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Comparative Study of the Drilling Operation in Duplex Stainless Steels with Drills of Two and Three Cutting Edges

João Marouvo[1,a], Pedro Ferreira[1,2,b] and Fernando Simões[1,2,3,c*]

[1]Polytechnic Institute of Coimbra, Coimbra Institute of Engineering, DEM, Coimbra, Portugal

[2]I2A - Institute of Applied Research - Polytechnic Institute of Coimbra, Coimbra, Portugal

[3]CEMMPRE-Center for Mechanical Engineering, Materials and Processes Univ.Coimbra, Portugal

[a]a21250424@isec.pt, [b]pmsf@isec.pt, [c]fsimoes@isec.pt

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Abstract. The three cutting edge drills are not the most common drills, nevertheless, are characterized by superior stability, excellent precision and finishing, due to the intersection of three cutting edges at one point. In general, stainless steels are considered as difficult to machine materials due to their tendency to work harden, their toughness and relatively low conductivity, leading to poor surface finish, poor chip breaking and built-up-edge formation. In the case of duplex stainless grades, the high strength, and the very good corrosion resistance, only compared with austenitic steels, make these materials as an alternative to the austenitic stainless steels, with superior mechanical properties. In this study, the performance of the drills with two and three cutting edges were evaluated in the drilling of duplex stainless steels, when low-pressure external cooling or high-pressure internal cooling were applied.

Whether used drills of two or three cutting edges, the most important factor to increase the number of holes made, is the use of high-pressure internal cooling, in detriment of external low-pressure external cooling. The drills of three cutting edges have better results in roughness and dimensional tolerance of the holes. However, these drills proved to be more fragile and more sensitive to the cutting parameters. The use of three cutting edges drills is recommended for situations where hole quality is more important, while two cutting edges drills is recommended for situations where productivity is the main objective.

Introduction

Stainless steels are Fe-C aloys with more than 11% of Cr. Chromium has a high tendency to oxidize. It is the ability of this element to react with the oxygen present that makes it possible to form a film of protective oxides, which give rise to the phenomenon of passivation that prevents the propagation of oxidation. The exposed material surface is coated with a impermeable and adherent chromium oxide film Cr_2O_3, with an average thickness of 3 nm to 5 nm. These properties, combined with the regenerative capacity of this film, allow stainless steel to resist oxidation in the most varied corrosive environments. Stainless steels are usually divided into 5 groups, according to the percentage weight of nickel and chromium (Fig. 1), which have different levels of corrosion resistance and mechanical strength. The equal amounts of α-ferrite and γ-austenite phases present in duplex stainless steels, combines the inherent benefits of both phases, providing superior corrosion resistance with high tensile and yield strength. For these reasons, duplex stainless steels are often selected for oil, gas, chemical and food industrial applications.

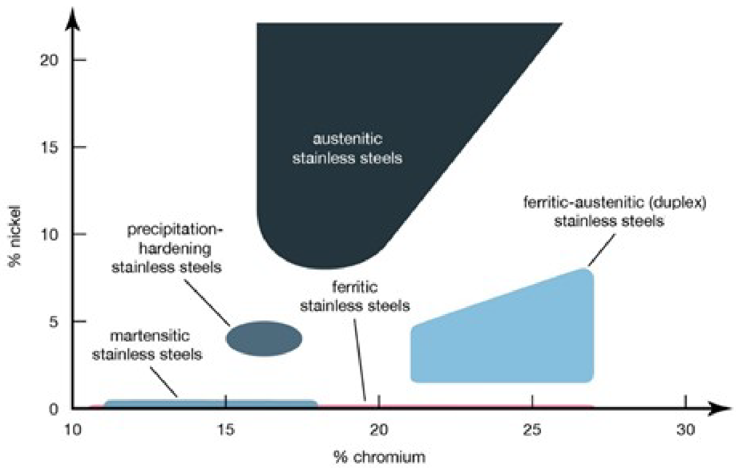


Figure 1. Nickel and chromium content (wt %) in stainless steels groups [1]

Machinability is defined as a measure of ease with which a work material can be satisfactory machined. The machinability is of considerable importance for production engineers to know in advance about the machinability of a work material so that the processing can be planned in an efficient manner [2]. Numerous studies report the increased difficulty to machine stainless steels compared to not alloyed steels [3, 4], as is shown in Fig. 2, concerning to the relative machinability. The high work hardening, the low thermal conductivity, the built-up-edge formation and toughness, are considered the main factors for poor machinability of stainless steels. Beyond these factors, duplex alloys are considered one of the most difficult to machine due to higher hardness and strength.

