Int J Adv Manuf Technol (2015) 81:1591–1599
DOI 10.1007/s00170-015-7321-x

ORIGINAL ARTICLE

Specific cutting energy employed to study the influence of the grain size in the micro-milling of the hardened AISI H13 steel

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Received: 26 January 2015 / Accepted: 13 May 2015 / Published online: 27 May 2015
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Abstract Among the miniaturization processes, micro-machining is one of the most used processes in the modern industries. In spite of the high number of micro-machining applications, several gaps should be investigated, such as the size effect. This paper analyzes the influence of the size effect on the specific cutting energy. Workpieces of AISI H13 steel with different austenitic grain size were machined with a tool of 0.5 mm of diameter and coating of (TiAl)N. The input parameters were the cutting speed, feed rate, and radial depth of cut. The responses were the cutting force and specific cutting energy. The results showed that the reduction of the specific cutting energy with the increase of feed rate for small grain sizes corresponded to 73 %. In the same way, the reduction for the large grain size corresponded to 70 %.

Keywords Specific energy · Micro-milling · Grain size · Hardness steel

1 Introduction

In the last decades, the research about machining processes has contributed to the development of the productive sector providing a wide range of technological innovations. The improvement of machines, tooling, and devices, for instance, has enabled a great increase in cutting speeds and accuracy. This improvement is important because it is estimated that the machining process represents 15 % of the total cost of the manufactured products [1]. According to Taniguchi [2], the accuracy of ultra-precision machining was of 10 μm in 1930. However, nowadays, the standard precision in machining can be lesser than 1 μm. This evolution has allowed the production of miniaturized devices that are used in aeronautic, automobile, medical, odontology, and other industries.

According to Chae et al. [3], the development of the micro-tools used in micromachining has an important challenge for modern industry to produce micro-components. These tools can have specific geometry for each machining application. Moreover, the miniaturization associated with micro-tools, such as micro-drills or micro-cutters, provides several benefits, which include savings in energy and space with low costs. Bissacco et al. [4] comment that the micro-milling is the most powerful process in terms of versatility to obtain complex shapes and features. Thus, the flexibility of the machine tools associated with a database from technical catalogues and a wide range of tooling enables the manufacturing of all kinds of products.

Although similar to the traditional machining processes, the micro-machining processes cannot be offhand downscaled into the micro-range due to the size effect. When the uncut chip thickness has the same size of the grain, the homogeneous and isotropic characteristics of the machined material can change [5]. According to Vollertsen [6], the size effect can be defined as micro-variations of characteristics during the machining process. The size effect occurs due to the relationship between the specific process parameters, and in some situations, it may not be kept constant due to the process requirements [7].

Mian et al. [8] studied the dominant factors of the plastic deformation generated during the micro-scale cutting. The aims were to understand the dominant parameters of the size effect in micro-scale cutting and guarantee flexibility by identifying the optimum conditions to produce the best surface

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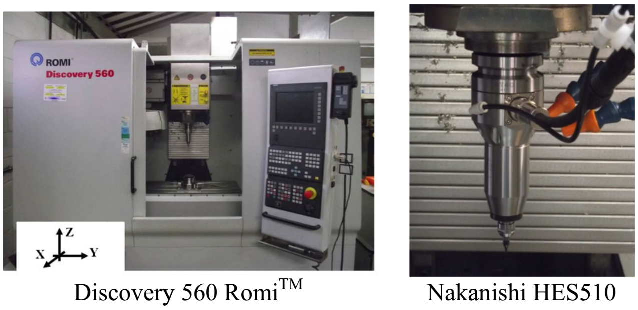


Fig. 1 Machining centre and high-speed electric motor spindle for the machining centre

