THE EFFECT OF CRYOGENIC HEAT-TREATMENT ON CUTTING FORCE AND TOOL WEAR DURING FLANK MILLING

GABOR KONYA, ANDOR MODRA, JANOS LISKA

Department of Innovative Vehicles and Materials, GAMF Faculty of Engineering and Computer Science, John von Neumann University, H-6000 Kecskemet, Izsaki St. 10., Hungary

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konya.gabor@nje.hu

In machining technology, increasing tool life is crucial for reducing manufacturing costs. One possible method to extend tool life is cryogenic heat treatment, which can improve the wear resistance of cutting tools. This publication investigates the effect of soaking time in liquid nitrogen (8, 16, and 24 hours) and tempering temperature (200 and 550 °C) on the hardness and run-out of the tool material. The highest hardness (716.12 *HV*) and lowest run-out (6.606 µm) were measured in the tool blank soaked for 24 hours and then tempered at 550 °C. Therefore, tools manufactured from this heat-treated material were used for the machining tests. During the machining tests, tools were compared under identical cutting times and varying cutting speeds (20, 25, and 30 m/min) in face milling operations with emulsion cooling. The comparison focused on the F_{xy} resultant cutting force and flank wear measured using untreated and cryogenically treated tools. At a cutting speed of 30 m/min, the cryogenically treated tool experienced catastrophic wear. At a cutting speed of 25 m/min, the cryogenically treated tool achieved nearly 10% lower flank wear and almost 50% lower resultant cutting force (Fxy) compared to the untreated tool.

KEYWORDS

cryogenic heat-treatment, HSS, milling, cutting force, tool wear, run-out of tool

1 INTRODUCTION

Increasing tool life is a key factor in machining technology. There are several approaches to achieve this, such as optimizing technological parameters [Kun 2019], using harder and more wear-resistant tool materials or tool coatings [Sousa 2021, Zhang 2024], optimizing tool geometry to match the workpiece material [Liu 2021], developing cooling-lubricating processes [Kónya 2024a, Kónya 2024b] and finally, applying cryogenic heat treatment to the tool materials [Dogra 2011, Chinnasamy 2022]. Cryogenic heat treatment is a type of low-temperature thermal process in which the samples are cooled under controlled conditions down to as low as -193 °C, depending on the applied coolant [Gu 2014, Firouzdor 2008]. The material is held at this temperature for a specified duration, then gradually brought back to room temperature in a controlled manner, followed by tempering at a defined temperature and duration to relieve internal stresses [Altas 2021]. The two most used coolants are liquid carbon dioxide and liquid nitrogen [Sert 2019], as they are the most cost-effective and widely applicable liquefied gases in industrial environments. Based on the temperature of the cooling gases, the literature distinguishes between deep cryogenic cooling and shallow cryogenic cooling. Arun et al. investigated the effects of these two types of cryogenic cooling technologies on thrust force, surface roughness, burr height, and hole cylindricity error during the drilling of austenitic stainless steel using tungsten carbide twist drills. In cases involving a higher number of holes, deep cryogenic cooling showed clear advantages in all the evaluated parameters, which the authors attributed to the increased hardness achieved through this method [Arun 2018].

Through cryogenic treatment, retained austenite—formed during conventional heat treatment—is transformed into martensite, and the distribution of carbides in the microstructure is improved. As a result, certain properties of the cutting tools are enhanced, including wear resistance, hardness, toughness, and electrical conductivity. Consequently, the tool life of cutting tools increases, tool wear and cutting forces are reduced, and surface roughness is improved [KALSI 2014, Çiçek 2012]. Firouzdor et al. investigated the wear behavior of untreated, cryogenically treated, and cryogenically treated and tempered M2 HSS drills during the drilling of normalized CK40 carbon steel under identical technological parameters. Compared to the untreated tool, a significant reduction in flank wear was observed for both treated tools. Furthermore, nearly a 50% reduction in flank wear was noted in favor of the tempered tool compared to the non-tempered cryogenically treated tool [Firouzdor 2008].