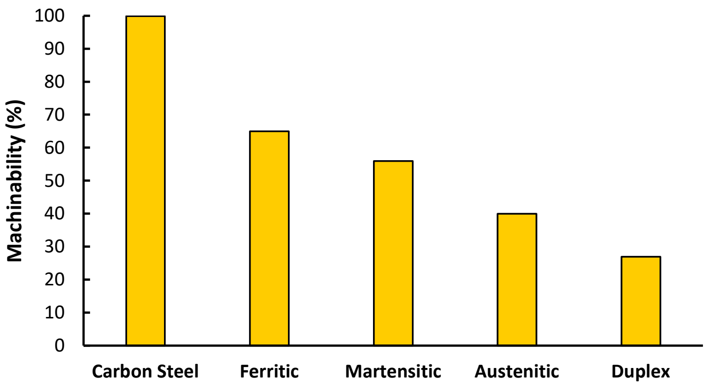


Figure 2. Machinability of stainless steels compared to the conventional carbon steels (relative machinability) [5]

The drilling operation is one of the most important metal cutting operations, comprising approximately 33% of all metal cutting operations [6]. In literature, it is possible to find several works focused on drilling operation of stainless steels and the tool life. It is known that in the execution of long holes, when the hole length is three times greater than its diameter (L/D > 3), is reported an increased difficulty in execution of the drill operation and the circularity of the hole increase.

In the overwhelming majority ~~of~~ studies, the drills used are based in geometries with two cutting edges. The use of drills with three cutting edges is not a common practice, despite being a technology with a considerable time. Few studies with this type of geometry have been carried out, having been published in the eighties and nineties of the last century [7-9]. Ema, *et al.,* [7] reported several advantages over conventional drills. The vibration associated with the rotation movement (designated by the authors as whirling vibration), common in conventional drills, tends to disappear when using drills with three cutting edges. This vibration is responsible for creating distorted polygonal holes with an odd number of sides and groove marks. Due to the absence of this vibration, the holes created tend to have superior roundness, circularity, and linearity. Agapiou [9] report that, the addition of a third cutting edge increases the cross-sectional area, which makes these drills significantly stiffer by having superior torsional stiffness and superior bending strength. However, despite the greater rigidity, three-edged drills prove to be more susceptible to cutting parameters, in contrast to conventional drills that tolerate more severe conditions.

Since they are practically unknown studies of the industrial application of this type of drills, it is relevant to carry out a comparative study of the performance of drills with two and three cutting edges, in this case applied to the duplex stainless steels.

Experimental Details

A duplex stainless steel GX6CrNiN26-7 (EN 1.4347) was selected to evaluate the effect of work material on the performance of the drills. A workpiece of 300x300x150 mm was produced by melting process in an electric induction furnace, followed by a quenching heat treatment with water cooling. The chemical composition and relevant mechanical properties are present in Table 1 and Table 2, respectively.

It was used the electric discharge machining (EDM) to divide the workpiece in small samples of 300x100x40 mm, which was firmly secured in a vise during drill operation.

Table 1. Chemical composition in weight percentage

Workpiece material	C	Si	Mn	P	S	Cr	Ni	Mo	Fe
Duplex Stainless Steel	0.03	0.95	1.47	0.02	0.00	25.12	5.89	0.20	65.86

Table 2. Mechanical properties of GX6CrNiN26-7

Tensile strength [MPa]	686
Yield strength [MPa]	456
Elongation [%]	25
Hardness [HB]	277

Palbit Hard Tools Solutions Company manufactured the 10 mm diameter drills of two and three cutting edges with internal cooling channels. The drills were sintered from tungsten carbide (WC) and coated with a 4 μm thick AlTiN film. The transverse edge of two cutting edges drills is shaped like a line due to the intersection of the two main output faces, while three edges cutting drills feature a star-shaped transverse edge due to the intersection of three main faces at one point (Fig. 3). The two cutting edges drills have a point angle of 135º degrees and a width margin of 1 mm, while three cutting edges drills have a point angle of 130º degrees and a width margin of 0,7 mm.