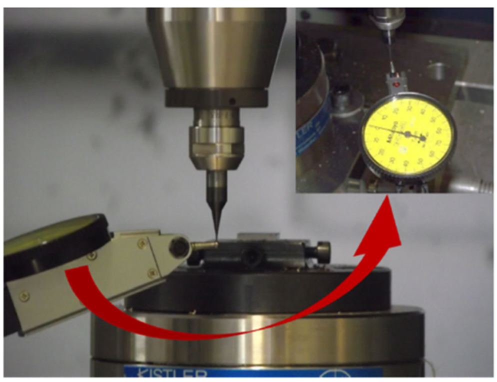


Fig. 2 Calliper gauge to measure the positioning error

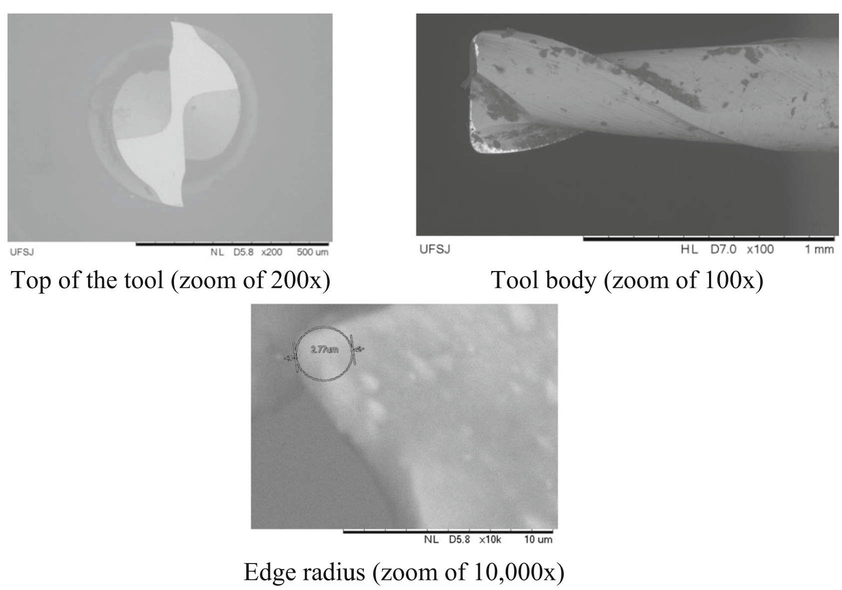
roughness. The authors observed that the specific energy, burr root thickness, and surface roughness of the micro-machined parts can be used as relevant responses to understand the size effect in micro-machining.

De Cristofaro et al. [9] applied high-speed machining (HSM), 91 m/min (29 krpm), and ultra-high-speed machining (UHSM), 141 m/min (45 krpm), in the micro-milling of AISI O2 steel with hardness of 62 HR_C using a cutter with a diameter of 1 mm. Nishikawa et al. [10] studied the micro-milling of A2024 aluminium alloy with 300 and 400 krpm and a cutter with a diameter of 0.4 mm. Generally, the diameters of the cutters range below 1 mm. Because of the small size of the cutters, the spindle rotation in micro-milling is usually high. Moreover, the micro-milling facility would require a smaller energy supply that can be supplied easily through alternative energy sources, not requiring new power infrastructure [11].

The analysis of the cutting forces is applied by several researchers because it provides a great understanding of the cutting phenomena: machinability of the material, tool wear and others. In the literature, it is possible to find studies showing that the cutting forces in the micro-milling are of low magnitude, for instance, the ones by Filiz et al. [12] (magnitude lesser than 1 N), Afazov et al. [13] (between 0.4 and 4 N, approximately), and Aramcharoen and Mativenga [14] (between 0.5 and 2.0 N, approximately).

Besides the study of the cutting forces, the analysis of the specific cutting energy is considered of interest in order to compare different tools, parameters, techniques and others. The specific energy is defined as the energy expended per unit of volume of removed material. Several models have been proposed by different researchers to define the magnitude of the specific energy and its dependence on the machining conditions. However, the studies on the specific energy were related to the traditional machining process, mainly for the grinding process.

Fig. 3 Microscopy of the micro-end mill (SEM)



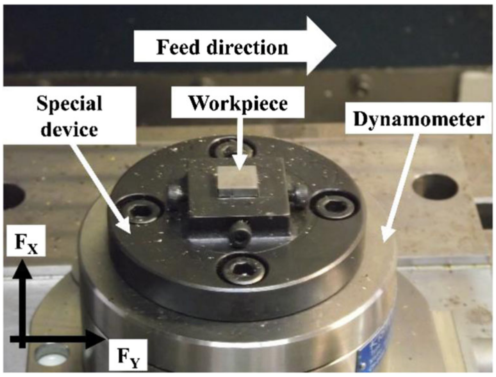


Fig. 4 Scheme of experimental tests

Table 1 Properties of grains after heat treatment

Workpiece	Grain size (μm)	Grain size (ASTM)	Hardness (HR_C)	Temperature (°C)	Time (s)	Cooling
G1	497	0	44	1250	7200	Oil
G2	40	6	46	1025	2700	

According to Singh et al. [15], the specific energy is the most important parameter to measure the performance of the abrasive processes. The application of the specific energy in the grinding process improves the understanding of the phenomena during the cutting (pull out of grains, breakage and flatness), which have a strict relation with the size effect and the abrasive grain. For instance, Ren et al. [16] studied the influence of the grain size in the grinding of tungsten carbides. The study demonstrated that the grain size has a great effect on the specific energy and surface topography in grinding. According to the authors, the physical-mechanical properties of the tungsten carbides with different grain size were modified elastically and then plastically and showed different behaviour when submitted to external loading.

