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EXPERIMENTAL STUDIES ON APPLYING CRYOGENIC COOLING BEFORE HARD TURNING OF 100CR6 (AISI 52100)

Irina BEȘLIU, Ioan TAMAȘAG, Laurențiu SLĂTINEANU

Abstract: Turning of hard materials is considered an efficient finishing process, capable of replacing grinding and offering multiple advantages, such as reducing machining costs, increasing productivity and improving surface texture. A full factorial experimental design (DOE) was used to analyze the correlation between input factors — cutting medium (dry and cryogenic), cutting speed and feed — and certain parameters of interest, such as cutting forces and surface quality. The material investigated is a high-carbon and chromium steel, commonly used for the manufacture of bearings, subjected to a heat treatment to obtain a hardness of 61 ± 2 HRC. The study highlights that cryogenic turning, at approximately -30°C , improves the process performance, generating shorter and more fragmented chips due to the embrittlement effect of the material. Also, the surface roughness obtained under cryogenic conditions was better, and although the cutting forces are slightly higher, the overall performance of the process improved significantly by comparison to dry cutting.

Key words: cryogenic machining, hard turning, surface roughness, cutting forces.

1. INTRODUCTION

In recent decades the advances in machine tools technology in terms of stability, stiffness, and power, and materials, especially tool material and coatings opened new possibilities for machining what previously were considered hard-to-cut materials. These advances were also backed up by the growing demands in the manufacturing industry for tight tolerances, complex surfaces, and hard parts. Hard machining is the machining process of parts made of materials with above 45 HRC material hardness. The mechanisms associated with hard machining - chip formation, machining forces, thermal regime, power, and tool wear are different from those specific to conventional machining.

Scientific literature stipulates that the material hardness has a beneficial influence on the machined surface quality. This is because up to a certain hardness value that depends on the type of the material discussed, the material tends to become brittle.

Another trend that has been explored in the last decades is the cryogenic cutting

environment. Cryogenic machining is a machining process by cutting or plastic deformation carried out at very low temperatures, using cryogenic liquids for cooling. The cryogenic machining environment is mainly used to improve the efficiency and functionality of cutting tools and the surface quality of machined parts. Several studies [1–9, 13] have demonstrated that implementing a cryogenic machining environment in manufacturing processes, especially for hard-to-machine materials, conduct to improved machinability by extending tool life, ensuring superior surface integrity, and facilitating efficient chip disposal.

Heat-treated steels may contain retained austenite, a soft and unstable phase that affects dimensional stability and machinability. By cryogenic cooling, the retained austenite transforms into additional martensite, which is harder and more stable [11]. Thus, the material becomes more homogeneous, which leads to reduced variations in machining behaviour and tool wear becomes more predictable. Previous applied machining processes can introduce internal stresses into the part material. The

cryogenic regime can relax these stresses, which prevents deformation during processing and reduces the risk of cracking [10]. During exposure to cryogenic temperatures, especially in the case of chromium-vanadium alloy steels, fine carbide precipitation occurs [12]. These strengthen the structure of the material and improve the stability of the cutting edges, reducing the phenomenon of chips sticking to the tool (especially when machining at high speeds) and therefore assuring a better surface finish.

100Cr6, also known as DIN 1.3505 or AISI 52100, is a bearing steel that lends itself to high loads and high wear demands. This material is mainly used for small and medium-bearing components due to its ability to withstand multiple cycles of mechanical stresses and strains. In the heated state, 100Cr6 offers high hardness, mechanical strength, and chemical purity, making it ideal for applications with intense mechanical stress.

