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INFLUENCE OF CUTTING PARAMETERS ON THE MACHINABILITY OF A SUPERDUPLEX STAINLESS STEEL

Augusto Freitas Vieira Campidelli [1]
Antônio Augusto Torres Maia [2]
Alexandre Mendes Abrão [3]
Graduate Program in Mechanical Engineering, Federal University of Minas Gerais
Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte, MG, CEP 31270-901, Brazil
[1] augustofvc@ufmg.br; [2] aamaia@demec.ufmg.br; [3] abrao@demec.ufmg.br

Abstract. *In the last decades, the use of stainless steels has increased considerably. Among these alloys, superduplex steels stand out due to their high strength and, consequently, difficult machinability, which results in high tool and time costs. The investigation of the material behavior during machining is of great importance to aid in the development of measures that contribute to increase productivity. In the light of these facts, the aim of this work is to study the influence of the cutting parameters (cutting speed and feed rate) on the turning of UNS S32760 stainless steel using coated carbide inserts. For this purpose, the response surface methodology was applied to the main spindle current consumption, cutting force and chip temperature. The results showed that feed rate has a greater effect on the gradient of the response surfaces. The cutting speed influence was more evident for feed rates above 0.15 mm/rev, which suggests an effect of the chip thickness in the heat transfer between cutting zone and workpiece. Finally, the values of main spindle current and cutting force were related to each other with a coefficient of determination of 0.9156, thus indicating the relationship between these variables.*

Keywords: *turning, duplex stainless steel, power consumption, cutting force, chip temperature.*

1. INTRODUCTION

The wide application of CNC machine tools has significantly improved machining efficiency and product quality in the metal cutting industry. The cutting parameters, such as feed rate and cutting speed, are usually selected by experienced CNC programmers prior to the machining process. However, in order to avoid potential machine overload and tool failure, the CNC programmers tend to use conservative values for these parameters (Liang et al., 2002).

The use of stainless steels has increased dramatically since its advent. The combination of good corrosion resistance, wide range of mechanical properties, good formability and aesthetically pleasing appearance made stainless steels a good alternative for a wide range of applications (Selvaraj et al., 2014). Among the grades of stainless steels, Oliveira Junior et al. (2014) highlight the robustness of superduplex alloys, which are extremely resistant to corrosion and have high mechanical and thermal resistance, as well as high ductility. The authors also point out the difficulty in the machining of these alloys, which results in long production cycles and high tooling costs.

Duplex stainless steels are a dual-phase alloy composed of austenite and ferrite at a nominal volume fraction equivalent to 50% for each of these constituents (Elhound et al., 2011). The basic difference between stainless steels classified as duplex and superduplex consists mainly of the chromium, nickel, molybdenum and nitrogen contents of these alloys. This difference in composition of alloying elements is the reason for the higher mechanical strength and superior pitting corrosion resistance presented by superduplex stainless steels when compared to duplex stainless steels (Gamarra and Diniz, 2018).

This bi-phased microstructure characteristic of duplex stainless steels implies in the coexistence of two materials with different hardness values. The presence of ferrite, however, means that these steels have a ductile brittle transition temperature. Hence, during machining process, the tool will alternate cutting between soft and hard grains of the duplex structure, leading to an automatic tendency to initiate chatter in the cutting system. When compared to standard austenitic stainless steels of similar corrosion resistance, the duplex alloys possess moderately higher mechanical strength and lower ductility, hence are expected to be more difficult to machine (Koyee et al., 2014). Among the challenges encountered in machining operations of duplex stainless steels are included irregular wear of the cutting tool and formation of built-up edge. These phenomena result in degradation of the workpiece surface quality and reduction of the cutting tool life (Krolczyk et al., 2014).

