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COMPARISON OF OPTIMIZED AND CONVENTIONAL COOLING WHEN TURNING STAINLESS STEEL

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Abstract

Stainless steels are materials whose consumption increases constantly. However, their machining can be problematic. A cutting tool is under higher mechanical and thermal stress than in the case of carbon steels, thereby rapid tool wear can occur. To avoid this, cutting speeds are often kept low, increasing tool life despite lower productivity. The application of cutting fluid has also a beneficial effect, nevertheless, it can be increased when coolant is supplied directly to the cutting edge. Optimized tools with internal channels allow directing fluid precisely there. The main aim of this paper is to compare tool wear when precision and conventional cooling systems are used. The surface roughness of turned specimens made of AISI 316 stainless steel was also recorded. Based on the findings, it can be noticed that the precision cooling system has a significant influence on tool wear and the cutting speed can be set higher. In other words, the productivity of machining is improved. What is more, tool wear is more predictable, and the cutting process is reliable.

Keywords: internal cooling; tool wear; surface roughness; turning; stainless steel

1. Introduction

Steel alloying is a way to improve its properties. As a result, material requirements such as strength, high-temperature properties, ductility, toughness, corrosion resistivity and others can be achieved. Stainless steels are highly alloyed iron-based materials where mainly chromium is added to provide corrosion resistivity. It makes them suitable in applications where long life, maintenance free and human health are crucial. Additional elements, particularly nickel, molybdenum and manganese, mainly promote structure changes and improve corrosion resistivity in specific environments and strength [1]. According to chemical composition, three main structures of stainless steels can be achieved – austenitic, ferritic, and martensitic, where the austenitic structure is the most used [2] [3]. During the last 15 years, stainless steel production increased about twice, creating requirements for efficient processing [3].

When machining, complex technological property of material named ‘machinability’ is plays significant role. It describes how is difficult to cut (machine) material and is used to determine cutting conditions (cutting speed v_c, feed rate f, depth of cut a_p). Nevertheless, it was observed that if steel corrosion resistivity increases, its machinability decreases [4]. In comparison with non-alloyed steels, there are several differences which cause decrease in machinability, thereby rapid tool wear and consequently lower productivity because of frequent insert changes and lower cutting conditions.

Firstly, thermal conductivity is about three times lower, causing high tool temperature and a rapid degradation process. In addition, thermal expansion is higher, so it is harder to maintain tight tolerance. Secondly, work-hardening phenomena occurs. It means that after deformation (e.g. machining), there is a thin surface layer, which is strengthened and hardened hence tool is more stressed in the next cut. Finally, high ductility decreases chip breakability and promotes formation of build-up edge (BUE) which can damage the machined surface after its break off [5]. Mentioned problems cause rapid tool wear, thus low cutting speeds are often used to maintain high tool life. The influence of cutting speeds on tool wear and surface roughness was explored by Korkut et al. when turning The American Iron and Steel Institute (AISI) 304 austenitic stainless steel. The experiment was carried out without cutting fluid and they optimized the cutting speed at 180 m/min where the lowest tool wear and surface roughness Ra was obtained [6].

Every machining process happens in some cutting environment usually in the form of neat oil, water-based fluid (emulsion), gas, or mist [7]. Cutting fluids are commonly used when machining steels with carbide tools. It is because machining is a process where most of the energy is transformed into heat [8]. Application of these fluids cools down the cutting zone, lowering tool wear. A lubrication effect is also required to decrease friction on the tool-chip and tool-workpiece interface. As a result, cutting forces, heat generation and tool wear are lower. Cutting fluids also help to accomplish better surface. Last but not least, fluids control BUE formation, wash away chips and protect a machine from rust [5].

Different cooling systems can be used to ensure the above-mentioned effects. Flood cooling is conventional. Cutting fluid flows through a nozzle outside the tool holder in large amounts, where a pipeline and flow rate are adjustable [9]. Fluid immerses a tool and workpiece in the cutting zone, absorbing generated heat. Conversely, modern tools are equipped with internal channels where a cutting fluid flows. An exit of these channels is designed in a clamp or insert holder body near the cutting zone, directing fluid precisely to both – the rake and flank face of an insert [10]. Furthermore, the usage of high pressure penetrates the interface between the rake face and the chip more effectively, which results in lower friction, tool temperatures, and better chip breaking [10]. In order to accomplish this, the machine must be equipped with high-pressure pump.