In the milling process, Rodrigues and Coelho [17] analyzed the influence of the tool geometry using the specific cutting energy that can be considered an adequate parameter for understanding the HSM mechanism. Pfefferkorn [18] stated that studies on the specific cutting energy are very important in both traditional machining and micro-machining because they are an indicator of the energy consumption in a machining process. This indicator can be used to improve tool geometry and coatings.

In the micro-machining, the specific cutting energy is applied to study the size effect that has a sizeable influence on this process. According to Vollertsen et al. [19], the size effect in metal cutting is understood as a non-linear increase of the specific cutting energy due to the decrease of the undeformed chip thickness. Ng et al. [20] analyzed the specific cutting energy and the coefficient of friction to justify that the size effect that occurs as an undeformed chip thickness is proportional to the cutting edge radius (60 to 100 nm); in both, the values increased non-linearly with a decrease in the undeformed chip thickness.

The same evaluation can be made in micro-machining due to the diminished size of tooling. Studies on the specific energy in micro-machining processes such as micro-milling and micro-drilling, however, are limited. The difficulties found are due to the relation between the diameter and load machining. Similarly than for the traditional machining processes, in particular grinding processes, the studies on the specific energy in the micro-machining can contribute to improve the quality of tools, coatings, and fixing systems.

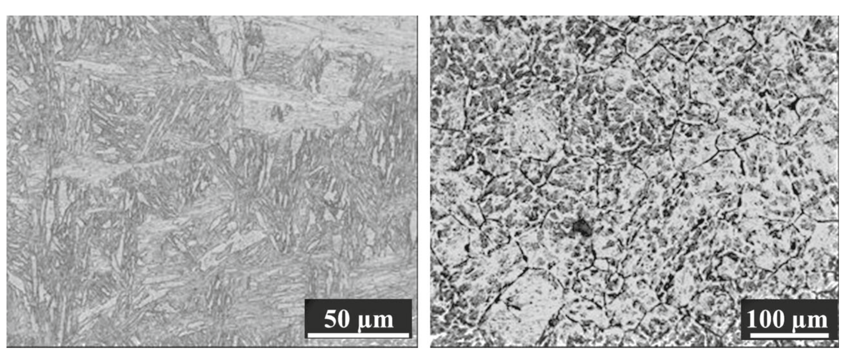
The present study is focused on the definition of the specific energy in the micro-milling of hardened AISI H13 steel with different grain sizes. The aim of this work is to define the influence of grain size on the specific energy.

2 Methodology

2.1 Experimental tests—micro-milling

A high-speed electric motor spindle for a machining centre, Nakanishi™ model HES510, with 50,000 rpm and 300 W

Fig. 5 Microstructure of workpieces (grain size of 40 μm)



a) Aspect of the microstructure b) Detail of grain size

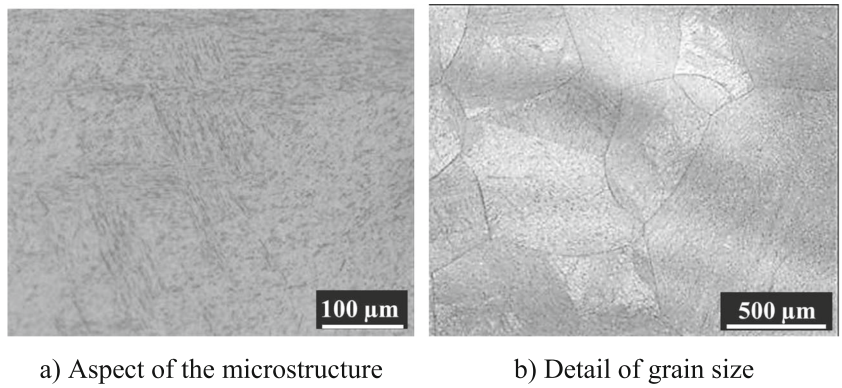


Fig. 6 Microstructure of workpieces (grain size of 497 μm)

attached to a machining centre was used to increase the cutting speed (Fig. 1). The micro-milling process requires machine tools with high rotational speed capabilities and very high positioning accuracy. In this experimental, the rotation of the tool was therefore performed with a high-speed electric motor spindle for the machining centre, and the displacement of the tool was regulated by the axes *X*, *Y*, and *Z* of the machine centre; thus, the machining centre was set to displace in the *Y* direction, feed, in function of time.

