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Characterization of tool wear when machining Alloy 718 with high pressure cooling using conventional and surface-modified WC–Co tools

Coolant supplied by high pressure into the cutting zone has shown the lower thermal loads on the tool when machining difficult-to-cut materials as the Alloy 718. In this study, we investigate how the combination of high-pressure cooling and tool-surface modifications can lead to further improvements regarding tool life. The general approach is to enhance the coolant-tool interaction by increasing the contact area. Therefore, we machined cooling features into flank and rake faces of commercially available cemented tungsten carbide inserts. In this way, the surface area was increased by ~ 12 %. After the cutting tests, the tools were analyzed by scanning electron microscopy combined with energy-dispersive X-ray spectroscopy. Compared with conventional tools, the tool modifications reduced the flank wear by 45 % for the investigated cutting parameters. Furthermore, we were able to significantly increase the cutting speed and feed rate without failure of the tool. The investigated surface modifications have great potential to enhance the productivity of metal cutting processes.

***Keywords**: superalloy, high pressure jet assisted machining, tool modification, wear characterization.*

INTRODUCTION

During machining of Ni-based superalloys, the cutting tools are subjected to high temperatures and stresses. The consequence is a rapid wear by the simultaneous actions of abrasive, adhesive, and diffusion wear. Therefore, cutting speed and feed rate are usually low, which leads to low overall productivity when these alloys are machined [1]. Productivity becomes especially relevant when considering that up to 80 % of an initial forging's volume is removed by machining before the final shape of the component is attained [2]. In this context, the development of new, more advanced alloys will further increase the challenges in metal cutting [3]. Given the importance of superalloys, it is of utmost importance to improve tool life in today's machining technologies in order to produce jet engine components in a more effective and economical way.

Traditionally, in order to lower the thermo-mechanical loads on the tool during the cutting operation, flood cooling is applied. However, the uncontrolled flooding of the chip top-side does not provide effective cooling of the cutting zone. The high temperatures cause the coolant to vaporize and the zones where highest temperatures occur are not reached and cooled [4]. One effective way to reduce cutting temperatures is directing high pressure jets precisely into the cutting zone. Thus, the coolant is able to reach closer to the cutting edge and forms a liquid wedge between chip and tool rake. Several studies have shown that this leads to better chip breakability, improved tool life, and the possibility to apply higher cutting speeds and feed rates [4–7]. For example, Krämer et al. [5] have investigated how an increased coolant supply pressure and flow rate influence the cutting tool temperature when Alloy 718 is turned. A temperature reduction up to 30 % for the highest pressure and flow rate was reported. As a consequence, the uniform flank wear was reduced up to 50 %. Hence, high pressure jet assisted machining shows great potential to increase process productivity and stability.

However, the required coolant supply pressures are often very high and need implementation of more powerful high pressure pumps. Alongside the initial investment for a new pump, additional energy consumption during production has to be taken into account. As shown by Klocke et al. [8], this additional energy outweighs under certain conditions the benefit gained from shorter machining times. It is therefore desirable to find ways to improve the productivity without increasing the energy input for higher coolant supply pressures. One possible way is the use of textured cutting tools. Several studies have shown that application of certain textures on rake and flank-side improves tool life when steel and aluminum were machined with conventional coolant supply pressures [9–11]. This was mainly attributed to the fact that the textures act as micro-reservoirs for cutting fluid, and thus increase the cooling and lubricating effect. As shown by N. Tamil Alagan et al. [12, 13], the combination of tool surface texturing and high pressure cooling is highly promising in achieving an increased heat dissipation from the cutting zone and improved the tool life.

This paper is a continuation of the previous work [13] regarding the initial cutting tests of Alloy 718 using surface-modified metal cutting inserts combined with high-pressure coolant supply. The influence of the tool modifications on the wear behavior is investigated. Focus is put on the flank wear behavior, which is often the most relevant tool-life criterion in production as it directly influences the dimensional accuracy of machined components.

EXPERIMENTAL

Materials

Alloy 718 (cast with average hardness of 381±21.8 H_V10) was used as a workpiece material as it is the most used Ni-based superalloy [14]. The material was supplied in the form of rings with an outer and inner diameter of 742 and 672 mm, respectively. The height was 22.30 mm. Uncoated cemented tungsten carbide inserts (RCMX 12 04 00 H13A) were used as tools in the conventional state and after surface modification. For the modification, on both rake and flank sides features were machined into the tool surface as seen in Fig. 1. In that way, the surface area was increased by about 12 % [13].

