,019673	1,80	0,207
Tool rotation speed (RPM)	1	0,140273	0,140273	12,85	0,004
Error	12	0,130968	0,010914		
Total	17	0,316238			

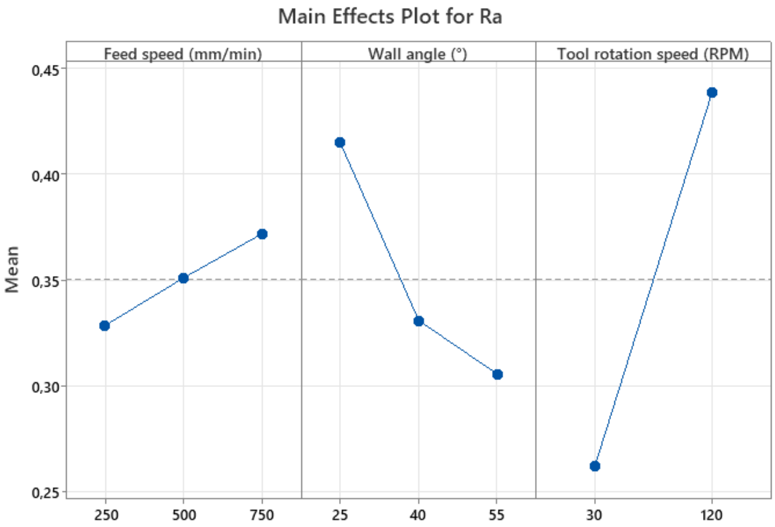

Figure 9. ANOVA roughness (Ra) 2205 steel

The analysis of variance confirms the conclusions obtained by the graph, the increase in the angle of the cone provoked a reduction in the average roughness, while the increase in the rotation provoked an increase in the roughness. The value of F represents the strength of a given parameter in changing the roughness of the part. The P value represents the reliability of this result, the smaller the P value, the greater the confidence. Rotation speed had the greatest influence on roughness, followed by cone angle. The increase in feed speed caused a slight increase in roughness, starting from 0.33 µm for the 250 mm/min feed speed, going through 0.35 µm for the speed of 500 mm/min, and reaching 0.372 µm for the 750 mm/min speed. We can observe the low influence of feed rate on roughness through its F value, but the high P value makes any definitive conclusion impossible.

Table 7. ANOVA roughness (Ra) 304 steel

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Feed speed (mm/min)	2	0,03781	0,01891	0,85	0,452
Wall angle (°)	2	0,05762	0,02881	1,29	0,310
Tool rotation speed (RPM)	1	0,06915	0,06915	3,10	0,104
Error	12	0,26751	0,02229		
Total	17	0,43210			

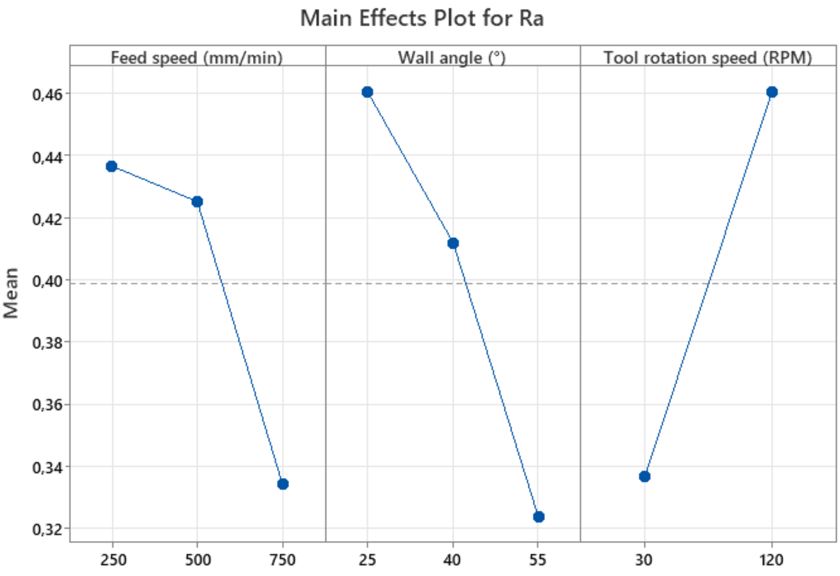

Figure 9. ANOVA roughness (Ra) 304 steel

The AISI 304 steel showed results similar to those of the 2205 steel in terms of angle variation and rotation speed. Increasing the cone angle caused a reduction in roughness, while increasing the rotational speed caused an increase in average roughness. The feed speed exhibited an inverse behavior to that observed in the 2205 steel, the increase in speed caused a reduction in roughness. This result goes against the one presented by Sales (2018) for the same AISI 304 steel, where an increase in feed speed caused an increase in roughness. In his work, Sales (2018) obtained in stamped parts at 250 mm/min a Ra of 3.64 µm while the stamped parts at 500 mm/min presented a Ra of 7.63 µm, an increase of more than 109% in relation to the first speed. In this study, for the same feed speeds, the parts stamped with 250 mm/min had an average roughness close to 0.439 µm, and the ones formed with 500 mm/min reached an average roughness close to 0.425 µm. The greatest variation occurred in samples stamped at a speed of 750 mm/min, reaching an average roughness lower than 0.34 µm.

3. CONCLUSIONS

The roughness of the stamped parts was mainly affected by the tool rotation speed, with the wall angle being the second parameter in terms of influence. AISI 2205 steel demonstrated smaller variations due to stamping parameters. AISI 304 steel presented an overall average roughness 14% higher compared to 2205 steel, and proved to be more sensitive to stamping parameters.

4. ACKNOWLEDGEMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

5. REFERENCES

Breda, M., Brunelli, K., Grazzi, F., Scherillo, A., Calliari, I., 2015. Effects of Cold Rolling and Strain-Induced Martensite Formation in a SAF 2205 Duplex Stainless Steel, *Metallurgical and Materials Transactions A*, Vol. 46.

Dakhli, M., Boulila, A., Manach, P., Tourki, Z., 2019. Optimization of processing parameters and surface roughness of metallic sheets plastically deformed by incremental forming process, *The International Journal of Advanced Manufacturing Technology*.

Dwivedy, M., Kalluri, V., 2019. The effect of process parameters on forming forces in single point incremental forming, *Procedia Manufacturing* Vol. 29.

Emmens, W.C., Sebastiani, G., Boogaardc, A.H., 2010. The technology of Incremental Sheet Forming—A brief review of the history, *Journal of Materials Processing Technology* Vol. 210.

Fedorov, A., Zhitenev, A., Strekalovskaya, D., Kur, A., 2021. Quantitative Description of the Microstructure of Duplex Stainless Steels Using Selective Etching, *Mater. Proc.*

Hussain, G., Gao, L., 2007. A novel method to test the thinning limits of sheet metals in negative incremental forming, *International Journal of Machine Tools and Manufacture*, Vol. 47.

Michalska, J., Sozańska, M., 2006. Qualitative and quantitative analysis of σ and χ phases in 2205 duplex stainless steel, *Materials Characterization* Vol. 56.

Rodrigues, D.G., Maria, G. G. B., Viana, N. A. L., Santos, D. B., 2019. Effect of low cold-rolling strain on microstructure, texture, phase transformation, and mechanical properties of 2304 lean duplex stainless steel, *Materials Characterization* Vol. 150.

Sales, F.S., 2018. *Incremetal sheet stamping and its aplications (in Portuguese), Sciencomm* Vol. 8.

6. RESPONSIBILITY NOTICE

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