The drill operation was programmed on one Computer Aided Manufacturing (CAM) software with a depth of 30 mm (3x tool diameter) in a single pass, with 15 mm distance between holes, as shown in Fig. 4. Once one of the main objectives is to understand the holes quality differences, obtained with two and three cutting edge drills in similar conditions, this research was conducted with same machining parameters for both drills. Therefore, for all tests a cutting speed of 50 m/min (n=1592 rpm) and feed rate of 105 mm/min were defined. The defined cutting parameters result in the feed per revolution of 0,066 mm for both drills, corresponding to 0.022 mm/tooth for three edges cutting drill and 0.033 mm/tooth for the two edges cutting drill. Consequently, the chip thickness removed in the first case is smaller than in the second case.

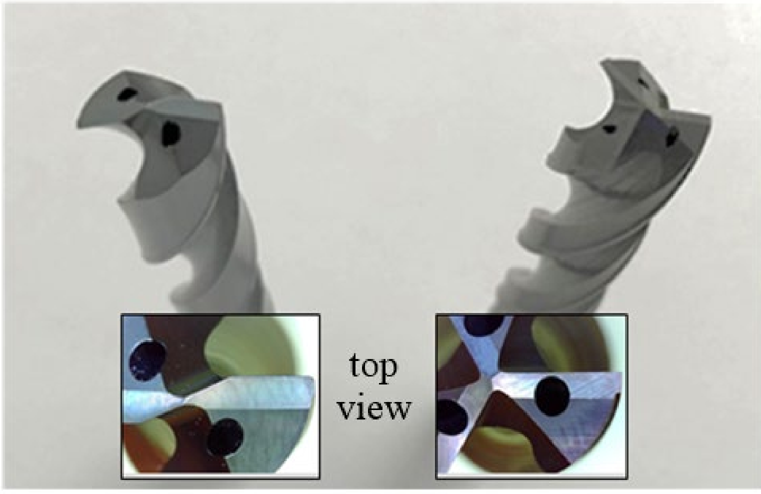


Figure 3. Two and three cutting edges drills

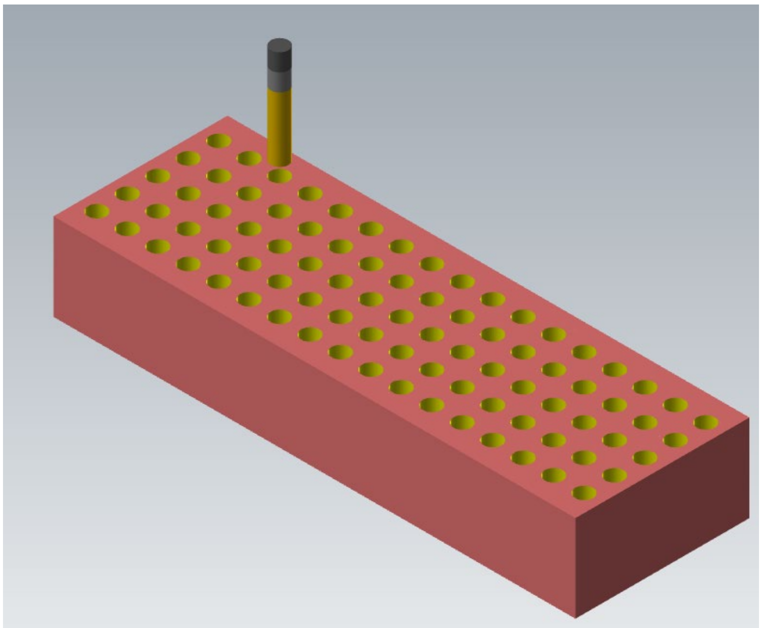


Figure 4. Drill operation simulated in a CAM software

To examine the wear of the tool was used a digital microscope Dino-Lite Basic integrated with image acquisition software and the tool damage measurements were then carried out via software Axion Vision LE. A Mitutoyo SJ-201 tester was used to measure the surface roughness of machined holes and the holes diameter was measured several times all the way around to find the maximum and minimum values. Diameter measurements were made with a Bowers XTDU10-BT 3-point internal micrometer, with an accuracy of 3 μm.

The tool vibration during the drilling was acquired by a piezoelectric triaxial accelerometer glued to the CNC equipment (Fig. 5). The accelerometer was connected to data acquisition card of National Instruments and the analog signal was converted to digital and then processed at a sample rate of 1613 Hz.

Electrical Discharge Machining (EDM) by wire erosion was used to cut some holes up to total depth, with the aim to separate the hole into two parts and carry out a visual analysis of the hole surface.