The cryogenic heat treatment process consists of four main stages: slow cooling to a predetermined temperature, soaking for a specified duration, slow heating back to room temperature, followed by tempering at a defined temperature and time. There is no clear consensus regarding the exact temperature and time parameters required for these stages. According to Kumar et al., the deep cryogenic treatment (below -145 °C) has been shown to provide greater benefits to tool performance compared to shallow cryogenic treatment (above -145 °C) [Kumar 2017].

Regarding the cooling rate, there are two methods: one involves slowly cooling the workpiece down to the soaking temperature, while the other involves quenching it rapidly. The disadvantage of the latter is that the rapid cooling can lead to the formation of microcracks in the material of the workpiece [Kalsi 2014, Gill 2010]. The major advantage of rapid cooling is that it can significantly reduce manufacturing costs, as the time required for the cryogenic heat treatment is considerably shortened [Reitz 2001].

The correct selection of soaking time also significantly influences the effectiveness of the heat treatment, as this is the period during which the retained austenite transforms into martensite, and a fine-grained microstructure is formed. Shirbhate et al. investigated the effect of 8, 16, and 24-hour soaking times on the performance of drills made from M2 high-speed steel (HSS). Their results showed that the 24-hour soaking time was the most favorable [Shirbhate 2012]. Singh and Zaidi opted for an 18-hour soaking time for the heat treatment [Singh 2020]. Arunram et al. found that during drilling with M2 HSS drills, the tool treated with a 30-hour soaking time exhibited the least wear [Arunram 2021].

Tempering is a crucial final step in the cryogenic heat treatment process, as it helps reduce the internal stresses within the tool. Singh and Zaidi performed tempering at 150 °C for nearly 9 hours [Singh 2020]. Arunram et al. did not temper the tools [Arunram 2021]. In general, the tempering duration ranges from 1–2 hours up to 6 hours [Klug 2020a, Klug 2020b, Kumar 2020], and the tempering temperature typically varies between

150 °C and 600 °C, although in some cases, a temperature as high as 1500 °C has been used [Klug 2020b, Dalwe 2021].

In the present publication, the first step involved investigating the effects of soaking time (8, 16, and 24 hours) and tempering temperature (200 °C and 550 °C) during cryogenic heat treatment on the hardness and run-out of the cutting tool preform. No relevant data on the latter factor can be found in the existing literature; however, it is a critical parameter in machining, as it influences vibration phenomena and, consequently, tool life.

In the second phase, flank milling experiments have been carried out using the tool that exhibited the highest hardness and relatively lowest distortion, as well as with an untreated tool. The tests have been conducted at cutting speeds of 20, 25, and 30 m/min for the same machining duration, with the aim of identifying the optimal combination of tool condition and cutting speed that yields the lowest cutting force and flank wear. This study provides valuable insights into the effects of cryogenic heat treatment parameters and machining parameters on cutting force and flank wear.

2 MATERIALS AND METHODS

In the present section, the cryogenically treated cutting tool material, the cryogenic heat treatment process, the measurement methods, the experimental setup, and the machined workpiece material are presented.

2.1 Cutting tool material

For the experiments, high-speed steel tools of M2 grade were used. M2 high-speed steel is characterized by good hardenability, excellent wear resistance, and good toughness. These properties are attributed to its martensitic structure with high thermal stability, reinforced by chromium, molybdenum, tungsten, and vanadium carbides [Fantineli 2020]. The chemical composition was determined using a FOUNDRY-MASTER PRO type spectrometer. The measurement was taken in 5 times, the average values of chemical composition are illustrated in Table 1. Before cryogenic heat treatment, the tool preforms were cut to size, and the cutting tool geometry was subsequently machined onto the preforms after the cryogenic treatment.