Several studies have focused on the effect of cryogenic cooling in the difficult machining of 100Cr6 bearing steel. Ortiz-de-Zarate et al. [1] performed an experimental and finite element method (FEM) analysis of the dry and cryogenic turning process of hardened 100Cr6 steel. The authors analyzed the influence of cutting speed (between 150 and 550 m/min) on fundamental parameters, such as cutting forces and tool wear, as well as on surface integrity. In the case of cryogenic cooling, tool wear manifests itself in two distinct regions, depending on the cutting speed. At speeds below 300 m/min, homogeneous wear and slightly higher forces are observed compared to dry machining conditions. At speeds above 300 m/min, the sharp increase in tool wear causes a sudden elevation in forces under cryogenic conditions. Microstructural analysis of the machined surface revealed a similar thermally affected layer in the cutting direction for the cooling conditions considered, but for cryogenic cooling superior tensile residual stresses were determined on the surface.

In another study [2], the sustainability of implementing cryogenic machining compared to conventional dry or liquid-cooled processes for the difficult machining of AISI 52100 steel was

analyzed. Cryogenic machining was reported to increase tool life by approximately 370% during turning of this hardened steel. Also, surface roughness values were comparable between the methods, but the surface quality obtained by cryogenic cooling was superior.

Huang et al. [4] presented experimental results on the mechanisms of chip formation and hardness changes that influence the quality of the machined surface, analyzing both cryogenic and dry machining of a difficult-to-machine material (AISI 52100 steel). The authors showed that, in cryogenic machining, chip segmentation occurs at lower cutting speeds for a given workpiece hardness. Also, Umbrello et al. [9] highlighted that cryogenic machining allows to obtain a lower roughness compared to dry machining of hardened 100Cr6 steel.

Numerous studies on cryogenic hard machining have focused on the effect of cryogenic cooling on the microstructural transformations of the machined surface. Some researchers [2, 8, 9, 10] have demonstrated that cryogenic cooling of the tool and tool-workpiece contact limits the thickness of the white layer, while others [1] have not observed such an effect.

This experimental investigation aims to determine the influence of superficial cryogenic cooling on the turning process of hardened 100Cr6 steel. Surface roughness and cutting forces were analyzed as output parameters.

2. MATERIAL AND METHODS

Orthogonal cutting tests, under dry and cryogenic conditions, were performed on hardened 100Cr6 steel bars using a universal lathe and cubic boron nitride (CBN) tools (Sandvik Coromat: CBN CNGA 120412S01035A 7015), mounted on a PCLNR2525M 12 tool holder, which offers an included angle of 80°, a cutting edge angle of 95°, a orthogonal cutting angle of -6° and a rake angle of -6°. Cubic boron nitride (CBN) is a super-abrasive material, frequently used in hard materials machining due to its good wear resistance and high hardness. It enables efficient machining of hardened steels, providing longer tool life and superior surface quality.

Bars with diameters of 22 mm, 29.7 mm, and 48.9 mm were used in the experiments. The bars were subjected to heat treatment to obtain a material hardness of 61 ± 2 HRC.

The experiments were conducted using a full factorial experimental design, considering two controllable factors: cutting speed, s [m/min] and cutting feed, f [mm/rev]. A full factorial design systematically tests all possible combinations of these factors. The input factors and their levels of variation for each are presented in Table 1.

Table 1

Input factors and their levels of variation		
Factor Level	s [m/min]	f [mm/rev]
1	110.5	0.06
2	149.2	0.16
3	245.6	0.2

The cutting depth used in the experiments was 0.3 mm. The cryogenic condition materialized by applying an instant cooling spray, produced by Termopasty, which ensures rapid cooling down to -55°C . The freezing spray was applied for 15 seconds in the machining area before the start of the cutting process. The cryogenic treatment led to the freezing of the part down to approximately -300°C . These values were measured using a high-speed infrared thermal camera, type $\times 6540\text{sc}$, produced by Flir (Teledyne Flir LLC, United States of America). Figure 1 presents the thermal image obtained just before turning, after applying the cryogenic spray to the cutting area.