High-speed electric motor spindle for the machining centre reaches speeds up to 50,000 rpm with a run-out of less than 1 μm. According to Bissacco et al. [4], the axial depth of cut is the most important parameter to be controlled. Generally, the use of micro-end mills in the micro-machining of hard materials is complex because of the propensity for breakage. The authors support that the errors in the control of the axial depth of cut may reach 30 μm, while the aimed depth of cut (DOC) can be as low as 5 μm. The set-up of the tooling was therefore carried out with a calliper gauge accurate up to 1 μm. The positioning error measured was 1 μm, which was within the margin specified by the manufacturer of the machining centre (Fig. 2).

The tool was a carbide micro-end mill with a diameter of 0.5 mm, two flutes, and (TiAl)N coating provided by SANDVIK Coromant™ (R216.32-00530-AE05G 1620) (Fig. 3). Workpieces of AISI H13 steel with dimensions of 11×11×11 mm were used in the tests. This material was selected because it is commonly used to fabricate die and moulds due to its high wear resistance. The chemical composition of AISI H13 steel was 0.40 % C, 1.00 % Si, 0.35 % Mn, 5.20 % Cr, 1.50 % Mo, 0.90 % V, and Fe in balance. All workpieces were ground before the experimental tests in order to ensure the accurate assembly on the fixture device (Fig. 4).

The workpieces were submitted to different heat treatments (Table 1) to obtain hardness of 45 HR_C ±1, that is, a mean value suggested for hot works [21]. Furthermore, these heat treatments produced two grains sizes: 40 μm (G1) and 497 μm (G2), as can be seen in Figs. 5 and 6, respectively. Although the grain size of 497 μm is not used in industrial applications, this grain size was used to provide a better understanding of the size effect. Similar studies were developed employing different edge radii. However, in this study, only one tool was used to avoid the effect of the small variations of the tool geometry.

Table 2 shows the input parameters used in the experimental tests. The values for axial and radial depth of cut, cutting speed, and feed rate were defined according to the catalogue of the tool's manufacturer. The design of experiments (DoE) was designed by three replicates with three repetitions for all conditions that were conducted in random order.

To measure the cutting forces, a dynamometer Kistler™ model 9272, a multichannel charge amplifier Kistler™ model 5070 and the software DynoWave™ model 2825A-02 version 2.4.1.6 were used. The natural frequency of the dynamometer in the *X* and *Y* direction was 3.1 kHz. The dynamometer was

Table 2 Input parameters for experimental tests

Input parameters	Level of the input parameters	
	−1	+1
Spindle speed (rpm)	21,000	49,000
Approximate cutting speed (m/min)	33	77
Feed per tooth (μm/th)	1	5
Axial depth of cut (μm)	25	
Radial depth of cut (μm)	500	

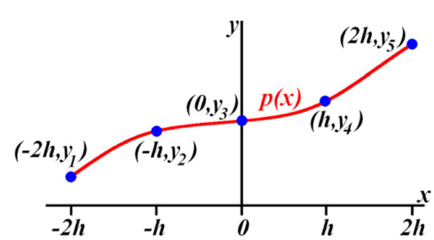
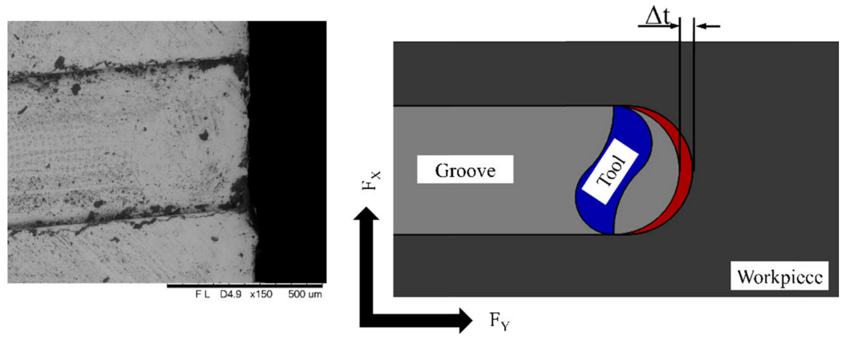


Fig. 7 Interpolation of a polynomial of 4° $p(x)$



a) Machined groove (zoom of 150x)

b) Schematic cutting

Fig. 8 Scheme of the milling operation on the workpieces

set based on the indication given by Afazov et al. [13] and Shaw [22]. The sample frequency was defined in 6.5 kHz and the time acquisition was 40 s for all tests. To qualify the signal (denoizing), the Wavelet transform was used.