Naves et al. evaluated tool wear when turning AISI 316. High pressure (10, 15 and 20 MPa), dry turning and overhead cooling approaches were compared. The result is that high pressure cooling significantly reduces adhesion wear, by contrast, dry turning attained the highest flank wear [11]. Bleicher et al. investigated tool wear when turning P750 austenitic stainless steel with low cutting speeds. External cooling, internal cooling through the insert, and both external and internal cooling were used. It was concluded that combined external and internal cooling decreased tool wear the most [12]. Kostadin enquired about the difference between emulsion and chilled air cooling when machining martensitic stainless steel. The result was that there is no surface roughness difference between emulsion and chilled-air cooling. In addition, “the feed rate f has the greatest influence in reducing the surface roughness parameter Ra, followed by depth of cut a_p, cutting speed v_c and cooling method” [13]. Janda and Fulemova studied surface roughness when milling ferritic-martensitic stainless steel with external cooling. Six different tool materials were used (4 cemented carbides, and 2 cermets). Carbide tools showed lower tool wear, and surprisingly, surface roughness was better at lower cutting speeds [14].

This paper compares tool flank wear of tools when conventional flood and precision cooling strategies are used during turning experiments. In addition, the surface roughness parameter Ra was monitored. Turned material was AISI 316 austenitic stainless steel.

2. Materials and methods

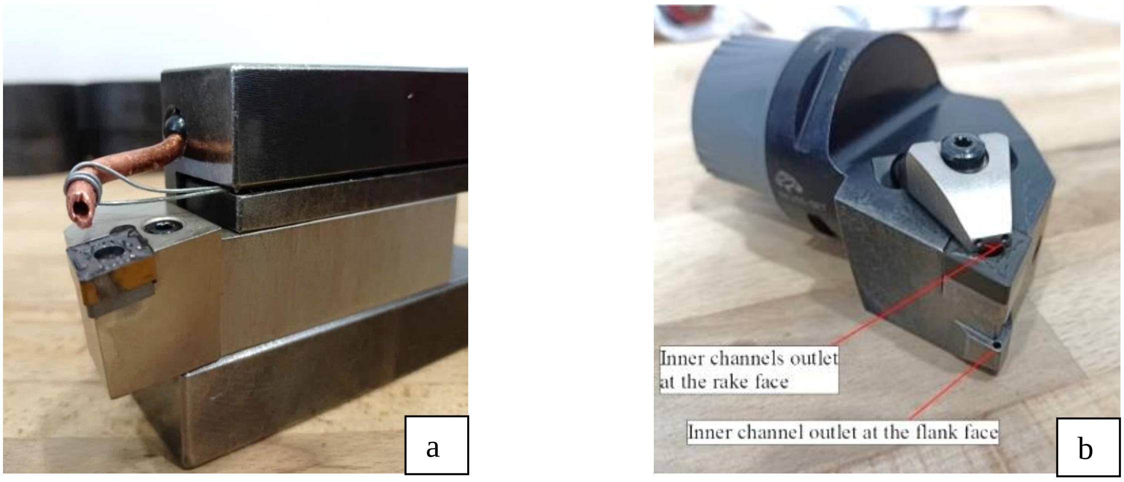

Fig. 1. a) Tool with conventional cooling b) Tool with precision cooling

The used specimens, round bars with an initial 200 mm diameter and 300 mm length of AISI 316 (for chemical composition see

Table 1) austenitic stainless steel were turned. The final machined length was 282 mm due to clamping with jaws.

[%]	Fe	Cr	Ni	Mo	Mn	Si	N	C	P	S
Min.	62	16	10	2	0	0	0	0	0	0
Max.	72	18	14	3	2	0,75	0,1	0,08	0,045	0,03

Table 1. Chemical composition of AISI 316 [15]

The experiments were conducted with the following cutting conditions:
- cutting speeds vc = 160; 250; 300 m/min
- feed rate f = 0.25 mm/rev
- depth of cut ap = 1.5 mm

The turning process was carried out using DMG MORI CTX BETA 1250 TC turn-milling machine with a maximum of the main spindle power of 32 kW . The 6% cutting emulsion was used at a maximum pressure of 40 MPa. The cemented carbide cutting inserts CNMG 120408E-NMR:T7325 with MT-CVD coating and negative rake were used. According to the manufacturer, the inserts are suitable for the versatile turning of stainless steel and interrupted cuts [16]. The surface roughness was measured with a SURTRONIC DUO tester. The flank wear of used inserts was analysed after every cut using a KEYENCE VHX-6000 digital microscope with 100× magnification. The ISO 3685 standard divides flank wear into four possibilities (Fig.2.) - VB_A (at tool corner), VB_{Bmax} (maximum flank wear)., VB_B (average flank wear), VB_C (notch wear) [17]. VB_B wear was measured.