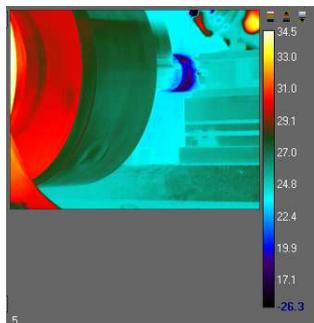


Fig. 1 Thermal image of machining setup

The parameters analyzed in this research included the cutting force components, chip shape and surface roughness. The three orthogonal components of the cutting forces, F_x , F_y and F_z , were measured using a multi-

component piezoelectric dynamometer, type 9257B, manufactured by Kistler Instruments AG, Winterthur, Switzerland. The recorded values were subsequently processed and analyzed using the specialized Dynoware software, connected to the equipment.

The roughness parameter considered for this investigation was S_a [μm]. This parameter represents the average roughness and is determined as the average height of all measured points in the areal measurement. The areal surface roughness parameter was selected over the widely used R_a parameter because it provides more accurate information regarding the surface quality by expanding the surface analysis three-dimensionally.

The surface roughness parameters and surface textures were obtained by using a profilometer that applied confocal microscopy and integrated white light interferometer type CWM 100, produced by Mahr GmbH - Göttingen, Deutschland.

Table 2 presents the design of the experiment (DOE) experimental setup, and the value obtained for the parameters of interest for each experimental run.

Table 2

DOE experimental table and the values obtained for the investigated parameters

Exp. run.	Cutting environment	Cutting speed s , [m/min]	Cutting feed f , [mm/rev]	F_x , [N]	F_y , [N]	F_z , [N]	S_a [μm]
1	dry	110.5	0.06	60.82	91.56	72.63	1.795
2	dry	110.5	0.16	76.22	128.98	141.75	2.155
3	dry	110.5	0.2	97.17	149.11	191.2	3.130
4	dry	149.2	0.06	110.48	126.47	103.47	1.300
5	dry	149.2	0.16	103.96	155.96	161.67	2.280
6	dry	149.2	0.2	106.01	169.92	184.34	3.165
7	dry	245.6	0.06	91.5	134.7	79.71	1.730
8	dry	245.6	0.16	92.78	146.36	146.94	2.815
9	dry	245.6	0.2	103.82	165.18	182.87	3.220
10	cryo	110.5	0.06	108.92	114.25	103.21	1.495
11	cryo	110.5	0.16	141.72	115.3	127.07	1.625
12	cryo	110.5	0.2	208.59	171.96	336.23	3.660
13	cryo	149.2	0.06	120.22	140.24	105.97	0.799
14	cryo	149.2	0.16	124.93	152.09	193.23	2.370
15	cryo	149.2	0.2	117.15	167.44	204.7	3.005

16	cryo	245.6	0.06	109.23	166.94	124.29	1.610
17	cryo	245.6	0.16	110.67	175.56	150.11	2.407
18	cryo	245.6	0.16	80.61	168.63	130.57	3.090

3. RESULTS AND DISCUSSION

By analyzing the values obtained for the cutting force components (Table 2), we can conclude that the forces obtained for the cryogenic cutting environment are slightly higher than those recorded when applying dry turning (F_x when turning in a cryogenic environment is 0.33% higher than for dry environment, F_y for cryogenic machining exceeded with 1.89% the F_y values obtained for dry machining; F_z in cryogenic cutting were by 3.12 % higher than those obtained in dry turning). As the temperature in the cutting zone decreases, the hardness and brittleness of the workpiece material increase.

Consequently, the material will resist plastic deformation more, so the tool must exert higher forces – resulting in higher cutting forces.

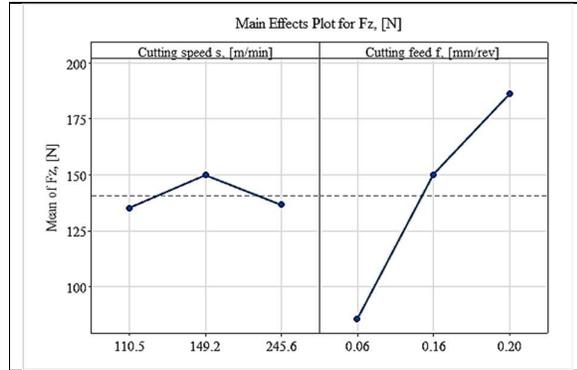


Table 4.