Fe (%)	C (%)	Mo (%)	Cr (%)	V (%)	W (%)	Ni (%)	Co (%)
80.32	0.97	4.57	4.1	2.07	6.37	0.25	0.38

Table 1. The chemical composition of M2 HSS tool material

2.2 Procedure of cryogenic heat-treatment

Based on the results of literature research, it can be stated that there is no clear consensus regarding the optimal duration for soaking tool materials in liquid nitrogen, nor the appropriate temperature for subsequent tempering. Therefore, as a first step, the investigation focused on how these factors influence the hardness of the tool material. The experimental design is shown in Table 1. During the liquid nitrogen soaking, the test specimens were positioned in a vertical orientation, whereas during the tempering, they were placed in a horizontal orientation. The tempering time was 2 hours.

Soaking time, *t* (h)	Tempering temperature, T (°C)
8	200
16	200
24	200
8	550
16	550
24	550

Table 2. Soaking time and tempering temperature of HSS cutting tools during cryogenic heat-treatment

2.3 Run-out, hardness and tool wear measurement

Heat treatment processes often result in warping, which can significantly affect the runout of cutting tools. During machining operations, it is crucial to minimize tool runout, as it induces vibrations that can greatly reduce tool life. Therefore, it is necessary to measure and compare the runout of untreated and heat-treated tools. For run-out measurements, a Mitutoyo Roundtest RA-1500 roundness measuring instrument was used.

An increase in hardness is expected as a result of cryogenic treatment; to measure this, a Wolpert Diatronic 2RC hardness tester was employed. Hardness was measured five times on each sample: one measurement was taken at the center of the sample, and the remaining four were taken along the edges at 90° intervals. This way, the variation in hardness provides a good representation of the homogeneity of the resulting microstructure.

For measuring flank wear after the machining tests, an Axio Imager M2m microscope was used. Flank wear was measured at three positions along each cutting edge, resulting in a total of 12 measurements per tool. The average flank wear, along with the standard deviation, was later presented based on these values.

2.4 Experimental setup

The cutting tests were performed on an NCT Eml-850D CNC machine centre. Cutting force measurements were conducted using a KISTLER 9257B three-component dynamometer in combination with a KISTLER 5007 analog charge amplifier. The measurement uncertainty was ±5 N. Data acquisition was managed with DynoWare® software (version 3.2.5.0), and the subsequent data analysis was carried out using OriginPro® 2021 software. The sampling frequency was set so that one measurement was recorded for every 3° of tool rotation. Subsequently, a median filter was applied to the raw force measurement data. The experimental setup is illustrated in Figure 1.

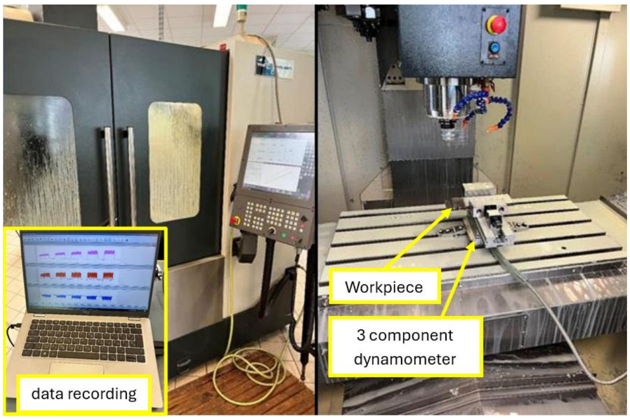


Figure 1. The experimental setup

The machining time was 5 min each tools. The machining length was 85 mm in 1 pass. During the flank milling, the cutting speed was the variable parameter, with values of v_c = 20, 25, and 30 m/min. The effect of all three cutting speeds was investigated in terms of cutting force and tool wear for both treated and untreated tools. All other machining parameters were kept constant: the feed per tooth was f_z = 0.02 mm, the axial depth of cut was a_p = 8 mm, the radial depth of cut was a_e = 0.8 mm, which corresponds to 10% of the tool diameter. During the experiments, down milling was used, as it is more favorable than up milling for this specific workpiece material–tool material combination due to the chip formation mechanism [Masek 2019]. For these difficult-to-machine materials, it has been found that down milling results in lower cutting forces, reduced tool wear, and lower cutting temperatures [Hadi 2013] [Kaltenbrunner 2022].