2.2 Specific energy—mathematical model

The aim of this work was to define the specific cutting energy in micro-milling processes. For that, a two-dimensional model is used. The specific cutting energy can be defined according to Eq. 1; where u_c is the specific cutting energy (J/mm^3), F_x and F_y are the components of the force vector (N), v_c is the cutting speed (m/s), V_{rem} is the removed chip volume (mm^3), and t_c is the cutting time (s).

$$u_c = \frac{v_c}{V_{rem}} \int_0^{t_c} \sqrt{Fx^2 + Fy^2} dt \quad (1)$$

The removed chip volume was obtained by simple calculus because the milled region was a linear groove generated by the cutter. The F_x and F_y components were recorded during the experiments using the DynoWave™ software and exported to text a text file (.txt) that was employed to calculate the average value. Based on the F_x and F_y force values for each cutting condition, it was possible to define the resultant force (F_R).

The resultant force was defined in intervals of time (Δt) equally spaced. Numerical methods were applied based on the Simpson rule 2/45. This rule uses the polynomial functions $p(x)$=a^0+ax+a$^2x^2$+a$^3x^3$+a$^4x^4$ where the coefficient is ‘a’, the variable is ‘x’ and the degree of the ‘x’ is four. Furthermore, the integration of the adjusted data was performed taking five to five values as can be seen in Fig. 7.

Figure 7 shows a coordinate system of the function $p(x)$ where a linear system can be defined with five equations and five unknown quantities. The solution of this system gives the unknown parameters of the polynomial. The integration of the function in the range [−2h, 2h] provides the solution according to Eq. 2 and allows the calculus under the adjusted area (Simpson 2/45).

$$\int_{-2h}^{2h} p(x)dx = \frac{2h}{45} / (7y_1 + 32y_2 + 12y_3 + 32y_4 + 7y_5) \quad (2)$$

Thus, by the substituting Eq. 2 in Eq. 1 and considering h=Δt, Eq. 3 can be obtained for the calculus of specific energy.

$$u_c = \frac{v_c}{V_{rem}} \frac{2\Delta t_c}{45} \begin{pmatrix} 7Fr_1 + 32Fr_2 + 12Fr_3 + 32Fr_4 + 7Fr_5 \\ + 7Fr_5 + 32Fr_6 + 12Fr_7 + 32Fr_8 + 7Fr_9 \end{pmatrix} \quad (3)$$

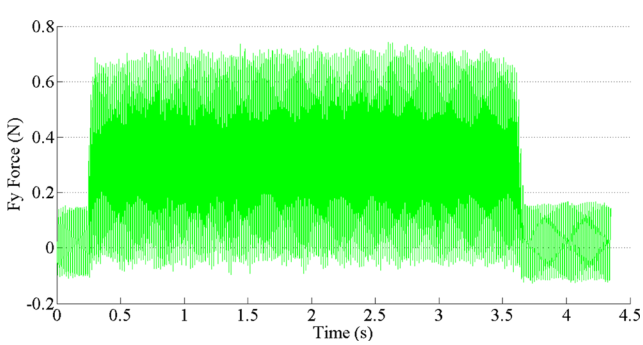


Fig. 9 Signal with oscillation (noise)