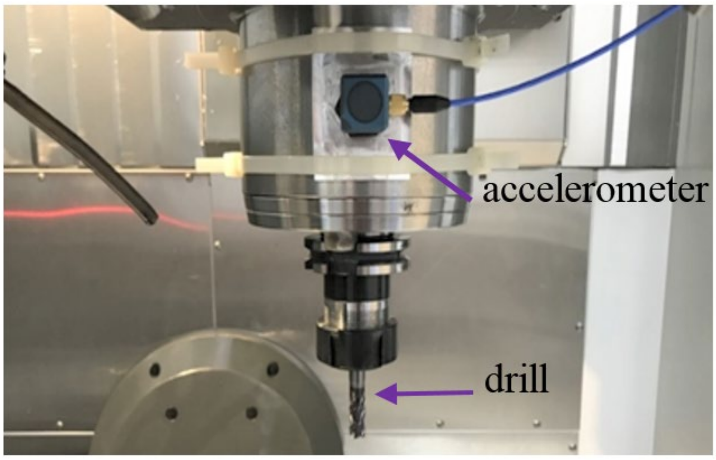


Figure 5. Accelerometer fixed to the CNC spindle

Results and Discussion

Tool deterioration and number of holes performed

A total of four tests were carried out under different conditions, as shown in the Table 3.

Table 3. Conditions applied on tests and number of holes performed

Samples Material	Twist Drill	Cooling Type	Nº holes performed	Test
Duplex Stainless Steel	Two Cutting Edges	External	60	**A**
		Internal	60	**B**
	Three Cutting Edges	External	30	**C**
		Internal	60	**D**

The international standard ISO 8688-1 was used as reference to characterize the type of deterioration that occurs in the drills and to determine the end of life of the tool. Despite ISO 8688-1 has been developed to face milling operations with carbide tools, with suitable modifications, this standard describes well the damage phenomenon of other types of tools and operations. In some circumstances of the tests performed, it is observed built-up edge and loss of tool fragments (non-uniform chipping - CH2). During tests **A**, **B** and **D**, the main damage observed was a progressive development of constant flank wear by abrasion (uniform flank wear - VB1), where the standard establishes the maximum admitted value of VB=0,35 mm. For test C, the main damage observed was non-uniform chipping, where the standard establishes the maximum admitted value of CH2=0,4 mm. According to these criteria, in test **C** the maximum VB value was reached after 30 holes performed. For the remaining tests, once the flank wear stayed away from the criterion, it was decided to stop the tests after 60 holes.

Concerning to the two cutting edges drills, despite being applied in test **A** external cooling and in the test **B** internal cooling, it was possible performed 60 holes in both cases and the flank wear evolution was similar. However, the evolution of flank wear observed is a little higher when low-pressure external cooling is applied (Fig. 6). For three cutting edges drills, the cooling type applied has a remarkable influence in the number of tests performed, implying that it is only possible to drill 30 holes in the case of external cooling. The internal high-pressure system improves not only the cooling rate and chip transportation but also the chip breakage. For all tests, the deterioration values of flank wear tend to stabilize after the first holes, following up a steady wear stage, interrupted by an abrupt growth in the case of test C.

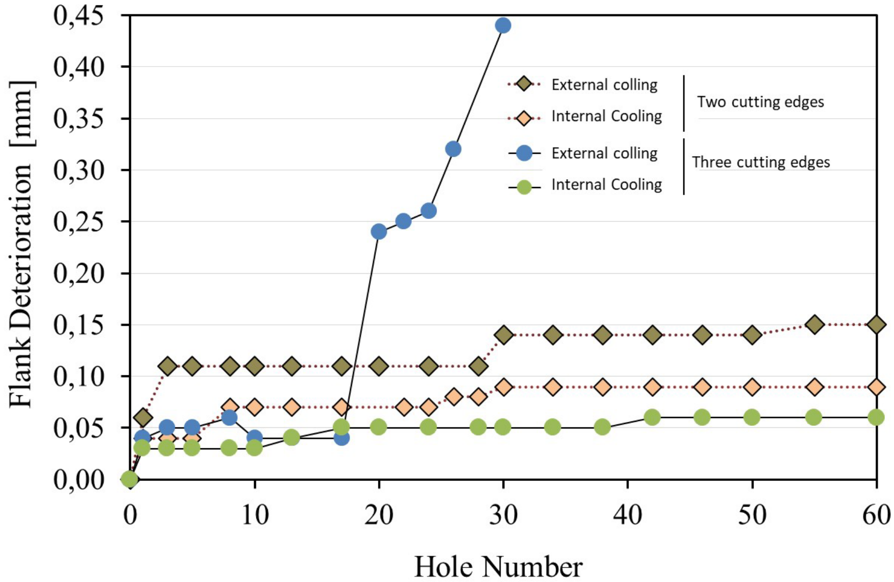


Figure 6. Evolution of flank deterioration for for drills with two and three cutting edges