Investigating the material response during machining operations is a typical strategy to understand the machinability of any metal. This study also provide insight to what are the essential questions and which aspects of the process require more attention (Nomani et al., 2013). In recent years, some authors have studied the machining operations of duplex stainless steels. Nomani et al. (2015) investigated the chip formation mechanism and machinability of wrought duplex stainless steels alloys SAF 2205 and SAF 2507. After the drilling operation of the duplex alloys using 12 mm diameter (TiAlN+TiN coated) solid carbide twist drills with internal coolant supply, the authors concluded that tool wear was dominantly due to the adhesion process which developed from built-up edge formation. The authors also verified that hardness profiles transit from the workpiece to the chip, evidencing the heterogeneous nature of the material in relation to the cutting forces.

Krolczyk et al. (2017) studied dry turning of duplex stainless steels with carbide tools. The authors sought to identify the optimal machining strategy and conditions, which will lead to the reduction of pollution generated by cooling/lubricating with coolants and emulsions, as well as the reduction of energy consumption when machining. The results showed that dry turning with the appropriately selected cutting tool grade and proper machining conditions leads to a longer tool life. It has also been shown that cutting tool life when machining duplex stainless steels depends on the following problems: difficult chip control and excessive thermal and mechanical loads of the cutting tool. Finally, the authors concluded that a reasonable solution in terms of energy consumption involves a combination of higher cutting speed and lower feed rates.

In view of the above, the aim of this work is to study the influence of the cutting parameters on main spindle current, cutting force and chip temperature in turning of UNS S32760 superduplex stainless steel. Thus, a better understanding on the behavior of this difficult to machine steel is expected. This information can help in the further development of measures that contribute to reduce tool wear rate and improve surface finish quality when turning duplex stainless steels.

2. METHODOLOGY

In this work, the influence of cutting parameters on the turning conditions of UNS S32760 superduplex stainless steel was studied. The nominal composition of the work material is shown in Tab. 1.

Table 1. Chemical composition (nominal) of the UNS S32760 stainless steel (Sandvik, 2017).

Element	C	Si	Mn	P	S	Cr	Ni	Mo	N	W	Cu	Fe
% wt.	≤0.030	≤1.0	≤1.0	≤0.030	≤0.010	25.5	7	3.8	0.26	0.7	0.8	bal.

For a range of cutting speed and feed rate values, main spindle current (RMS values), cutting force and chip temperature were evaluated.

The experiment was planned in the Minitab software, using the response surface methodology. Based on the recommendations of the carbide inserts manufacturer, Minitab was supplied with cutting speed values of 80 and 160 m/min and feed rate values of 0.10 and 0.20 mm/rev, which were defined as cube points (depth of cut was kept constant at 1.0 mm). Using these values as reference, the software calculated the center points and axial points that complement the set of cutting parameters employed in the experiment. The axial points were calculated with a standard value of alpha (distance from the center point), equivalent to 1.41421. Table 2 presents the cutting parameters values used in the tests. For this experiment, three replicates were adopted, resulting in 39 tests.

Table 2. Cutting parameters employed in the turning tests.

Point Type	Cutting Speed (m/min)	Feed Rate (mm/rev)
Cube point	80.0	0.10
Cube point	160.0	0.20
Center point	120.0	0.15
Axial point	63.4	0.08
Axial point	176.6	0.22

Dry turning tests were carried out on a CNC lathe with 5.5 kW and maximum rotational speed of 3500 rpm. Tungsten carbide inserts ISO grade M20-30 coated with AlTiN were used (Mitsubish Carbide grade CNGG120408-MJ VP15TF). The main spindle current (root mean square – RMS value) was monitored with a non-invasive current sensor SCT-013 connected to an ATmega2560 microcontroller. The main cutting force was measured with a Kistler 9272 dynamometer connected to a charge amplifier and NI acquisition board. Temperature measurement was performed using a Raytek Marathon MM2ML pyrometer. Figures 1 and 2 show the experimental setup and the electric current sensor attached to the CNC lathe, respectively.