Flood cooling was applied during the machining process. For the emulsion, MOL Emolin 120, a biostable, semi-synthetic coolant, was used with a 9% oil concentration. This concentration was chosen based on previous experiments, which showed that a higher oil content in the emulsion is more favorable when machining difficult-to-cut materials [Kónya 2025].

During the experiments, 8 mm diameter, 4-flute tools without corner protection were used. Figure 2 shows the untreated and cryogenically heat-treated tools.

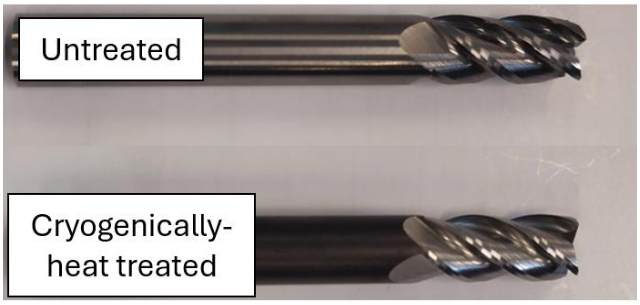


Figure 2. Untreated and cryogenically heat-treated cutting tools

2.5 Machined material

The material selected for machining was 1.4306 austenitic stainless steel, which is well-suited for cutting tests due to its reputation as a difficult-to-machine material, attributed to its high strength and low thermal conductivity [Kónya 2024c]. The chemical composition, mechanical and physical properties of the material is shown in Table 3 and Table 4.

Fe (%)	C (%)	Si (%)	Mn (%)	Cr (%)	Ni (%)	Co (%)	Cu (%)
71.2	0.03	0.12	1.38	17.9	8.00	0.11	0.48

Table 3. The chemical composition of 1.4306 [Kónya 2024c]

Tensile strength, R_m (MPa)	Elongation, A_5 (%)	Hardness, *HB*	Thermal conductivity, λ (W/m·K)
629	42	218	15

Table 4. The mechanical and physical properties of 1.4306 [Kónya 2024c]

3 RESULTS

The first part of this section presents the investigation of the effects of cryogenic heat treatment parameters on the hardness and run-out of the tool blank. The second part focuses on the impact of cutting speed and tool condition (untreated and treated) on cutting force and tool wear.

3.1 Hardness of cutting tool material

The variation of HV hardness of the tool preforms as a function of soaking time and tempering temperature is illustrated in Figure 3.