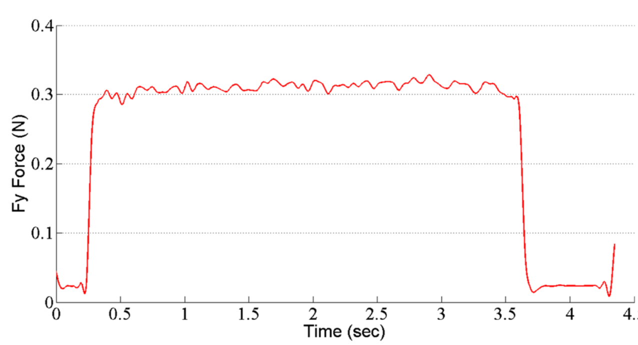


Fig. 10 Denoised signal

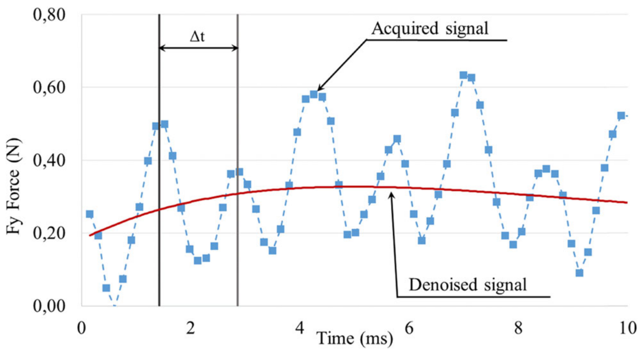


Fig. 11 Detail of Δt (1.43 ms) in the condition with cutting speed of 33 m/min and feed rate of 5 μm/th

The micro-cutter produced grooves with 0.5 mm of width and length of 11 mm. Figure 8 shows details of micro-milling in workpieces. The Δt value applied in the calculus of the specific energy, according to Eq. 3, was proportional to the feed rate used in the experimental test shown in Table 2. The cutting time, therefore, is also proportional to the feed rate used in the tests. Based on this, the minimum micro-milling time to produce a groove with feed rates of 42, 98, 210, and 490 mm/min corresponds to cutting times between 1.35 and 15.71 s. Thus, the value of Δt is linked directly to the cutting dynamic and ranged from 0.612 to 1.43 ms.

3 Results and discussion

Figure 9 shows a typical graph of the force recorded during the experimental tests. The original signal without the excitement of the source (cutter) showed a variation of −0.1 to 0.7 N. The F_x

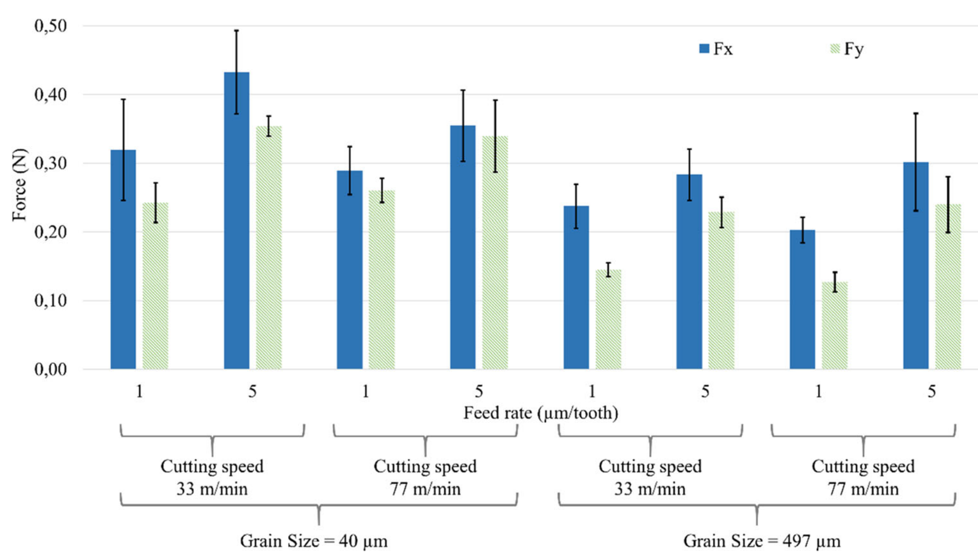
Table 3 Taguchi method for cutting forces F_y and F_x

Level	Grain size (μm)	Cutting speed (m/min)	Feed rate (μm/th)
F_y force			
1	10.484	11.115	12.497
2	11.84	11.209	9.826
Delta	1.356	0.094	2.671
Rank	2	3	1
F_x force			
1	9.123	11.608	13.756
2	14.925	12.440	10.292
Delta	5.803	0.832	3.464
Rank	1	3	2

and F_y forces correspond to the excitement of the cutter during the milling of the workpiece. The oscillation of the F_y force shown in Fig. 9 demonstrates a great variation of the cutting force in the F_y direction. After applying the Wavelet transformation, the maximum value was 0.32 N (Fig. 10). An algorithm was developed to define the maximum values for F_x and F_y in all cutting conditions. Furthermore, the algorithm allowed the exact definition of the micro-milling region. Thus, it was possible to eliminate the points after and before the cutting process.