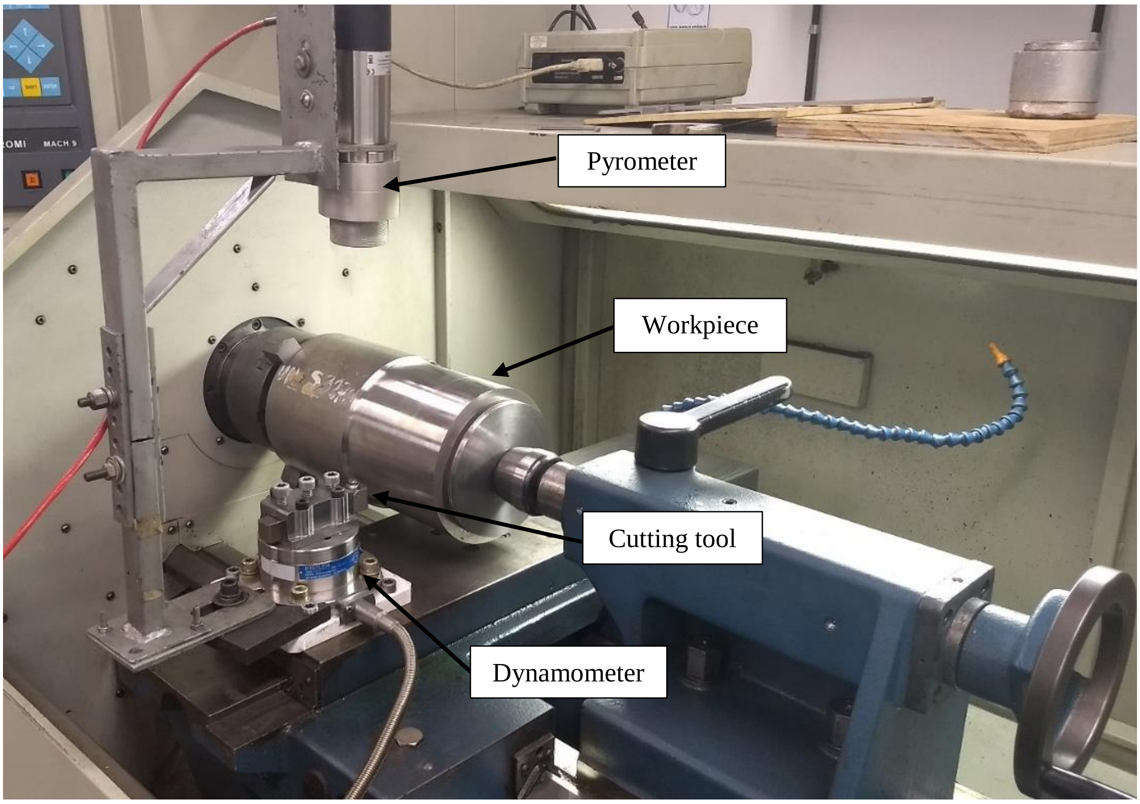

Figure 1. Experimental setup.