Cutting forces variations under cryogenic cooling

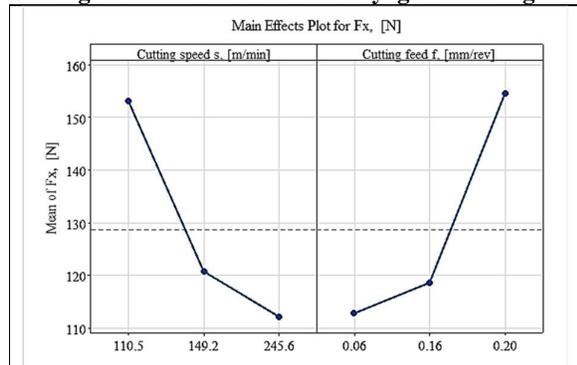
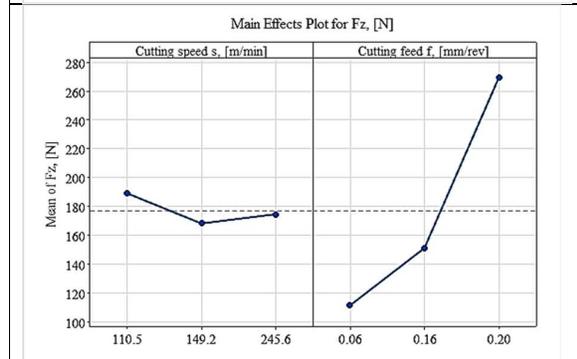
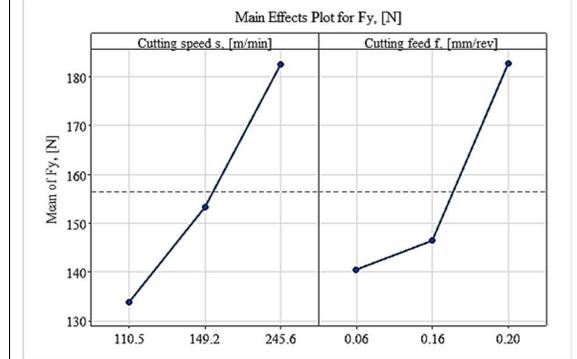
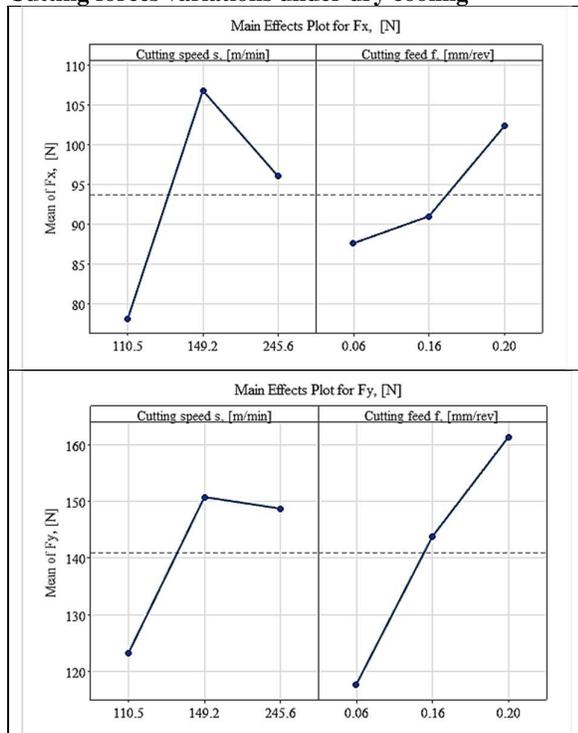


Table 3.

Cutting forces variations under dry cooling



The main effects plots that present the influence of the input factors - cutting speed and cutting feed variations over the cutting force components variations are presented in Table 3

for dry cooling conditions and Table 4 for cryogenic cooling conditions.