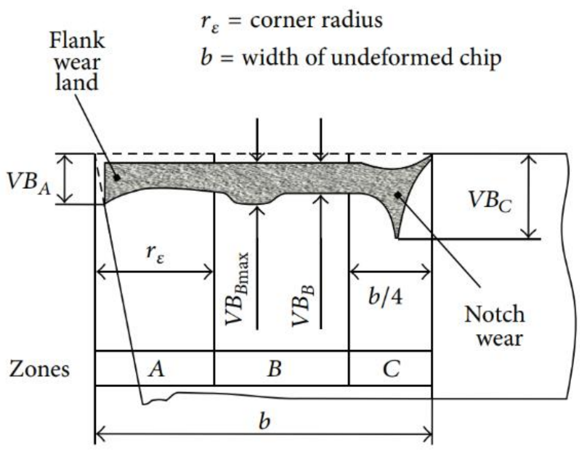

Fig. 2. Flank wear division [17] (adapted)

The development of flank wear progresses typically in three phases (Fig. 3). An initial wear increases rapidly due to the running-in of a new insert. Subsequently, a steady state occurs with a uniform rate. Finally, the failure region is characterised by accelerated wear [18].

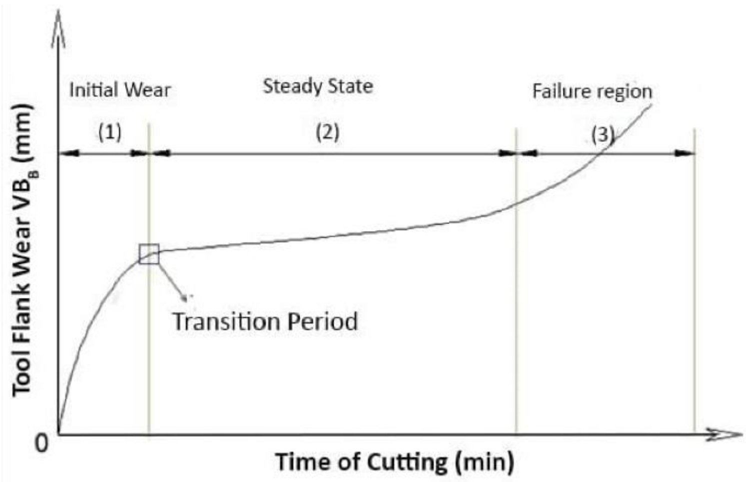

Fig. 3. Typical flank wear curve [18]

The experiment was stopped if one of these criteria came:

- Insert flank wear VBB is greater than VBcrit.= 0.4mm
- Insert failure
- Too low tool flank wear acceleration

3. Experimental results and discussion

3.1. Test 1: vc=160 m/min

The cutting speed v_c=160 m/min was defined according to the maximal recommended value by the insert manufacturer. Although criteria flank wear $VB_{BCRIT.}$ was not reached, the test was discontinued after 20 minutes of cut, due to low flank wear rate. It will not reach the criteria wear in a brief time if the test continues (Fig. 4.). The figures show that there was only a slight difference between flood and precision tool flank wear. Despite this, there was observed a significant difference in notch wear. Flood cooled tool showed a significant notch, whereas there was almost no notch at the precision cooled tool.