In Fig. 7, it is showed the uniform flank wear observed after 60 holes performed in duplex stainless steel with the drill of two cutting edges and internal cooling.

After 60 holes (int. cooling)

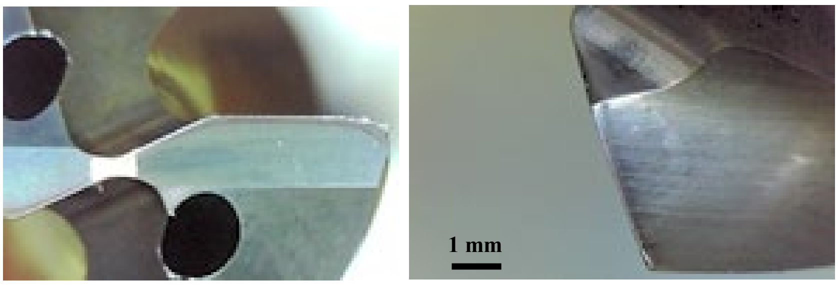
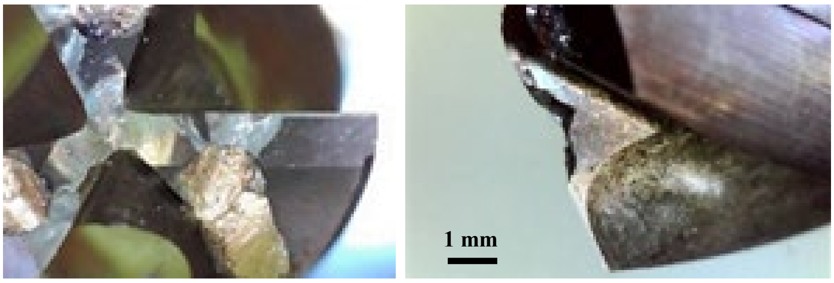


Figure 7. Flank wear observed for two cutting edges drill

For three cutting edges drills (Fig. 8), a remarkable wear at chisel is reported, where the effective cutting speed is lower. A small flank wear tool deterioration is observed when internal cooling is applied. In opposite, a large chipping is reported for external cooling, which tend to damage, hide, and block the drill's lubrication channels.

After 30 holes (ext. cooling)



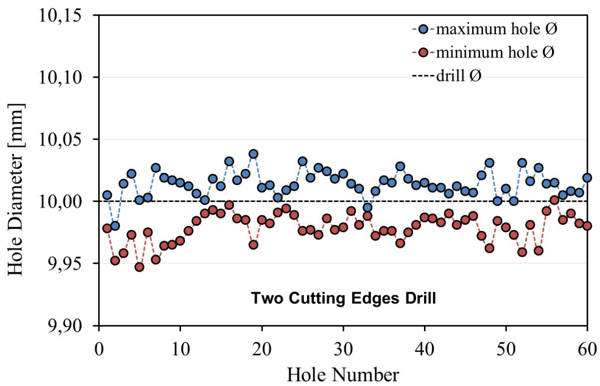
After 60 holes (int. cooling)

Figure 8. Flank wear observed for three cutting edges drills

Hole quality

The circularity and the linearity of the holes was evaluated to measure the quality of the holes made. The circularity was evaluated by measuring the difference between the maximum and minimum hole diameter at the depth of 25 mm.

In the fig. 9. are represented the results of the circularity of holes made with internal cooling with two and three cutting edges drills. As would be expected, the best results of circularity were reached with three cutting edge drills due to the self-centering effect of star-shaped transverse edge. The type of cooling system has a minor effect in this evaluation.