As can be seen in the graphs from Table 3, for the dry machining conditions, the influence of cutting speed on the cutting forces components is complex, with a tendency to increase and subsequently decrease with the increasing cutting speeds. This may be because at low speeds plastic deformation is more predominant and the temperature in the cutting zone is relatively low. The material is hard, the cutting resistance becomes also higher, therefore the cutting forces increase. The temperature in the contact area increases significantly; the material becomes softer (thermo-softening effect). At the same time, the friction coefficient decreases, leading to a decrease in cutting forces. This effect is specific to materials that undergo softening at high temperatures and is often encountered in hard machining.

When cryogenic cutting conditions are used the extreme cooling reduces friction and cutting resistance but introduces fracturing behaviour that increases F_y . At low temperatures, the material may have an increased tendency to fracture suddenly and irregularly. The chips are more contorted (as can be seen also in Figure 2), which leads to the increase of the cutting force in the transverse direction (F_y). Also, in the cryogenic environment, the surface layer of the part may have a different strength, affecting the distribution of forces.

Figure 2 presents microscopic images of the cutting chips obtained in the test runs carried out with a cutting speed of 245.6 m/min.

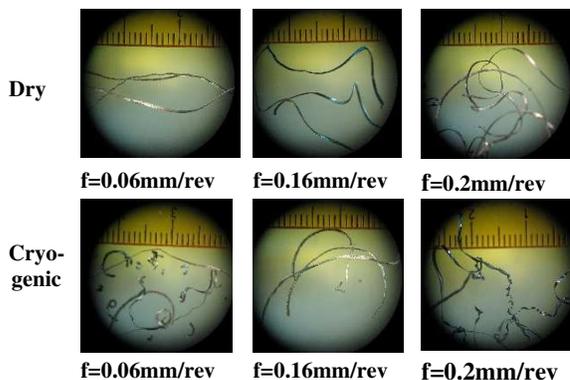


Fig. 2 Cutting chips obtained by turning 100Cr6 with a cutting speed of 245.6 m/min

As can be seen, for the dry machining environments, the cutting chips appear straighter and more continuous, which may indicate higher material plasticity and higher cutting temperatures. When turning in a cryogenic machining environment the cutting chips appear to be more fragmented and contorted, suggesting that the material becomes more brittle due to low temperatures.

The values obtained for the surface roughness S_a parameter were approximately 7.13% lower for the cryogenic turning than for the dry machining conditions.

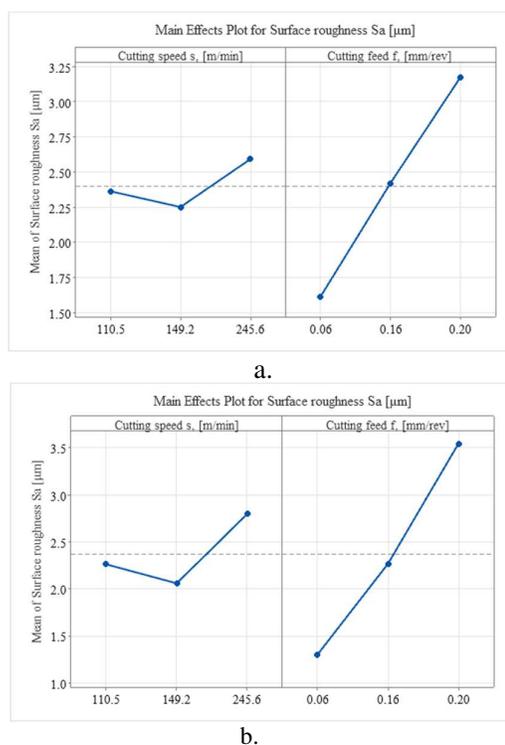


Fig.3 The main effects plots for S_a surface roughness parameter: a - dry machining; b - cryogenic machining

In Figure 3 the main effects plots for the surface roughness parameter S_a are presented. For both machining conditions, the considered input parameters exert a negative influence over the investigated surface roughness parameter (S_a). At low speeds, the tool interacts more strongly with the material, which can lead to increased roughness due to vibration and material build-up on the cutting edge. As the speed increases, the roughness tends to decrease, reaching a minimum value at an optimal machining speed. However, at too high speeds,

the roughness increases again, due to accelerated tool wear and process instability.