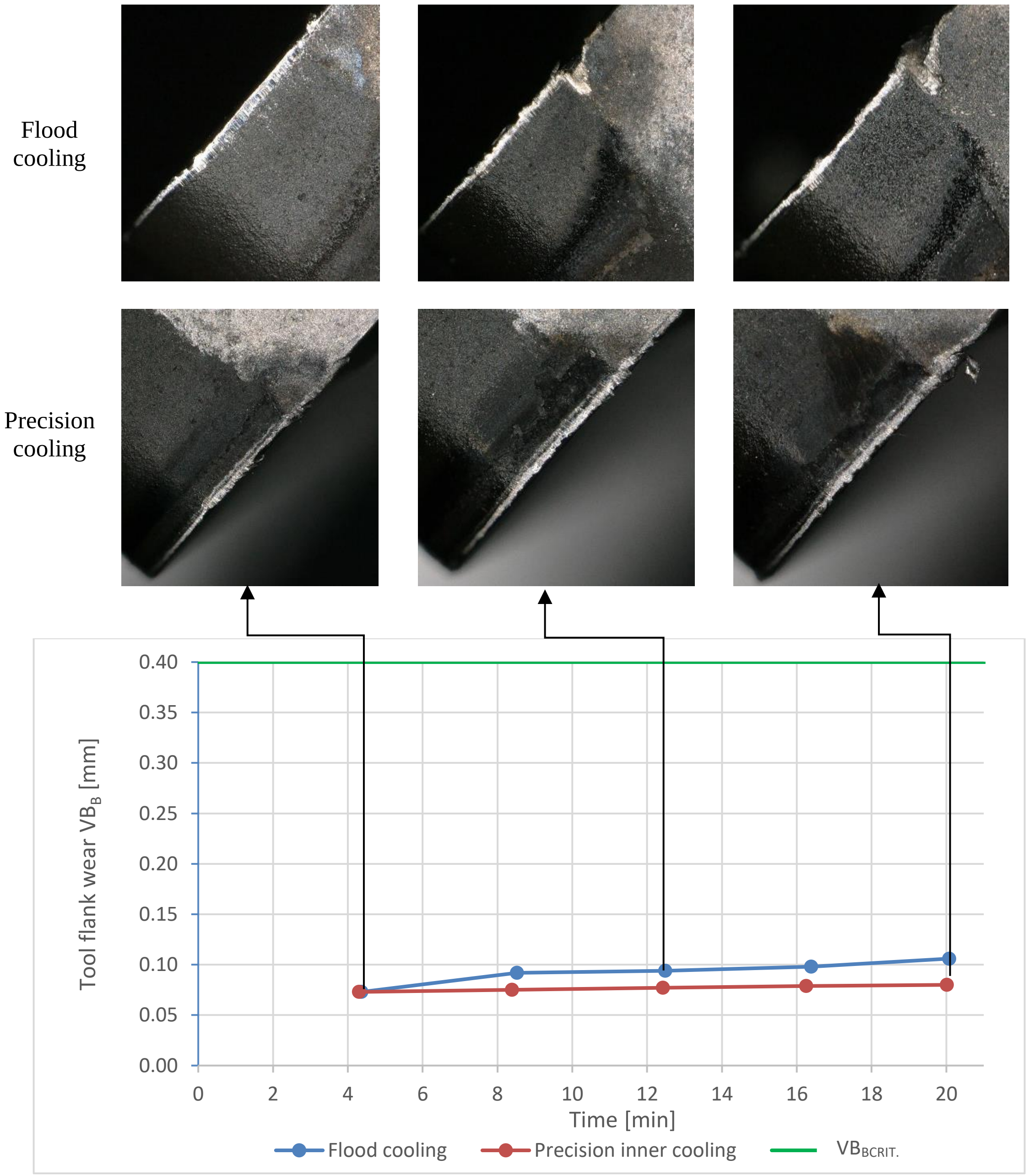

Fig. 4. Development of flank wear, v_c=160 m/min

3.2. Test 2: vc=300 m/min

As a result of slow flank wear increments during the previous test, the new test and insert with cutting speed of v_c = 300 m/min was set to accelerate it. These tests had to be ended due to tools failures, where flood cooled tool failed during the 3rd cut and precision cooled tool during the 7th cut. Excessive tool wear in combination with high mechanical and thermal stress led to tool tip break off.