Due to the high acquisition rate, several points were recorded in the Δt interval in order to avoid errors during the analysis (Fig. 11). The signal in the F_y direction increases constantly, pushing the dynamometer to its limit. Then, a reduction occurs, showing a contrary condition because the dynamometer pushes the cutter in the opposite direction. This cutting condition was similar and cyclical during all milling

Fig. 12 Cutting forces for all micro-milling experiments



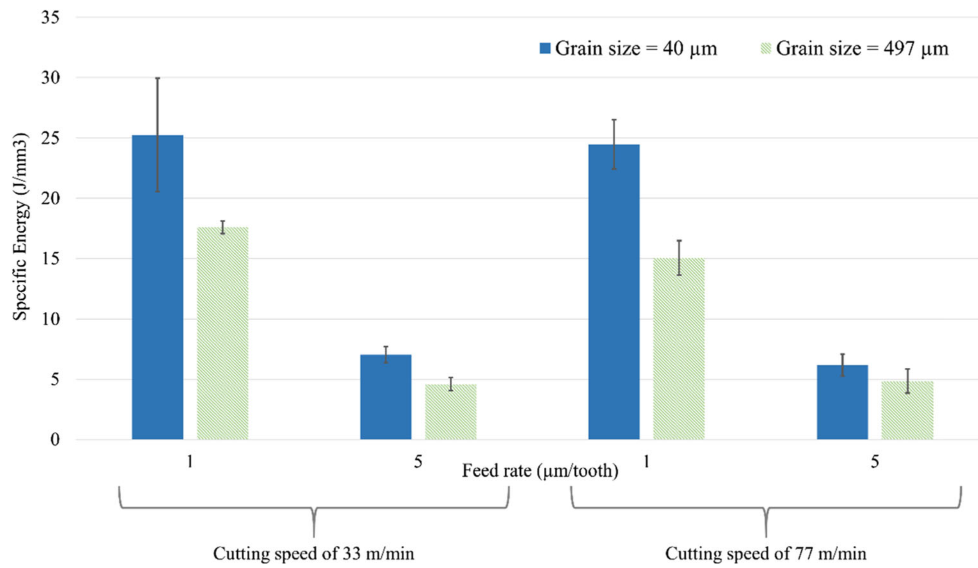


Fig. 13 Specific cutting energy for all experimental tests

operations, varying in intensity according to the input parameters.

Figure 12 shows the general results for the F_x and F_y forces for all micro-milling experiments. In summary, the highest force values were registered for the grain size of 40 µm when the same cutting conditions are compared. The different grain sizes provided variations between 15.0 and 34.5 % for the F_x forces and 29.4 to 51.2 % for the F_y forces. The decreasing of the cutting forces was smaller in the feed rate direction. A Taguchi method was used to analyze the cutting forces, as can be seen Table 3, being possible to observe that the cutting speed was the parameter with the lower influence for both directions. Furthermore, the feed rate was more significant than the grain size for the F_y force, which can be explained because this force was measured in the direction of the displacement of the tool. However, for the F_x force, the significance was contrary.

According to Strafford et al. [23], the cutting forces depend strongly on the grain size and the proportion of pearlite and ferrite phases in the steels. The higher strength and hardness of the pearlite phase cause higher cutting forces in machining processes and change the machinability of steels. Weule et al. [24] and Schmidt et al. [25] affirm that the multiphase materials with ferrite and pearlite phases are inhomogeneous showing different radii to grain size, changing the ductile phase and influencing the cutting mechanism. According to Jin et al. [26], specimens with ultra-fine grains have not only high tensile strength but also large elongation. Thus, the cutting forces are high due to the strain-induced martensitic transformation. In addition, according to Aramcharoen and Mativenga [14], when the grain size has a proportional size to the chip thickness, the cutting edge tends to fracture a single grain, which will increase the cutting forces. Thus, it can be defined that the small grain sizes generated higher cutting forces than the large grain sizes.

Figure 13 shows the results of the specific energy for all micro-milling experiments. The increase in feed rate provided a reduction in the specific cutting energy. In average, 73.5 % for the grain size of 40 µm and 70.9 % for the grain size of

Table 4 S/N responses for specific cutting energy

Level	Grain size (µm)	Cutting speed (m/min)	Feed rate (µm/th)
1	−22.25	−20.84	−26.14
2	−18.90	−20.31	−15.02
Delta	3.35	0.53	11.12
Rank	2	3	1

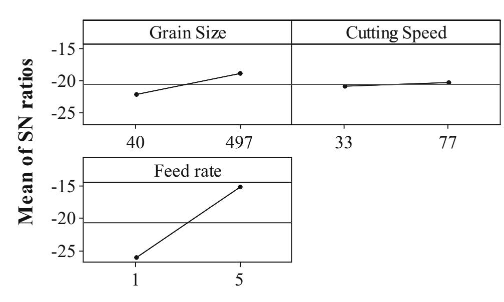


Fig. 14 Main input parameter for the S/N ratios considering the specific cutting energy