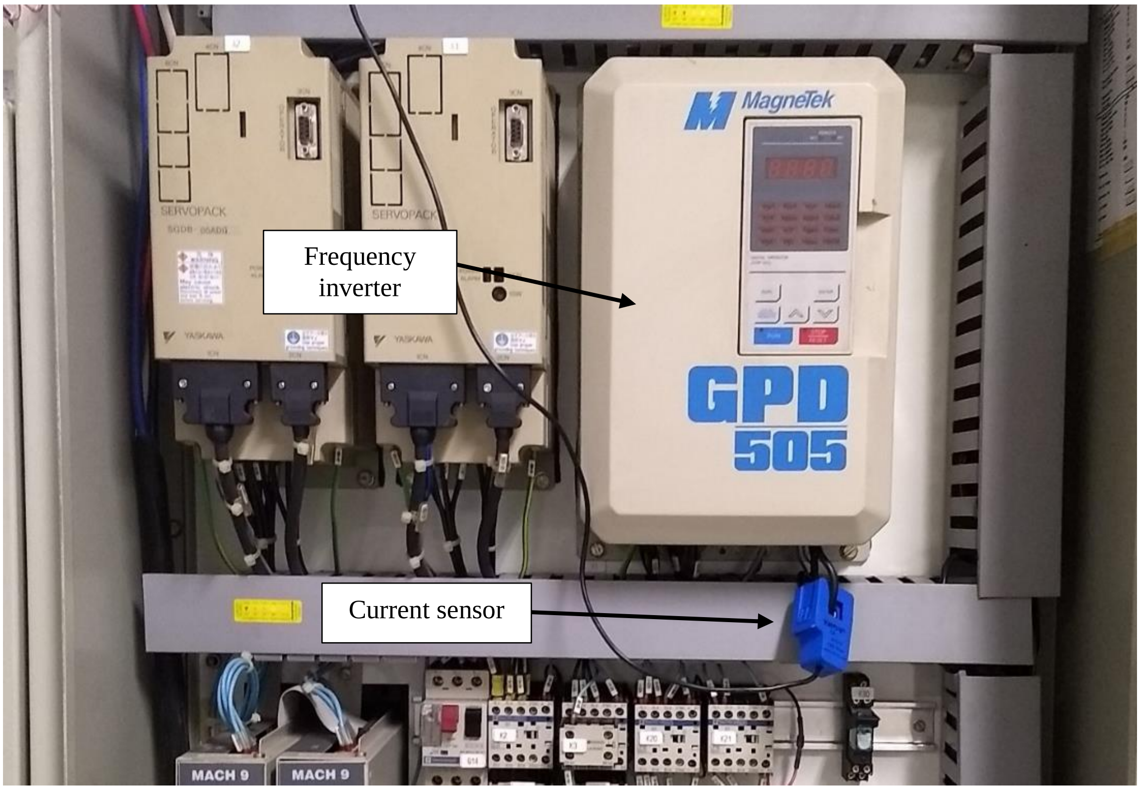

Figure 2. Main spindle current measurement.

As shown in Fig. 1, the pyrometer was fixed above the cutting tool in order to position its focus on the cutting edge. Thus, the temperature values measured during the tests are equivalent to the temperature of the chip that has just been removed from the workpiece. The measurement of the main spindle current was performed at the input cable of the frequency inverter drive, as shown in Fig. 2. In this assembly, the SCT-013 sensor monitors the instantaneous electric current consumed by the main spindle motor when turning and sends the measurement signal to the ATmega2560 microcontroller, which calculates the RMS current and transmits the resulting values to a computer via serial port. Finally, the duration of each test was set as 15 seconds.

3. RESULTS AND DISCUSSION

Response surface charts were generated from the domain formed by the combination of points shown in Tab. 1 and the respective values of main spindle current, cutting force and temperature obtained when turning UNS S32760 stainless steel. Figures 3-5 show the surface contour plots for main spindle current, cutting force and chip temperature, respectively.

Figure 3 shows the behavior of the main spindle current for changes in cutting speed and feed rate during UNS S32760 steel turning. When analyzing the influence of feed rate, it can be seen that an increase in this parameter directly implies in an elevation of the electric current consumed by the main spindle motor. This tendency is directly related to the greater amount of material removed by the cutting tool when the feed rate increases, leading to higher cutting forces and, consequently, higher power required for cutting. The effect of the cutting speed variation on the main spindle current is slighter at lower feed rate values. However, when the feed rate exceeds 0.15 mm/rev, it can be seen that the main spindle current decreases when cutting speed is elevated. For a feed rate of 0.20 mm/rev, the main spindle current decreases by approximately 1 A when the cutting speed is increased from 80 to 160 m/min. This reduction in the power required for cutting occurs due to a decrease in the material strength caused by the higher heat generation in the tool-chip interface when the cutting speed increased. Considering that higher cutting speed values implies augmented material flow rate at the tool-chip interface, which results in a greater frictional energy dissipation between tool and workpiece. Apparently, this effect becomes more noticeable for feed rate values above 0.15 mm/rev, which may be explained by the need of a minimum chip thickness for a satisfactory heating of the workpiece when turning UNS S32760 stainless steel.