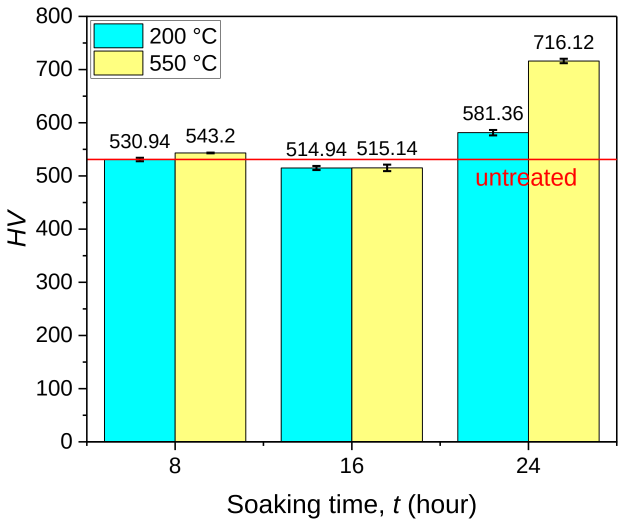


Figure 3. The effect of soaking time and tempering temperature on HV hardness

It is evident that soaking time exerts the most significant influence on the hardness of the tool preforms. At soaking durations of 8 and 16 hours, no substantial difference in hardness was observed compared to the untreated preforms; in fact, a slight decrease in hardness was detected following 16 hours of heat treatment. This indicates that the retained austenite did not transform into martensite, and carbide precipitation did not occur. In contrast, a soaking time of 24 hours proved sufficient to promote both the transformation of retained austenite into martensite and the precipitation of carbides. Furthermore, the tempering temperature of 550 °C promoted the precipitation of chromium carbides, as well as vanadium and tungsten carbides, which play a significant role in increasing the hardness. At a soaking time of 24 hours and a tempering temperature of 550 °C, a 26% increase in hardness was achieved relative to the untreated condition. Fantineli and colleagues also concluded in their research that cryogenic heat treatment increases the hardness of M2 HSS, reduces its variability, and improves its toughness and abrasive wear resistance [Fantineli 2020]. The study conducted by Gill and colleagues also showed an approximately 10% increase in hardness between conventionally quenched and tempered and deep cryogenically treated specimens. The wear resistance was also higher in the specimens that underwent deep cryogenic heat treatment [Gill 2012]. Xu and colleagues have pointed out in their research that a tempering temperature of at least 350 °C is required to initiate carbide precipitation. The maximum level of carbide precipitation was achieved at a tempering temperature of 550 °C [Xu 2022].

3.2 Run-out of blank

The effects of cryogenic heat treatment on the run-out error of tool preforms have not yet been investigated. However, tool runout has a significant impact on cutting forces, tool wear, and the integrity of the machined surface [Aldo 2017] [Chen 2022]. The run-out of the tool preforms as a function of soaking time and tempering temperature is presented in Figure 4. In general, it can be stated that higher tempering temperatures have a more favorable effect on reducing run-out deviation due to their more effective stress-relieving impact. Nevertheless, in all cases, the run-out values remained higher than that of the untreated tool. The run-out measured for the untreated tool, 3.71 mm, is considered fully acceptable under industrial conditions. In comparison, the run-out of the tool soaked for 24 hours and tempered at 550 °C deteriorated by 78%. In all other cases, an even greater deterioration in run-out was observed.

Taking into account both the run-out and hardness data, it can be concluded that the best overall results were achieved with the tool preforms treated with a 24-hour soaking time and a tempering temperature of 550 °C. Therefore, the cutting edge geometries for further experiments were manufactured using tool preforms improved by this specific heat treatment process.

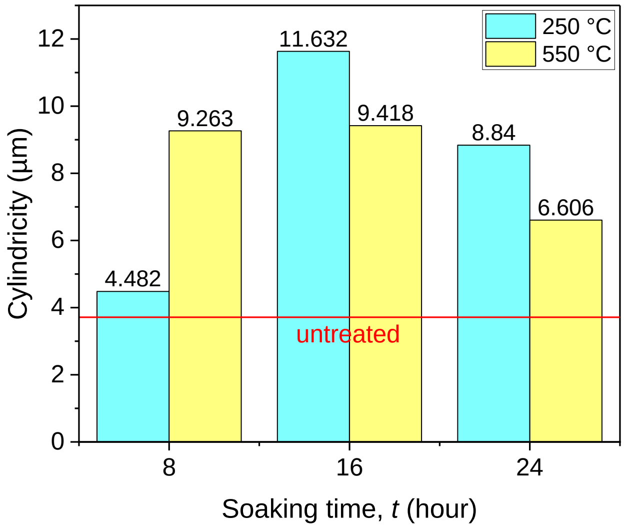


Figure 4. The effect of soaking time and temperature on run-out of blanks

3.3 Cutting force

The literature does not contain information comparing the cutting forces and tool wear of cryogenically and non-cryogenically treated high-speed steel tools under varying cutting parameters in case of milling. The typical research approach found in the relevant literature focuses on investigating the effects of cryogenic treatment parameters on tool life, cutting force, and surface roughness under identical cutting conditions. Consequently, the comparative investigations discussed below provide novel and original results. The F_{xy} resultant cutting force as a function of machining time for both untreated and treated tools at cutting speeds of 20, 25, and 30 m/min is presented in Figure 5, Figure 6, and Figure 7, respectively.