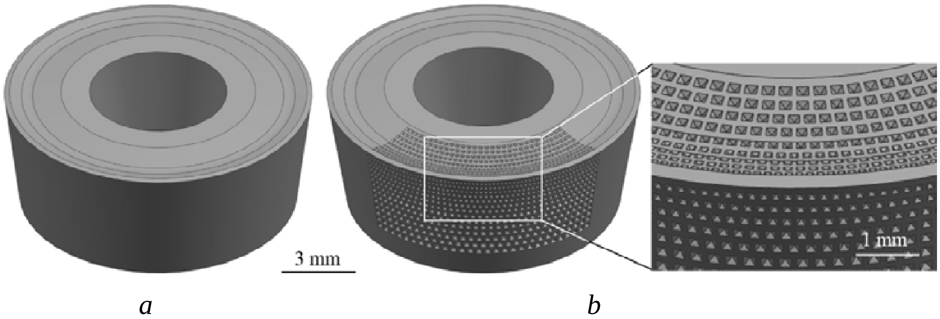


Fig. 1. Cutting tools used in this study: conventional (*a*), surface-modified with rake and flank patterns at higher magnification (*b*).

Turning tests

Experiments were conducted with a 5-axis CNC machine equipped with a high-pressure pump. Coolant (5 % emulsion) was supplied to both rake and flank faces. At the rake, three nozzles of orifice diameter 0.8 mm and a pressure of 160 bars were used, while at the flank two nozzles of orifice diameter 1.0 mm and a pressure of 80 bars were applied. The table below summarizes the three cutting tests. Two tests were done with the same cutting parameters but with and without the tool modifications. A third test was performed with twice the cutting speed and with tripled feed rate in order to push the tool towards its thermo-mechanical load limit. The cutting parameters in this test were the maximum cutting speed and feed rate, the surface-modified tool was able to withstand without immediate failure. The high wear rate in this test was the reason for decreasing the spiral cutting length. It is noteworthy that the conventional tool failed upon entering the workpiece at cutting speed and feed rate of 90 m/min and 0.1 mm/rev, respectively.

Summary of the investigated cutting conditions

Test abbreviations	Tool conditions	Cutting speed, m/min	Feed rate, mm/rev	Spiral cutting length (SCL), m	Machining time, min
A1	Conventional	60	0.1	~ 565	~ 9.4
A2	Surface-modified	60	0.1	~ 565	~ 9.4
B	Surface-modified	120	0.3	~ 70	~ 0.5

Note. Depth of cut was kept constant at a_p = 1 mm; coolant supply pressure to rake and flank were kept constant at 160 and 80 bars, respectively.

Removal of layers of adhering workpiece from flank

In order to analyze the wear patterns, the adhering layer of the Alloy 718 was etched away in 50 % HCl at 80 °C for 45 min. This was done with a conventional tool, which was used for the same machining conditions as in test A1.

Tool wear characterization

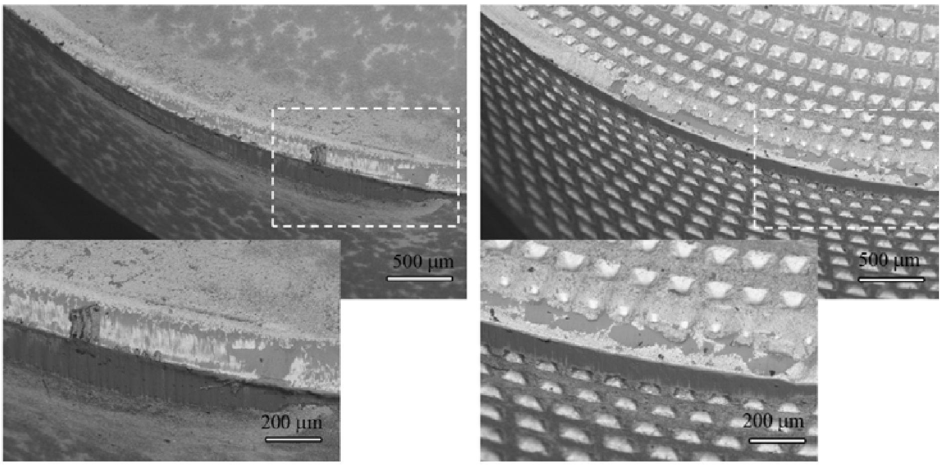
The resulting tool wear was characterized by LEO 1550 Gemini scanning electron microscope with field emission gun (FEG-SEM). Backscattered electrons

(BSE) and secondary electrons (SE) were used for imaging and energy dispersive X-ray spectroscopy (EDX) was applied for qualitative chemical analysis of the tool surfaces.