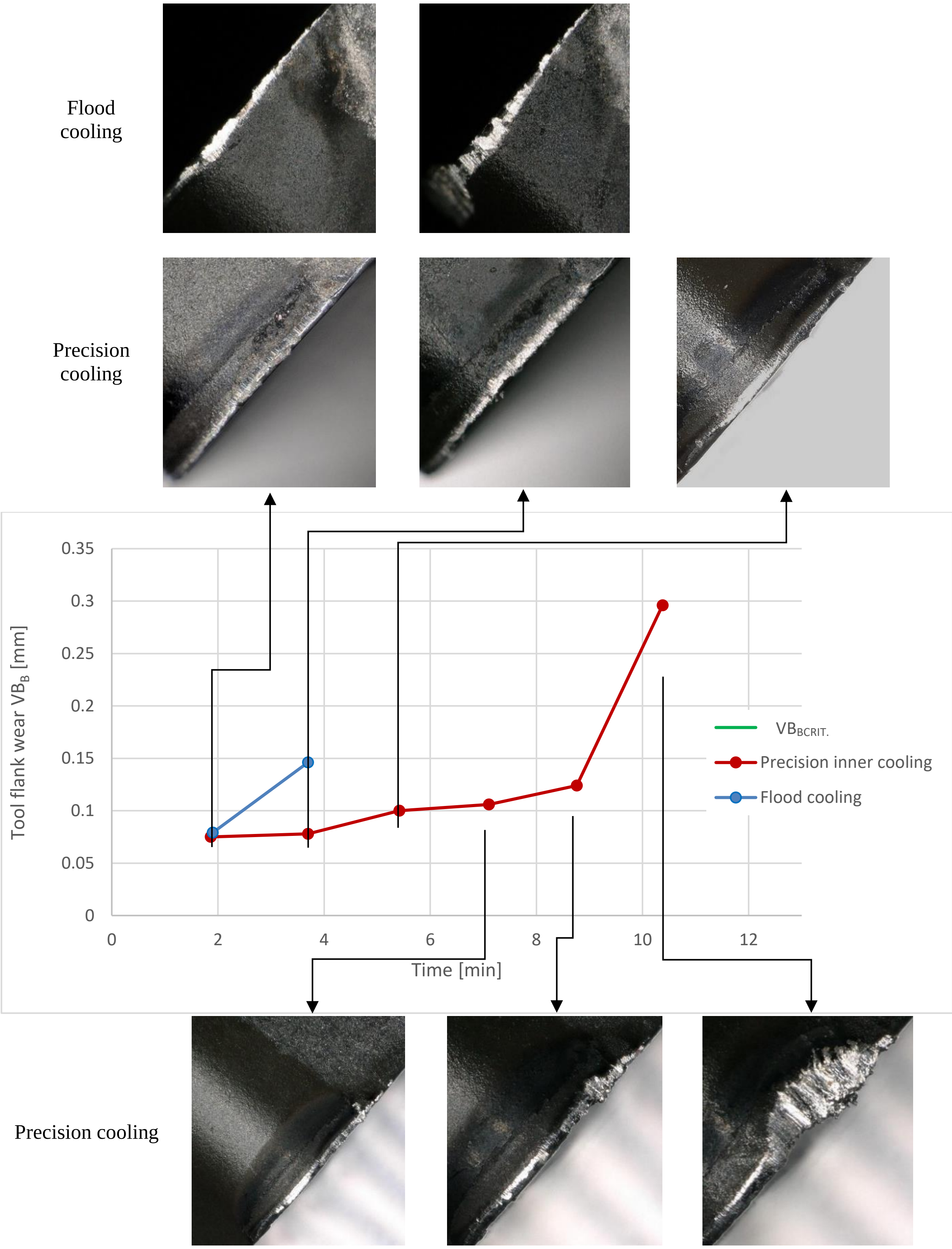

Fig. 5. Development of flank wear, v_c=300 m/min

3.3. Test 3: vc=250 m/min

During this test, the criteria flank wear $VB_{BCRIT.}$ was reached. The following graph (Fig.6.) shows the significant exponential rise of flood cooled tool after the twelfth minute, whereas the precision cooled tool started its exponential wear after 25 minutes.