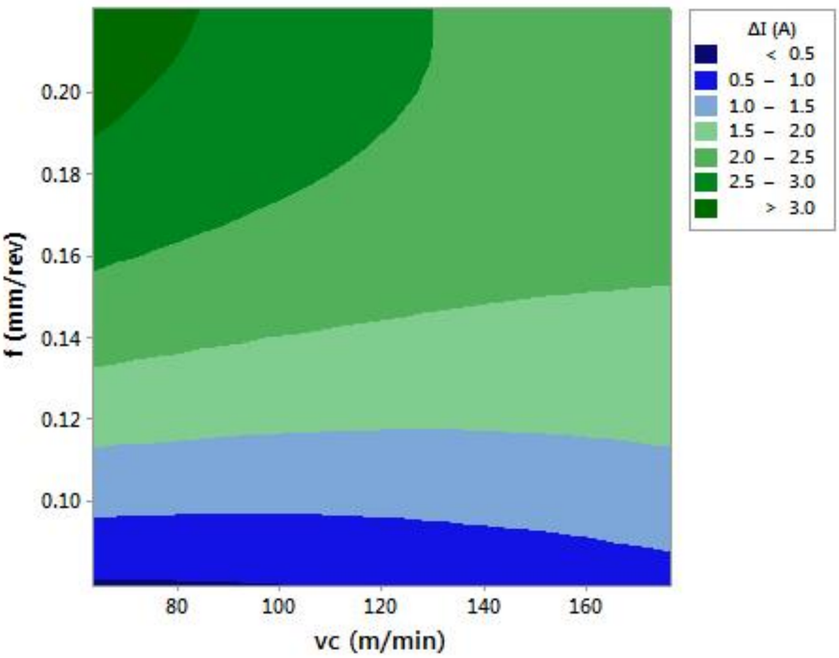

Figure 3. Contour plot of the main spindle current response surface.

Similar to the main spindle current, the cutting force increased when higher feed rates were employed and decreased for higher cutting speed values, as can be seen in Fig. 4. As the cutting force is directly related to the power consumed by the cutting, a behavior similar to that found for the main spindle current was expected. Again, the cutting speed effect becomes more pronounced for higher feed rates, especially for the range of values above 0.15 mm/rev, which evidences the existence of a correlation between main spindle current and cutting force.

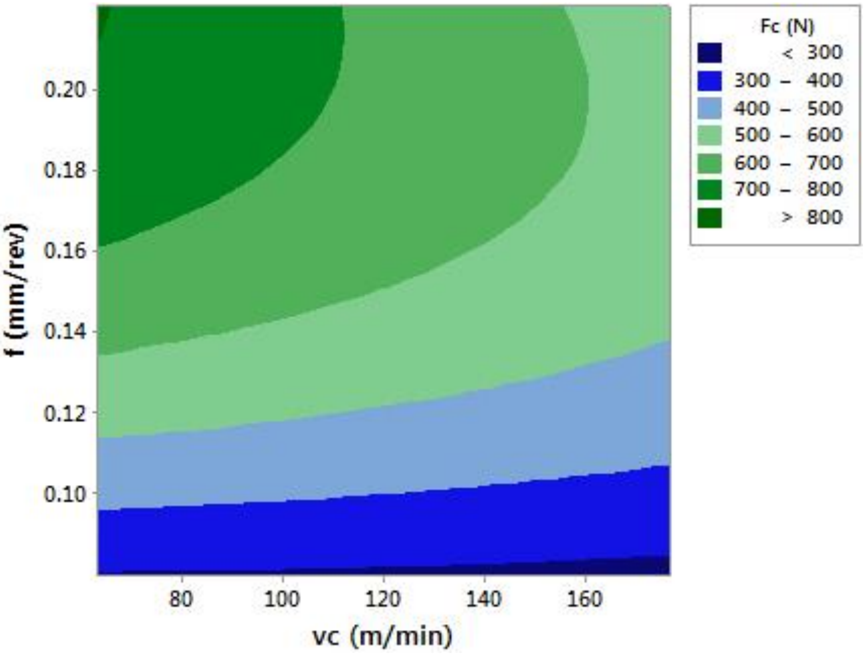

Figure 4. Contour plot of the cutting force response surface.