RESULTS AND DISCUSSION

Overview of cutting edge

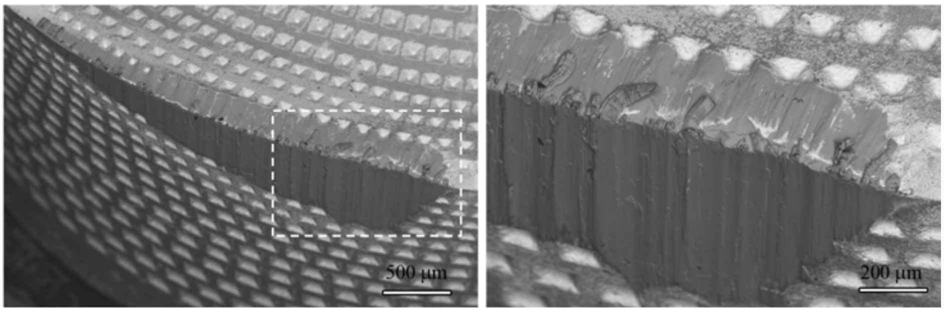
Figure 2 shows the cutting edges of (*a*) the conventional tool and (*b*) the surface-modified tool after machining 565 m spiral cutting length (tests A1 and A2). Neither of the tools shows signs of a crater wear on the rake side. Furthermore, no chipping or plastic deformation of the cutting edges occurred.



a *b*

Fig. 2. BSE images showing the appearance of the cutting edge after the tests with v_c = 60 m/min and f = 0.1 mm/rev with conventional insert (*a*) and surface-modified insert (*b*).

In Fig. 3 the cutting edge after test B is shown. The surface-modified tool was able to withstand higher cutting speeds and feed rates. Despite the fact that the applied cutting parameters were above the recommended values, no failure due to fracture or severe chipping occurred after 70 m of spiral cutting length. It is, however, difficult to assess changes in the geometry of the cutting edge since it is entirely covered by adhered workpiece material. Doubling the cutting speed and tripling the feed rate resulted in a much higher wear at lower spiral cutting length.



a *b*

Fig. 3. BSE images of the cutting edge of the surface-modified insert after test with v_c = 120 m/min and f = 0.3 mm/rev.

Flank wear characterization

With the used cutting conditions, the surface-modified tool showed a clear reduction of flank wear. Figure 4 shows SEM micrographs of the corresponding flank faces of the three tools used in the experiments. The BSE images are complemented by EDX elemental maps taken at the same location. The worn areas are easily distinguishable from the unworn areas by the adhered layers of Alloy 718 (dark zones in the BSE images and presence of Ni in the EDX maps). Adhered workpiece material can be found on all inserts, irrespective of the cutting parameters. After cutting of 565 m, the surface-modified tool (see Figs. 4, *c* and 4, *d*) shows a reduction of the maximum flank wear from 354 µm to 196 µm when compared with the conventional cutting tool (see Figs. 4, *a* and 4, *b*). Furthermore, the shape of the flank wear land has changed from non-uniform to uniform (*c*) with constant wear along the cutting edge. Figures 4, *e* and 4, *f* show the flank wear after machining with increased cutting speed and feed rate for about 70 m spiral cutting length (test B). The resulting flank wear is 990 µm.