At cutting speeds of 20 and 25 m/min, lower F_{xy} cutting forces were measured during machining with the treated tool compared to machining with the untreated tool. In the literature, this phenomenon is often attributed to the improvement in surface roughness after cryogenic treatment, which leads to a reduction in the coefficient of friction [Gogte 2014]. This can result in lower cutting forces compared to untreated tools. However, in this case, the tool geometry was formed after cryogenic treatment on the tool preform. The reduction in cutting forces can be explained by the sharpness of the tool edge. Although at a cutting speed of 30 m/min the treated tool exhibited greater flank wear than the untreated one — which would normally contribute to an increased cutting edge radius — the untreated tool showed significant built-up edge formation, which also increased the cutting edge radius and thereby contributed to higher cutting forces. A similar trend was observed at a cutting speed of 25 m/min, with the difference that the treated tool showed even lower flank wear, resulting in a less pronounced rounding of the cutting edge. During the turning of SS304 using cryogenically and non-cryogenically treated tools, Pradeep and colleagues found that, at any spindle speed, the cutting forces and tool wear were lower when cryogenically treated tools were used. They attributed this to the reduced friction associated with cryogenic treatment [Pradeep 2016].

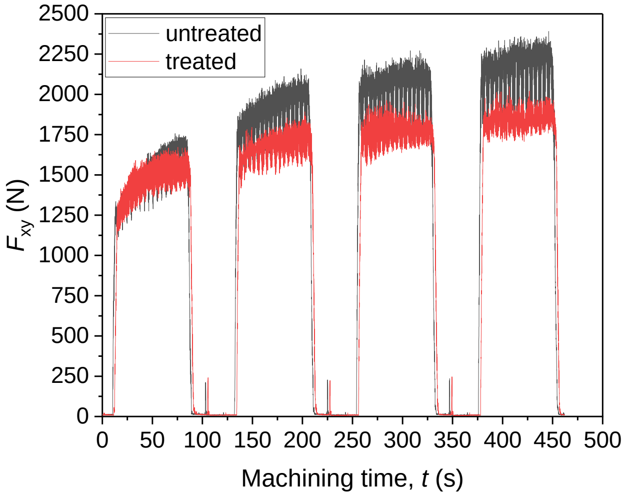


Figure 5. Cutting force as a function of machining time in case of 20 m/min cutting speed

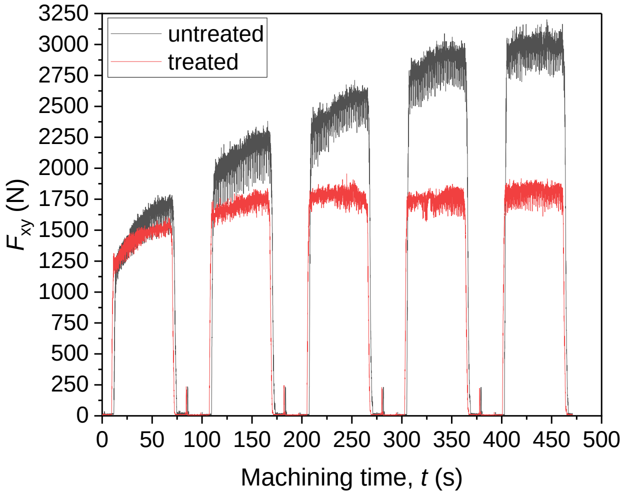


Figure 6. Cutting force as a function of machining time in case of 25 m/min cutting speed

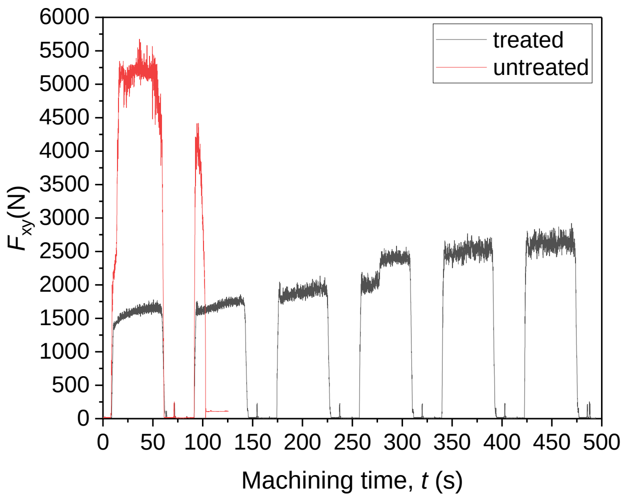


Figure 7. Cutting force as a function of machining time in case of 30 m/min cutting speed

During machining at a cutting speed of 30 m/min, however, the opposite behavior was observed: the cutting force measured with the treated tool was more than three times higher than that measured with the untreated tool. This can be attributed to the catastrophic tool failure visible in Figure 11. As can also be seen from the force signal, the tool could not withstand the targeted 5-minute machining time and failed completely after approximately 1 minute of cutting.