In Figure 4 there are presented some surface texture samples of the surfaces obtained by dry turning and turning in cryogenic environment. For the dry cutting conditions, the surfaces show redder and orange areas, indicating a higher roughness value. This could be a result of the fact that due to the lack of a cooling medium, friction, and higher temperature have been generated during machining. For the images obtained for the cryogenic cutting machined surfaces, the color distribution is more balanced, with more blue and green areas, indicating a smoother surface. This reflects that cryogenic cooling has reduced friction and tool wear, resulting in smoother machining.

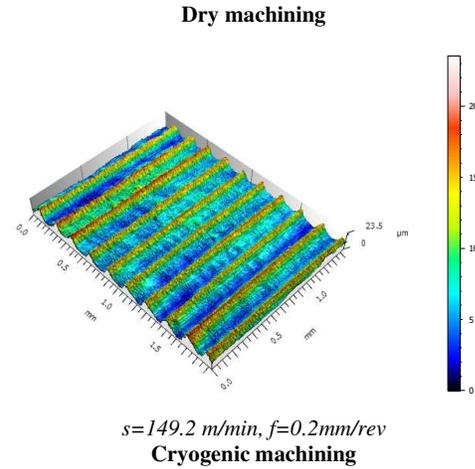


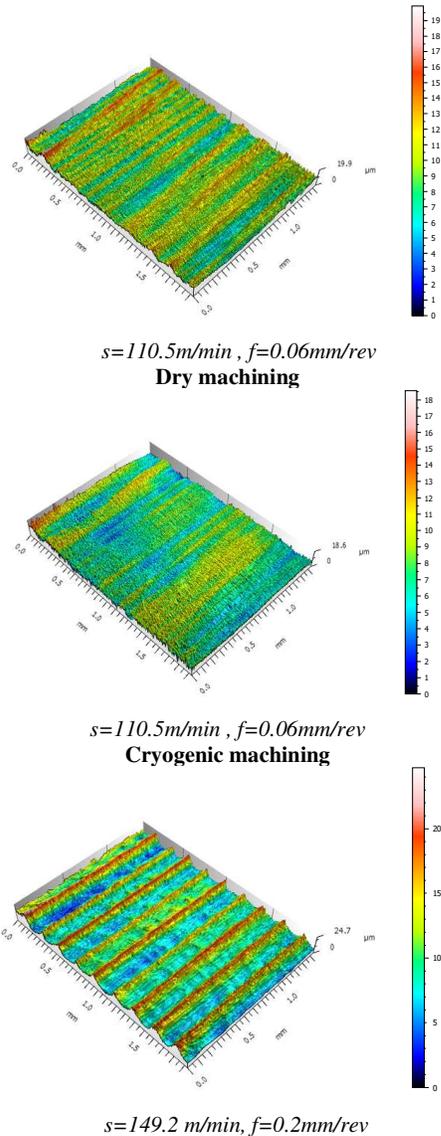
Fig. 4 Comparison of the surface textures obtained when turning in dry and cryogenic cutting conditions

In dry cutting, high temperatures can cause thermal deformation, oxidation, or microstructural changes, which may explain the larger asperities observed in the 3D graph. In cryogenic cutting, the lower temperature minimizes the thermal expansion of the material, which contributes to a more homogeneous surface and fewer defects.

4. CONCLUSIONS

The paper aimed to investigate the influence of cryogenic machining conditions over some interesting machining parameters - cutting force, and surface quality. The specialized literature specifies that cryogenic cutting can offer several advantages such as superior quality of machined surfaces, reduced tool wear, increased machinability of difficult-to-cut materials, reduced residual stress, etc. Cryogenic machining is a material machining process that uses extremely low temperatures (below -150°C) to improve the cutting process. This method involves the application of cryogenic agents (usually liquid nitrogen) to cool the material or tool.