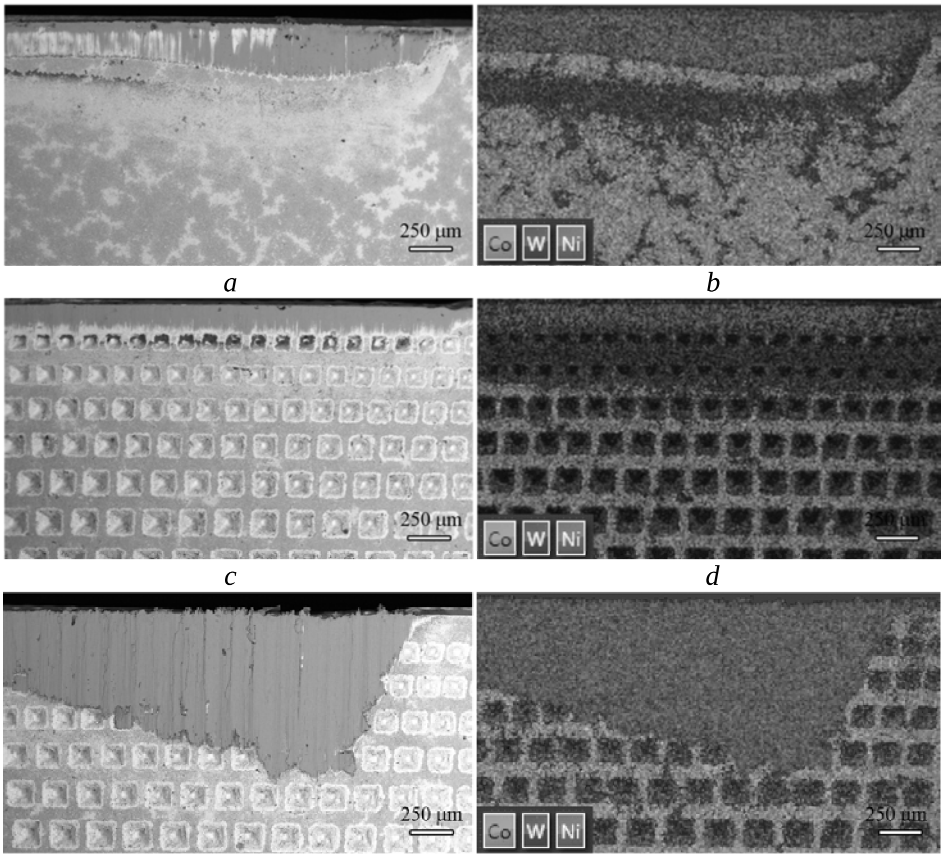
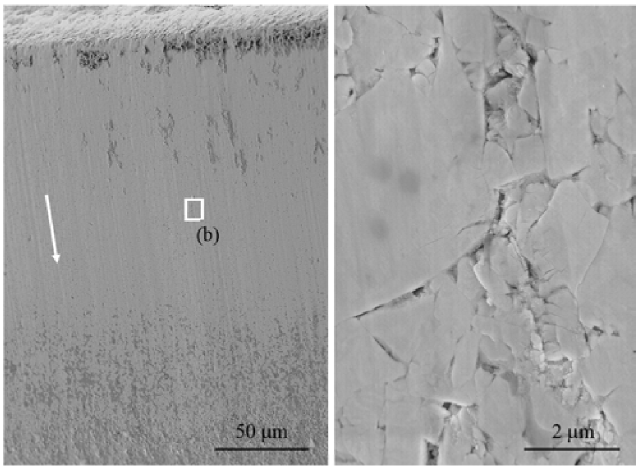


Fig. 4. BSE images of the tool flank faces in the region of VB_{max}: conventional tool after test A1 (*a*), surface modified tools after tests A2 (*c*) and B (*e*); the corresponding EDX maps are (*b, d, f*).

The reduction in flank wear and the ability to withstand higher cutting parameters can be attributed to more efficient cooling of the tool due to the larger tool-coolant contact area and the use of the high-pressure coolant jets. Several studies have shown that texturing of cutting tools on the rake and flank face results in reduction of cutting forces and wear [9, 10]. For milling of medium carbon steel, Sugihara et al. [9] investigated periodical arrangements of 5 µm deep grooves perpendicular to the chip/workpiece flow direction on the rake/flank of WC–Co cutting tools. They reported that without application of cutting fluid, only a slight reduction of wear was obtained, which was attributed to the reduced chip-tool contact area and the resulting decrease of friction. However, in presence of cutting fluid, the positive effect of the texturing was much more pronounced (up to 60 % reduction of crater depth on rake face and up to 30 % reduced maximum flank wear). The reason for this is the ability of the grooves to act as reservoirs for the coolant, which in turn increases the coolant's lubrication and cooling effects. In the present study, the increased cooling effect also enabled the tool to operate at higher cutting speed (test B) as thermal softening of the binder is suppressed, and the tool maintains its bulk strength up to higher cutting speeds.