3.4 Tool wear

The numerical comparison of flank wear for treated and untreated tools as a function of cutting speed is presented in Figure 8, while microscopic images of tool wear at cutting speeds of 20, 25, and 30 m/min are shown in Figure 9, Figure 10, and Figure 11, respectively. It can be observed that the lowest tool wear was measured on the tool used at a cutting speed of 20 m/min, followed by those used at 25 m/min and 30 m/min. It is evident that flank wear increases with increasing cutting speed. In general, untreated tools exhibited lower flank wear compared to treated ones, which may be attributed to the reduced toughness of the tool material resulting from increased hardness. As a result, the cutting edge becomes less capable of withstanding the dynamic loads occurring during the initial engagement with the material. An exception to this trend is observed at a cutting speed of 25 m/min, where the treated tool showed 7% less wear than the untreated tool. This can be explained by the rise in cutting temperature at higher cutting speeds, which, although not yet adversely affecting the tool material, contributed to the softening of the cutting zone, thereby facilitating chip formation. Although the flank wear measured at this cutting speed is more than 8% higher for the treated tool compared to the flank wear measured at 20 m/min, the material removal rate increased by 25%, which significantly enhances productivity. For the untreated tool, flank wear increased by more than 34% when the cutting speed was raised from 20 m/min to 25 m/min. During the turning of C45 steel at a cutting speed of 25 m/min using M2 high-speed steel, Piesko and colleagues achieved an approximate 10% increase in tool life when using cryogenically treated tools [Piesko 2024].

At a cutting speed of 20 m/min, only flank wear can be observed on the tools, accompanied by minimal built-up edge formation, which is a completely normal phenomenon when machining these materials with uncoated tools. At a cutting speed of 25 m/min, flank wear remains the dominant wear mechanism, although minimal edge chipping can also be observed on the untreated tool. In contrast, at a cutting speed of 30 m/min, significant wear and tool failure can be observed. On the untreated tool, pronounced flank wear is visible, along with built-up edge formation and edge chipping. Additionally, severe corner breakage occurred. For the treated tool, the cutting edge is almost completely worn away, and the extent of flank wear is immeasurable. This is attributed to the higher cutting speed, which subjected the tool to greater mechanical and thermal loads that it could not withstand due to the brittleness of the material. This excessive wear also explains the high cutting forces observed in Figure 7, and it is the reason why the tool failed to endure the targeted cutting time of 5 minutes.

Considering the above results, a cutting speed of 20 m/min is recommended for untreated tools, while for cryogenically treated tools, a cutting speed of 25 m/min is advisable. This is because, although the magnitude of flank wear is only 8% higher compared to that measured at 20 m/min for the same cutting time, productivity increases by 25% compared to the values observed at 20 m/min.