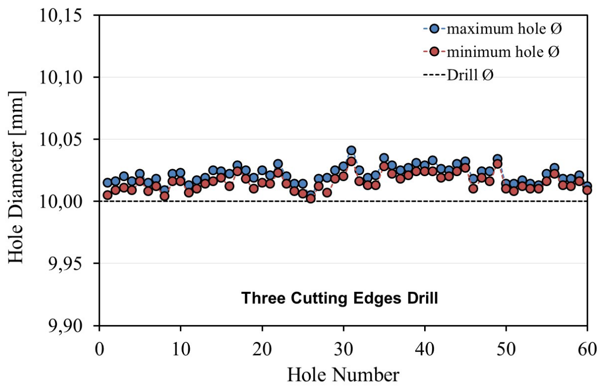


Figure 9. Maximum and minimum holes diameter made with internal cooling for two and three cutting edges drills

Concerning to the linearity, it was evaluated by measuring the maximum diameter at the depth of 8 and 25 mm and analysing the difference between both diameters (Fig. 10a). Fig. 10b allows to observe that the difference in diameter at the top and at the bottom, (average value and standard deviation) is less when holes are made with three cutting edges, and consequently are straighter. In the figure 10a it is possible to observe two holes with different linearities, caused by the deviation of the drill along the centerline.

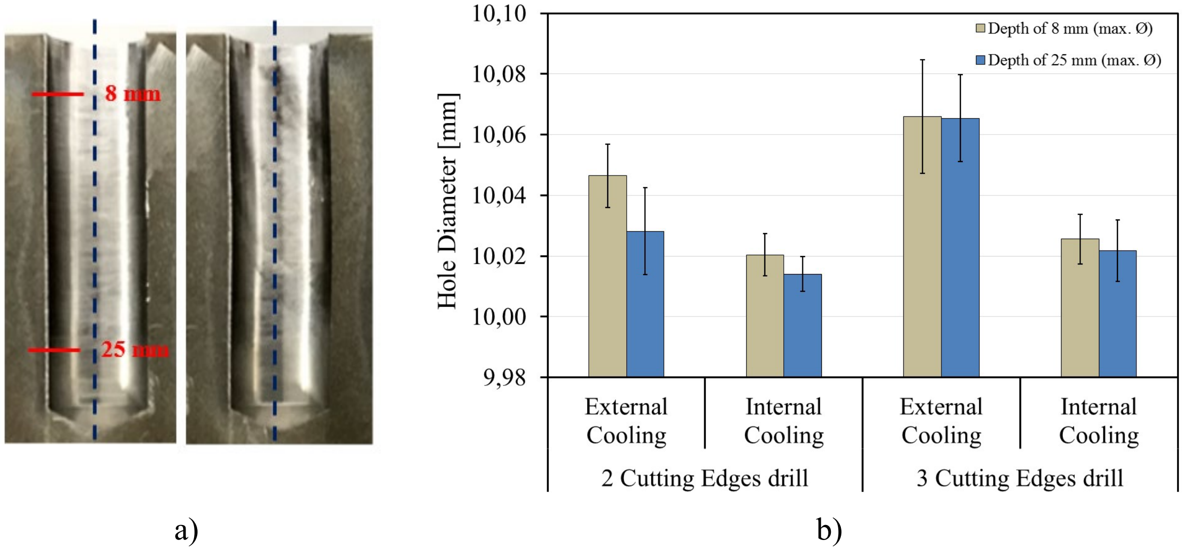


Figure 10. a) Evaluation of hole linearity; b) Evalutaion of hole linearity by difference in top and bottom diameter

Surface roughness

The Fig. 11 shows the roughness average (Ra) and the mean roughness depth (Rz) evaluated. The Ra and Rz values and the respective standard deviation are based on all holes performed for each sample. For each one drill type, the higher roughness values are obtained for external cooling, since in this situation the chip length is higher, the extraction is less fluid with more random movement, causing greater roughness on the surface of the hole. Comparing the roughness for both drills with external coolant, the Ra and Rz values are significantly lower for the three cutting edges drill. The smaller chip thickness removed per tooth and the smaller margin width for the three edges cutting drill, may have a positive effect in this case. However, when internal cooling is applied does not have a significant effect on roughness, since the Ra and Rz values are similar for two and three cutting edges drills. These results suggest that the geometry of drill used has a smaller impact on the roughness than the type of coolant used.