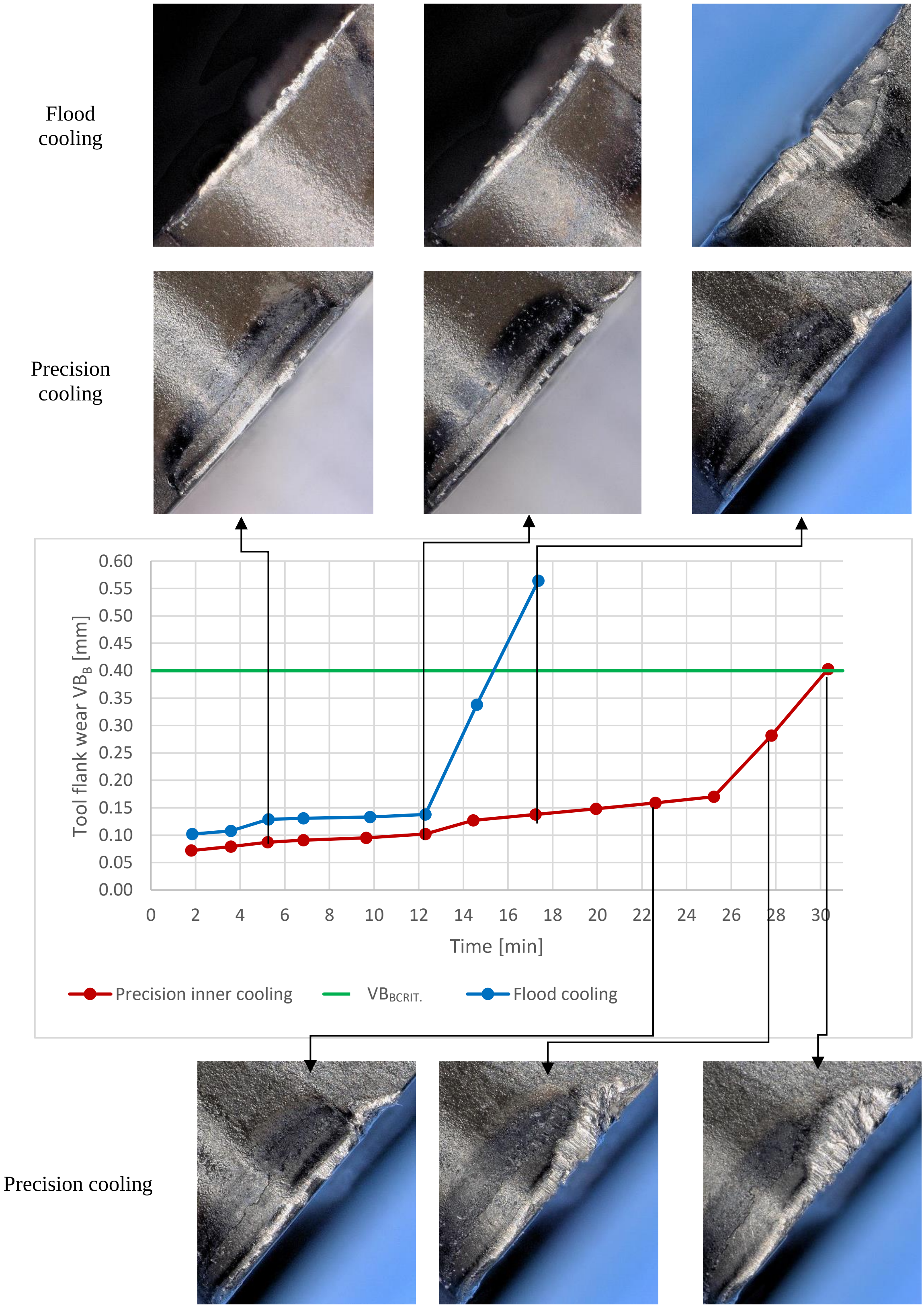

Fig. 6. Development of flank wear, v_c=250 m/min

Using linear interpolation, flood cooled tool reached criteria flank wear after 15 minutes, whilst precision cooled after the 30 minutes. In other words, tool life with the precision cooling system proved to be about 2× longer. This result was achieved with a 1.56× higher cutting speed than the maximum cutting speed recommended by the insert manufacturer. In the failure region, the flank wear of the flood cooled tool shoots up, whereas the precision cooled tool increases more gradually.

3.4 Surface roughness

It was concluded that at a cutting speed 160 m/min surface roughness ranged from 1.88 and 2.13 μm where the precision cooled tool showed a slightly better surface. However, the experiment with a cutting speed 250 m/min showed the opposite result. Flood cooled tool showed better surface even as flank wear increased, furthermore, it was better than precision cooling. This can be explained by higher temperature in the cutting zone which would promote plastic deformation of the surface. Although the exact mechanism would have to further investigated. In the case of v_c = 300 m/min, surface roughness went down continuously.