Figure 5 shows the flank wear land of a tool after machining with the same parameters as used in test A1. Additionally, the adhering workpiece layer has been etched away. At low magnification, the worn area appears smooth with wear tracks parallel to workpiece movement (see arrow in Fig. 5, *a*). The higher magnified view of one of the wear tracks in Fig. 5, *b* shows cracks and fragmentation of individual WC grains. These wear tracks are probably caused by hard precipitates in Alloy 718, which cause abrasion while they slide along the WC–Co tool during machining.



a *b*

Fig. 5. SE images after removal of adhering workpiece layer from a tool tested at the parameters of test A1: overview of flank face with wear tracks parallel to workpiece movement (indicated by arrow) (*a*); wear track at higher magnification (*b*) (location indicated in (*a*)).

Below the flank wear lands, it can be seen that cobalt was removed from the cutting tool surfaces (see Fig. 4). During cutting, the tool in these areas is not in contact with the freshly generated workpiece surface. Nevertheless, all EDX maps show reduced cobalt signals just beneath the flank wear land when compared to the unaffected tool surface. This is especially pronounced for tools in Figs. 4, *d* and 4, *e*. In all cases, these zones stretch along the whole width of the flank wear. When investigating these zones at higher magnification (Fig. 6), it can be observed that the cobalt is missing at the surface of the tool, while the WC particles seem unaffected. For comparison, a new, unused tool is shown in Fig. 6 as well. The removal of cobalt from the tool surface is likely to be caused by the impingement of the high-pressure coolant jets during the cutting process. The relatively soft binder is eroded by the mechanical action of the jets. The erosive capability of water jets has been studied extensively. For example, Oka et al. [15] claimed that erosion is caused by water-droplet impingement on the substrate surface. They reported erosion damage of an Al alloy ($H_V = 71$) impinged by a pure water jet at 10 MPa (100 bar) supplied through a 0.4 mm orifice at distances of 30 to 500 mm from the specimen. With these studies in mind, it is likely that the conditions in the present investigation can cause erosion of the cobalt binder.

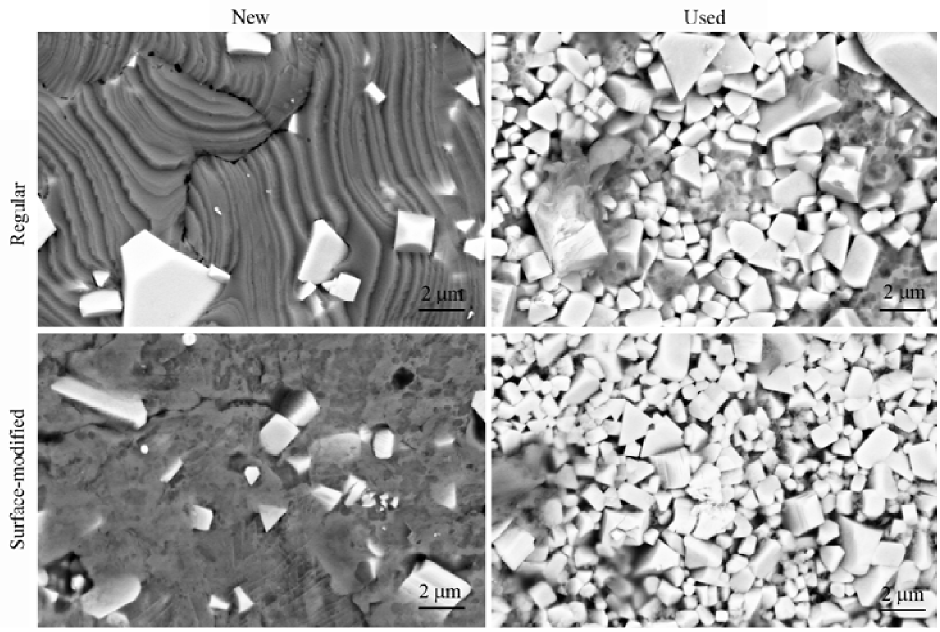
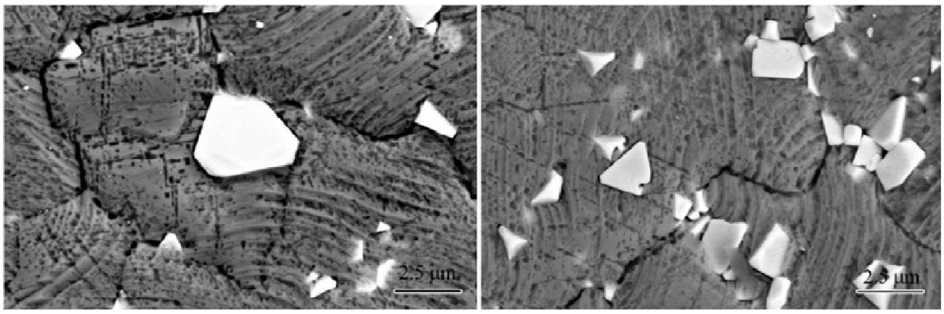


Fig. 6. BSE images of the tool flank face of conventional and surface modified tools in new, unused state (left) and after the machining tests with high pressure cooling (right), taken in the zone of depleted cobalt signal just below the flank wear land. The dark phase is the cobalt-binder and the bright particles are WC.