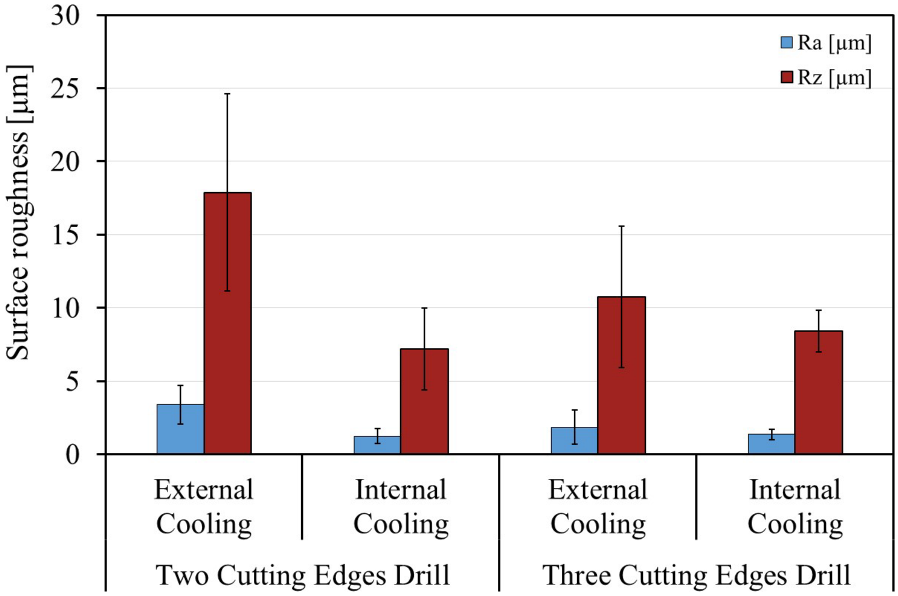


Figure 11. Surface roughness of the holes

Vibration analysis

The study of vibrations in milling operations has increasing the interest from researchers. In studies such as Simon and Deivanathan [10] a relationship between vibration and tool wear has been established, highlighting the ability to detect wear and chipping, even in early stages. Vibration signal in the time domain has been registered. Once this signal corresponds to the superposition of several phenomena with different frequencies, the Fast Fourier Transform (FFT) was applied to transform the vibration signal in frequency domain, where different frequencies are associated to drilling operation and others phenomenon such as, movement of equipment elements (rolling bearings, belts drives), electrical noise, etc. As mentioned in other works [11], the phenomenon of tool cutting is express by the spindle frequency (fs) and tool meshing frequency (fm) equations, which for the drills used in this research, present the characteristic frequencies indicated in Table 4 and respective harmonics.

Table 4. Spindle and tool meshing frequency for two and three cutting edges drills

Drill	**Nº of Teeth**	**Tool Rotation** [rpm]	**Spindle Frequency** [Hz]	**Tool Meshing Frequency** [Hz]
	Z	**N**	$f_s = \frac{N}{60}$	$f_m = \frac{N \cdot z}{60}$
Two cutting edges	2	1592	26.53	53.6
Three cutting edges	3	1592	26.53	79.6

The spikes of main natural frequencies and respective harmonics associated with the operation of the equipment were identified in a test with the equipment running without drilling, being indicates in the following figures with de designation “noise equipment spikes”. The tool deterioration is manifested itself mainly in the form of sidebands near the peaks of greater amplitude and a generalized increase in base noise. it is possible to identify these peaks by analysing the spectra as the number of holes performed increases.

Concerning to the drill with two cutting edges, the deterioration of the tool is slightly identified only in the case of external cooling. In this case, appears a spike slightly before 100 Hz, which is to the left of a characteristic peak of high amplitude (sideband) (Fig. 12).