In this paper, cryogenic cutting was achieved by applying a cooling spray in the cutting area before machining. In the experiments, a commercially available freezing spray was used. This spray is a specialized product that is used to apply very low temperatures (to about -45 °C or -55 °C) for various practical applications (more



often for assembling/disassembling metal parts or for technical repairs).

The results obtained in this study show that some machining parameters can be improved when using a cryogenic machining environment with a temperature of approximately $-30\text{ }^{\circ}\text{C}$, and by using more economically available solutions. By applying the cryogenic cutting medium, according to the specifications in the paper, shorter, more fragmented, and more contorted chips were obtained compared to those obtained by dry cutting. This may be the result of a clear embrittlement effect of the material, which leads to faster chip breakage.

Also, the roughness of the surface was better in the case of cryogenic cutting compared to dry cutting. This may be the result of the reduction of thermal deformations due to low temperatures and the increase in material hardness under the impact of the cryogenic environment.

Even if, turning in a cryogenic environment resulted in slightly higher cutting forces (with approximately 0.33 to 3.12% than the dry turning), overall, the machining performance was improved.

The experimental results suggest that hard turning can become more efficient by using cryogenic cooling environment with relatively higher temperatures than classical cryogenic cooling ($-150\text{ }^{\circ}\text{C}$), such as $-30\text{ }^{\circ}\text{C}$, which can address a series of challenges for the machining industry. Applying a cryogenic environment at less extreme temperatures can increase the performance of the machining process, resulting in more fragmented chips and better surface roughness, while the operational costs are significant, as the higher temperature cryogenic cooling equipment is less expensive and easier to implement in comparison. This would represent a cost-effective solution for the manufacturing industry, especially for applications involving hard materials, as both process performance and profitability can be achieved.

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STUDII EXPERIMENTALE PRIVIND APLICAREA RĂCIRII CRIOGENICE ÎNAINTE DE STRUNJIREA DURĂ A OȚELULUI 100CR6 (AISI 52100)

Strunjirea materialelor dure este considerată un procedeu de prelucrare de finisare viabil care poate înlocui procesul de rectificare și poate asigura o serie de avantaje, cum ar fi reducerea costurilor de prelucrare, productivitate crescută și o textură îmbunătățită a suprafețelor prelucrate. Un plan de experimente factorial a fost utilizată pentru a analiza corelația dintre factorii de intrare - mediul de așchiere (uscat și criogenic), viteza de așchiere și avansul de lucru și parametrii de interes precum forțele de așchiere și calitatea suprafețelor prelucrate. Materialul investigat este un oțel cu conținut ridicat de carbon, cu conținut scăzut de crom, utilizat în special pentru producția de rulmenți. Materialul a fost supus unui tratament termic pentru a obține o duritate a materialului de 61 ± 2 HRC. Studiul arată că strunjirea criogenică la o temperatură de aproximativ -30 °C îmbunătățește performanța procesului, rezultând așchii mai scurte și mai fragmentate ca urmare a efectului de fragilizare al materialului. De asemenea, rugozitatea suprafețelor obținute pentru suprafețele prelucrate a rezultat mai bună în cazul așchierii criogenice și, deși forțele de așchiere sunt puțin mai mari, performanța generală a procesului de prelucrare este îmbunătățită comparativ cu așchieria uscată.

Irina BEȘLIU, PhD Eng., Lecturer, 1 Mechanical and Technology Department, Stefan cel Mare University of Suceava, 13 Universitatii Street, Suceava 720229, Romania, irina.besliu@usm.ro

Ioan TAMAȘAG, PhD Eng., Assistant Lecturer, 1 Mechanical and Technology Department, Stefan cel Mare University of Suceava, 13 Universitatii Street, Suceava 720229, Romania, ioan.tamasag@usm.ro

Laurențiu SLĂTINEANU, PhD Professor, Eng., “Gheorghe Asachi” Technical University of Iași, Department of Machine Manufacturing Technology, Str. Prof. dr. doc. D. Mangeron nr. 59A, Iași, 700050 Romania, laurentiu.slatineanu@academic.tuiasi.ro