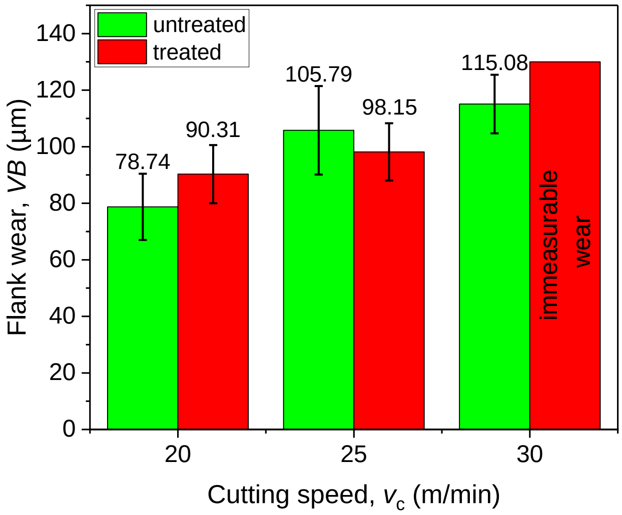
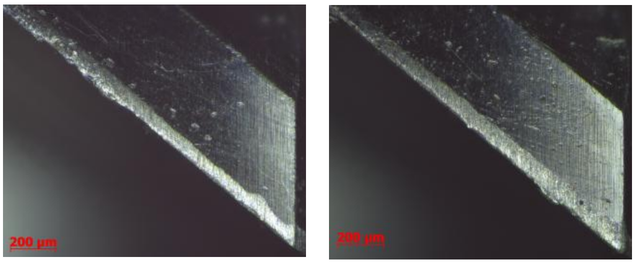
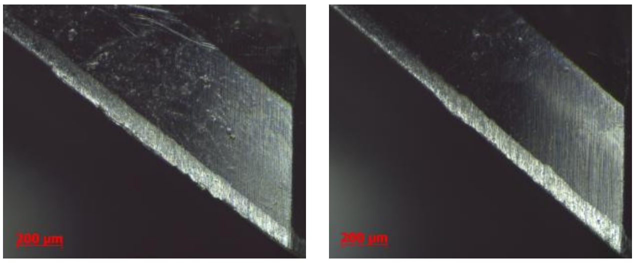


Figure 8. Flank wear as a function of cutting speed in case of untreated and treated tools



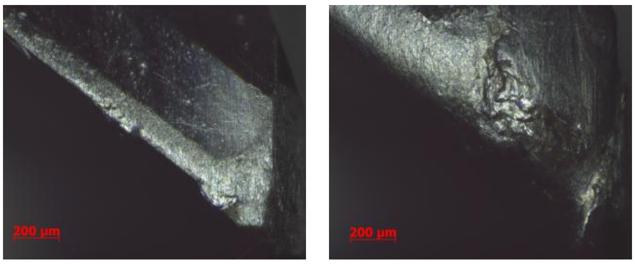
a) b)

Figure 9. Tool wear of a) untreated and b) treated tools under 20 m/min cutting speed



a) b)

Figure 10. Tool wear of a) untreated and b) treated tools under 25 m/min cutting speed



a) b)

Figure 11. Tool wear of a) untreated and b) treated tools under 30 m/min cutting speed

4 CONCLUSIONS

In the present publication, the effect of soaking time and tempering temperature during cryogenic heat treatment on the hardness and run-out of M2 grade HSS tool preforms was investigated. Subsequently, comparative machining tests were carried out to evaluate the influence of untreated and treated tools on cutting forces and tool wear at different cutting speeds. Based on the results, the authors have drawn the following conclusions:

- The highest hardness, along with a relatively low roundness error, was achieved by applying cryogenic heat treatment with a soaking time of 24 hours and a tempering temperature of 550 °C.

- The lowest cutting force was achieved during machining at a cutting speed of 25 m/min using the treated tool, due to the absence of built-up edge and the relatively low flank wear, which resulted in minimal cutting edge rounding.

- The lowest flank wear was measured after machining at a cutting speed of 20 m/min using the untreated tool.

- At a cutting speed of 25 m/min, the flank wear of the treated tool is more than 7% lower than that of the untreated tool. However, compared to the treated tool used at a cutting speed of 20 m/min, the flank wear is 8% higher, while productivity increased by 25%.

Based on the results obtained from the present study, future research will aim to investigate the performance differences between cryogenically treated tools, coated tools with different types of tool coatings, and tools that are both cryogenically treated and coated during flank milling of stainless steels.

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CONTACTS:

Gabor Konya, **assistant lecturer**
Department of Innovative Vehicles and Materials, GAMF Faculty of Engineering and Computer Science, John von Neumann University
Izsaki St. 10., Kecskemet, 6000, Hungary
konya.gabor@nje.hu