As a complement, a separate set of experiments was done in order to investigate the ability of the high-pressure coolant jets to erode the surface of the tools. Inserts of the conventional type without surface modifications were subjected to cooling at the same coolant supply pressures (160 bar rake cooling and 80 bar flank cooling) for 10 min without performing any machining. The test duration was set according to the machining times of tests A1 and A2. The resulting tool surfaces can be seen in Fig. 7. A clear difference in appearance can be observed when comparing the tool surface after erosion test with the unused conventional tool (see Fig. 6). The cobalt phase in the surface shows signs of erosion in the form of small pits. Nevertheless, the effect is not as pronounced as in the tools from the machining tests (right column in Fig. 6), where almost no cobalt phase remained at the surface.

To explain this difference, one has to bear in mind that during the cutting process heat is generated in the primary, secondary, and tertiary shearing zones. This heat partially dissipates into the tool, and the whole tool is subjected to elevated temperatures. As a direct consequence, the cobalt binder phase loses some of its strength, and is eroded more easily by the impact of the coolant jets. Figure 8 shows a range of reported hardness and tensile strength values of pure cobalt as a function of the temperature [16]. As can be seen, at room temperature cobalt has hardness in the range of 140 to 210 H_V and a tensile strength of 800 $\mathrm{MNm^{-2}}$. Both decrease steadily as temperature rises. At 500 °C, about half of the hardness and one third of the room temperature tensile strength is retained. However, the cobalt binder phase also contains some tungsten and carbon [17]. This is a consequence of WC dissolution into the liquid binder in the sintering step during production [18]. Hence, due to the solid solution strengthening, the cobalt binder phase is expected to have slightly higher hardness and tensile strength than provided in the graph in Fig. 8. Nevertheless, the coolant jets were able to erode the cobalt during machining.



a *b*

Fig. 7. Surface of the conventional tool after erosion test, i.e., after impact of the high-pressure coolant jets for 10 min without performing any machining: rake, 160 bar (*a*), flank, 80 bar (*b*).

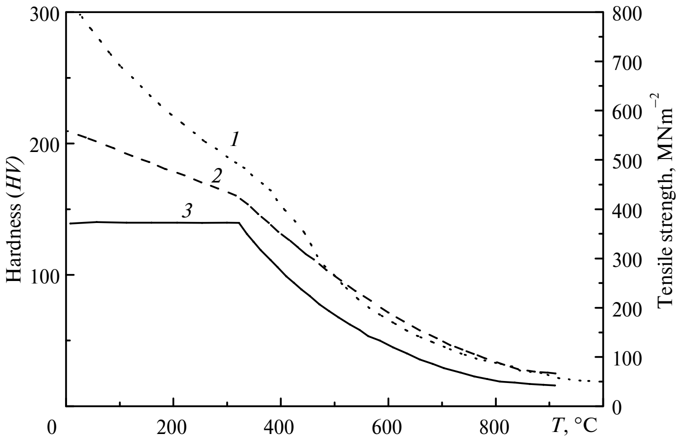


Fig. 8. Hardness and tensile strength of pure cobalt as a function of temperature; adapted from [16]: tensile strength (*1*), maximum (*2*) and minimum (*3*) hardness.

CONCLUSIONS

A combination of tool surface modifications with high-pressure coolant supply for machining of Alloy 718 has been investigated. The 12 % larger coolant–tool contact area leads to:

– 45 % reduced flank wear;

– possibility to operate tool at higher cutting speed and feed rate (120 m/min and 0.3 mm/rev, respectively) as compared to a conventional tool.

Furthermore, irrespectively of the tool type, the following observations were made:

– the adhesion of workpiece material to flank and rake wear lands;

– the removal of cobalt from tool surfaces due to erosion by the coolant jets during cutting.

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