The response surface obtained for temperature presented an opposite behavior when compared to the results for main spindle current and cutting force, as shown in Fig. 5. The temperature decreased for higher feed rates and showed a tendency to increase when higher cutting speeds were employed. Since the temperature was measured by a pyrometer located above the cutting tool, the obtained values refer to the temperature of the upper surface of the chip that has just been removed from the workpiece. Thus, higher feed rate values result in the formation of thicker chips, which causes an increase in the distance between the temperature measurement point and the zone where the heat generation occurs, i.e., the thickening of the chip moves its upper surface away from the tool-chip interface. Considering that the chip upper surface presents lower temperatures under these conditions, it was expected that the temperature values measured by emission of thermal radiation would decrease. Similar to the other experiments, the cutting speed effect becomes more evident for feed rates above 0.15 mm/rev, displaying higher temperature values when the cutting speed is increased. As mentioned before, the cutting speed increase implies a larger flow of material and, consequently, a higher dissipation of energy by friction in the tool-chip interface.

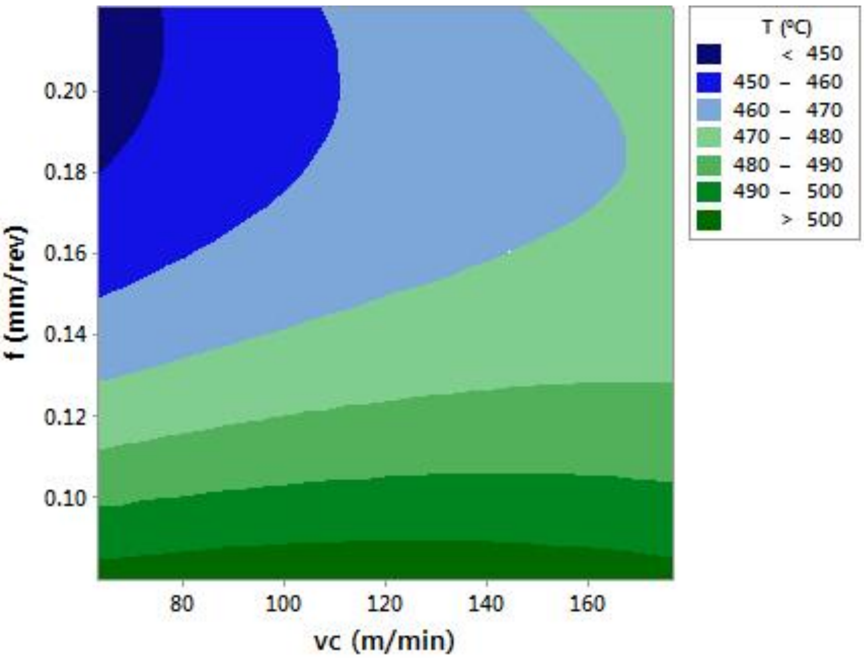

Figure 5. Contour plot of the temperature response surface.

Finally, the relationship between main spindle current consumption and the main cutting force was addressed. For this purpose, a graph was constructed where the main spindle current and cutting force values, obtained in the same tests, were plotted. The graph containing this relationship is shown in Fig. 6, where *Fc* stands for the main cutting force and *I* represents the electric current consumed by the main spindle motor to perform the cutting.