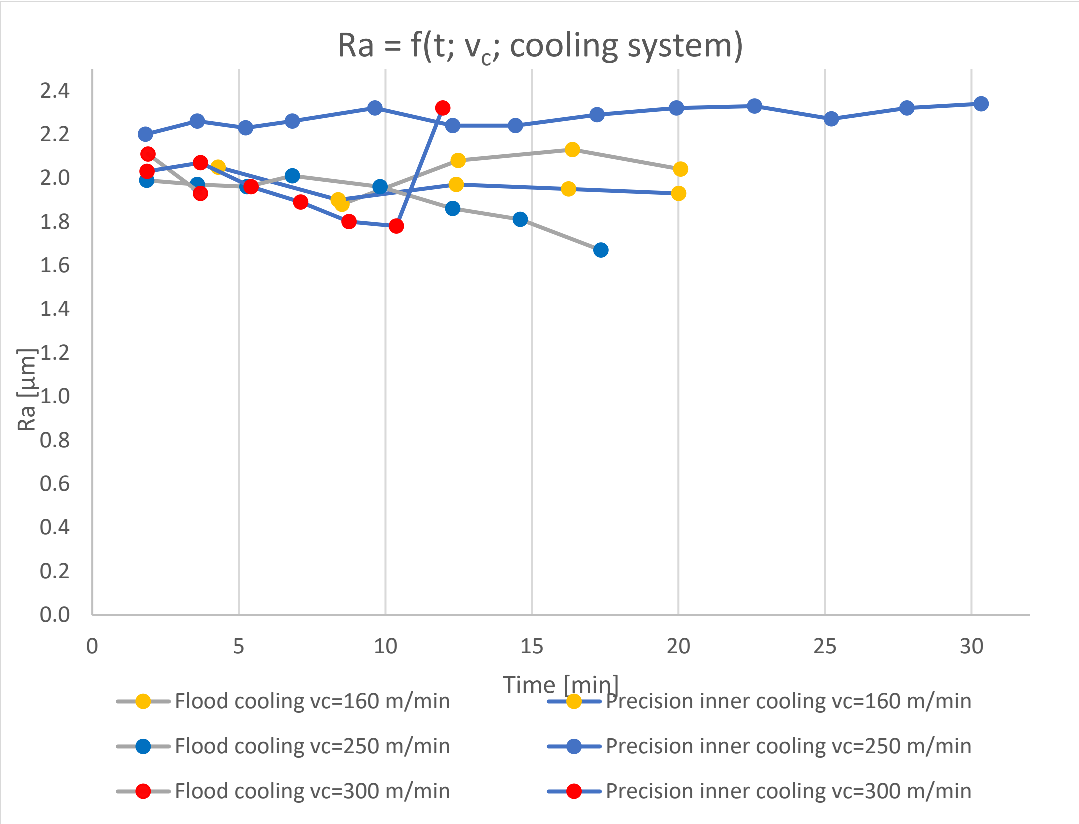

Fig. 7. The effect of cutting speed and cooling on the surface roughness

4. Conclusion

Stainless steels are various materials which show worse machinability than carbon steel and, therefore, cause rapid tool wear. Innovations in the cooling system allow to utilise cooling emulsion more effectively. Therefore, cutting speed or tool life can be increased, improving machining economics.

The purpose of this investigation was to compare tool life when conventional and precision inner cooling approaches were used. Stainless steel was chosen due to its low thermal conductivity which thermally and mechanically loads tools. Precision cooled tool always showed lower tool wear, however with higher cutting speeds the difference was more significant, namely tool life was about double when a 1.56 higher cutting speed than usual was used. On the other hand, during lower cutting speed there was small difference after the first 20 minutes in the cut. Although, it can be argued that the tool wear progression might look similar as with the cutting speed of 250 m/min. The benefits of precision cooling system would then be significant only when higher tool wear is reached. However, this research will be followed by investigation of tool wear behaviour at lower cutting speeds to verify this hypothesis. Moreover, precision cooled tool wear rises slower than conventional one, thus machining process is more predictable and reliable. As far as surface roughness, there was no clear difference between conventional and precision cooling. That is why these experiments should be repeated with more specimens.

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