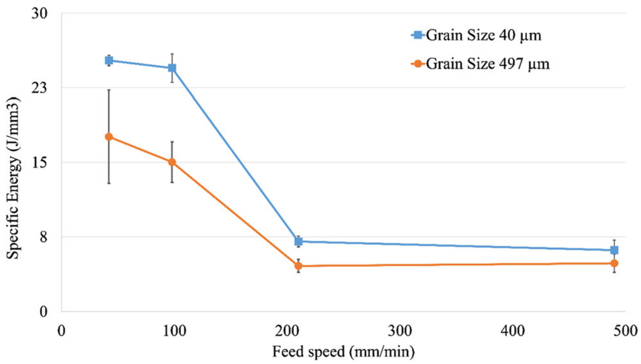


Fig. 15 Graphic of specific cutting energy vs. feed speed

Table 5 S/N responses for specific cutting energy with feed speed

Level	Grain size (μm)	Cutting speed (m/min)	Feed rate (μm/th)	Feed speed (mm/min)
1	15.738	13.602	20.580	21.397
2	10.501	12.638	5.660	19.763
3			5.808	
4			5.512	
Delta	5.237	0.965	14.920	15.885
Rank	3	4	2	1

497 μm, and it was the most significant parameter. The increase in the cutting speed did not affect the specific cutting energy, significantly, on average, 7.7 % for the grain size of 40 μm and 4.3 % for the grain size of 497 μm. However, the decrease in the cutting speed raised the specific cutting energy, 3.0 and 14.5 %, for the grain sizes of 40 and 497 μm, respectively, practically in all conditions.

On the other hand, an increase of 5.9 % in cutting speed variation for the grain size of 497 μm regarding the feed rate of 5 μm/th can be observed. But, when the influence of the grain size on the specific cutting energy is considered, a great reduction can be observed from the grain size of 40 to 497 μm; the specific energy decrease by 21.5 and 38.6 %.

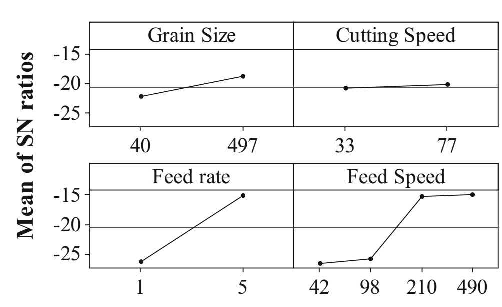


Fig. 16 Main effects plot (data means) for S/N ratios

Analyzing the feed rate of 1 μm/th, for different grain sizes, the reduction was of 34.5 % on average. Considering the feed rate of 5 μm/th, the difference was 28.2 % on average. In summary, the most significant parameter on the specific cutting energy was the feed rate (Table 4). Figure 14 shows the main input parameter for the S/N ratios.

When analyzing the specific cutting energy in a function of the feed speed, it was possible to observe that the specific cutting energy decreased when the feed speed increased for all conditions (Fig. 15). The use of the Taguchi method showed that the feed speed is the more significant parameter in micro-milling, as can be seen in Table 5 and Fig. 16.

4 Conclusions

The present study analyzed the influence of the grain size on the specific energy in the micro-milling of hardened AISI H13 steel. Based on the results of the performed experiments, it was observed that the grain size had influence on the cutting forces and specific cutting energy. The material with the highest grain size presented lower values of cutting forces in both directions (between 15.0 and 51.2 %) and specific cutting energy (between 21.5 and 38.6 %) compared with the material with the smallest grain size.

Analyzing the influence of the employed parameters, it was observed that the increase of the cutting speed affected the cutting forces and specific cutting energy, though the cutting speed was the parameter with the smallest influence. The feed rate presented a higher influence on the reduction of the specific cutting energy than on the cutting force. The reduction of the specific cutting energy, on average, corresponds to 73.5 % when the feed rate is increased on a small grain size. In the same way, the reduction for the large grain size corresponds to 70.9 %.

Acknowledgments The authors would like to thank the Ministry of Education's Coordination for the Improvement of Higher Education Personnel (CAPES) and the State of Minas Gerais Research Foundation (FAPEMIG). Additional thanks to Sandvik™ Coromant and Gerdau™.

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