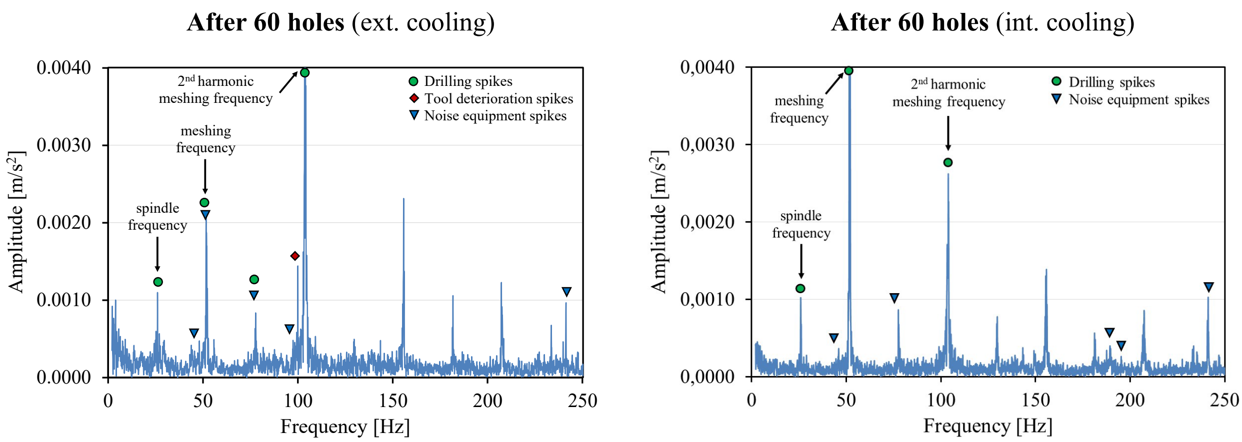


Figure 12. Vibration analysis for two cutting edges drills

To the drill with three cutting edges (Fig. 13), the deterioration of the tool is well identified in the case of external cooling, where after 30 holes, the tool life ends (Fig. 8). In this case, the spikes observed slightly after 50 Hz and 100 Hz are characterized by an increase in amplitude in relation to the base spectrum obtained with the equipment running without drilling (graph not presented). Besides, the peak at around 125 HZ and can be related to the tool damage, which did not exist in the base spectrum and which may be associated to the sidebands phenomenon.

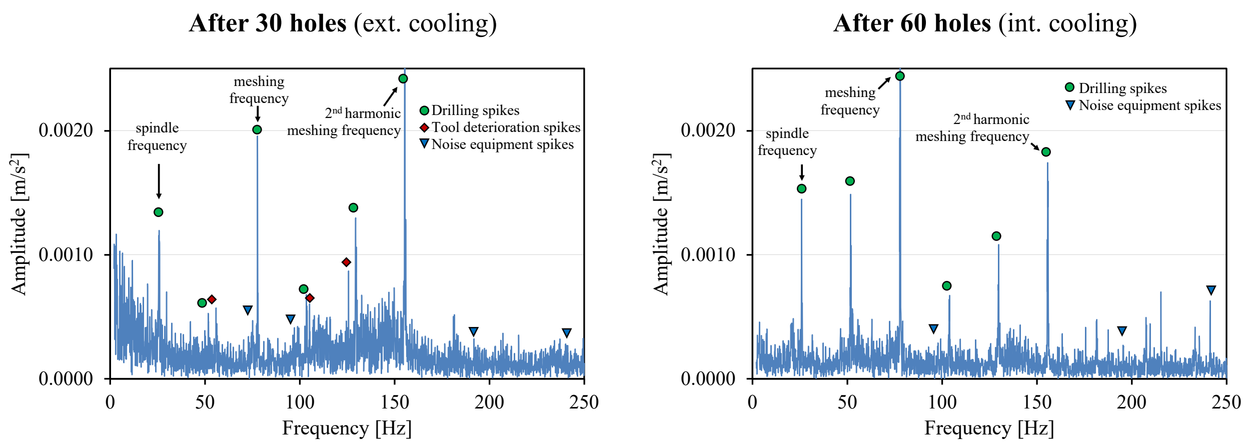


Figure 13. Vibration analysis for three cutting edges drills

Summary

The use of drills with three cutting edges is not a common practice, despite being a technology with a considerable time. Since they are practically unknown studies of the industrial application of this type of drills, it is relevant to carry out a comparative study of the performance of drills with two and three cutting edges, in this case applied to the duplex stainless steels. Although all the parameters in this research have an influence on the results obtained, it can be concluded:

The greatest effect in tool life is related to the type of drill used. The best results are obtained for two cutting edges drills.

The greatest effect in hole quality is related to the type of drill used. The best results are obtained for three cutting edges drills.

For the roughness of the hole, the biggest effect is related to the type of cooling used. The best results are obtained for internal high-pressure cooling.

The vibration analysis with Fast Fourier Transform is an effective method to identify and quantify various phenomena related with drilling operation and tool life.

As conclusion, it is possible to say that three cutting edges proved to be more fragile and more sensitive to the cutting parameters. The use of three cutting edges drills is recommended for situations where hole quality is more important, while two cutting edges drills is recommended for situations where productivity is the main objective.

Acknowledgements

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