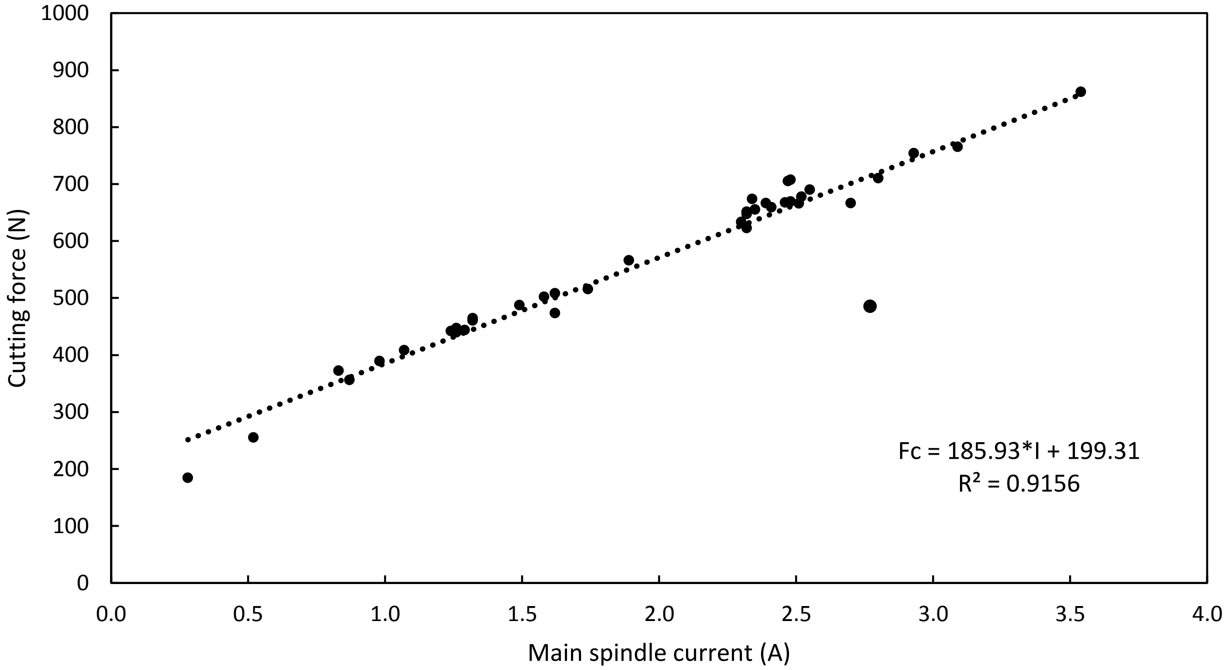

Figure 6. Correlation between main spindle current and cutting force.

Observing Fig. 6, it is possible to notice the correlation between main spindle current and cutting force when turning UNS S32760 stainless steel. For the set of points obtained in the tests, the model constructed by linear regression presented a coefficient of determination equivalent to 0.9156. Therefore, it can be stated that the cutting force can be monitored with high reliability by the measurement of the main spindle current when turning. Considering the high practicality in the measurement of the main spindle current when compared to the use of dynamometers for the cutting force monitoring, this result supports the use of non-invasive current sensors for the monitoring and control of cutting forces during the turning operation.

4. CONCLUSIONS

Considering the continuous interest in increasing the productivity of machining operations and the necessity to investigate the relations between process parameters to support the development of efficient solutions, this work aimed at studying the influence of cutting speed and feed rate on the behavior of UNS S32760 superduplex stainless steel when dry turning. For this reason, the response surface methodology was applied to the following output parameters: main spindle current, cutting force and chip temperature. Moreover, the relationship between main spindle current and cutting force was investigated.

For the addressed range of values, the results showed that feed rate is the parameter that most influences the main spindle current, cutting force and chip temperature when turning UNS S32760 stainless steel. Only for feed rate values above 0.15 mm/rev that the response surfaces showed a significant influence of cutting speed, suggesting the influence of the chip thickness in the heat transfer mechanisms between cutting zone and workpiece.

By the analysis of the response surface charts for main spindle current and cutting force, it was possible to notice that both presented similar behaviors within the range of studied cutting parameters. Finally, this relationship was confirmed by a fitted linear regression model. Thus, the reliability of cutting force monitoring through the measurement of main spindle current values could be demonstrated.

5. ACKNOWLEDGMENTS

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7. RESPONSIBILITY NOTICE

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