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**Research Paper:**

# Boiling of Coolant Near the Cutting Edge in High Speed Machining of Difficult-to-Cut Materials

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**This study investigates film boiling of coolant as a cooling inhibitor in a narrow wedge-shaped space between the tool flank face and the machined surface of a workpiece, observed during high-speed turning of stainless steel SUS304 and nickel-based superalloy Inconel 718. The boiling, likely triggered by high surface temperatures at both the face and surface close to the cutting edge, impedes coolant access to the tool tip area and efficient cooling. Therefore, the impact of coolant pressure on the boiling zone size was initially explored across pressures ranging from 0.1 to 20 MPa. A burn mark band due to coolant boiling, distinctly visible on the flank face of an insert with a yellow hard coating, expanded over cutting time. The film boiling area width, or the distance from the flank wear area to the band, decreased with increasing coolant pressure, reflecting the enhanced cooling ability and tool life with high-pressure coolant. Applying Boyle–Charles' law to film boiling indicated that vapor pressure was directly related to coolant velocity rather than pressure. In contrast, the boiling area width increased with increasing cutting speed.**

**Keywords:** boiling of coolant, burn mark, high pressure coolant, difficult-to-cut material, high-speed turning

## 1. Introduction

Coolants often drastically enhance the performance of high-speed machining, particularly for difficult-to-cut materials. Thus, in addition to traditional low-pressure coolants, cryogenic coolants, such as liquid nitrogen, liquid carbon dioxide, and high-pressure coolants, have been applied to low-efficiency machining processes. Cryogenic coolants have excellent cooling ability [1, 2]; however, their lubricity is poor. Therefore, when the lubricity of the coolant is required under specific cutting conditions, oil droplets are added, similar to minimum quantity lubrication machining, to the gas-phase cryogenic coolant, which is transformed from the liquid phase with evaporation and expansion during spraying through a nozzle. In contrast, high-pressure coolants with high cooling ability and moderate lubricity are often applied to high-speed turning, milling, and deep hole drilling of difficult-to-cut materials because they not only decrease the cutting temperature but also promote chip breaking. Therefore, a high-pressure coolant is much more cost-effective than a cryogenic coolant for different cutting methods under a wide range of cutting conditions.

The influence of a high-pressure coolant on cutting performance has been investigated from various perspectives. Tool wear and the associated tool life are among the primary areas of research. Several papers (e.g., [3–7]) have reported that high-pressure coolants contribute to a large extension of tool life. Bermingham et al. [8] showed that a high-pressure coolant decreased tool wear more significantly than liquid nitrogen. Another main research area is chip breaking and chip control, which was reviewed based on the relationship between chip type and coolant pressure [9]. The third is the understanding of the coolant flow near the tool-tip area [9–12] and the mechanisms of cooling and lubrication [13].

During research on high-speed turning of difficult-to-cut materials using high-pressure coolant, the authors observed a band of burn marks on the tool flank face. This band could be identified as the boundary zone between the liquid and gas phases of coolant during film boiling. Film boiling, occurring in a narrow wedge-shaped space between the tool flank face and the machined surface, likely acted as a cooling inhibitor by impeding the advancement of coolant toward the cutting edge, as illustrated in **Fig. 1**. Consequently, changes in the position of the burn mark with coolant pressure and cutting speed were observed during high-speed turning of stainless steel and nickel-based superalloy. Additionally, the influence of coolant pressure on changes in the maximum width of flank wear with cutting length was investigated to understand the cooling ability of high-pressure coolant.

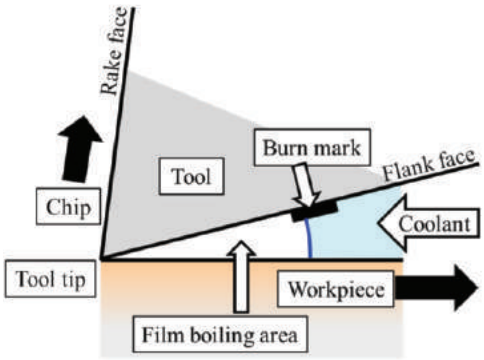


**Fig. 1.** Schematic of film boiling between the tool flank face and the finished surface, and the position of the burn mark.

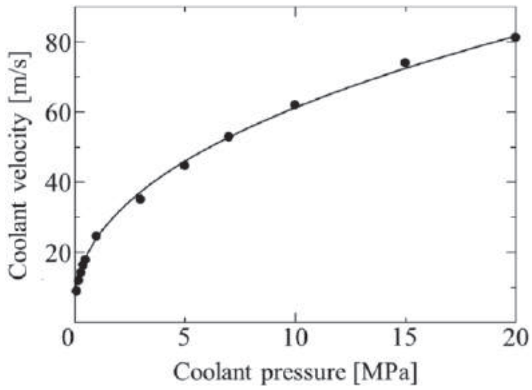


**Fig. 3.** Relationship between the coolant velocity and the coolant pressure.

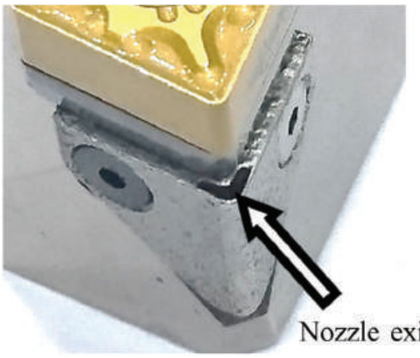


**Fig. 2.** Tool holder with a nozzle on the flank face.

## 2. Experimental Methods

The work materials used for the turning experiments were 18-8 stainless steel SUS304 and a nickel-based superalloy, Inconel 718. An M35-grade carbide insert with a single coating layer of a titanium compound was applied for turning SUS304, whereas an S01-grade carbide insert with three different coating layers of TiCN, $Al_2O_3$, and TiN was used for turning Inconel 718. These inserts had the same body shape as CNMG120408, but different chip-breaker shapes. The surface coatings were yellowish in color. This was essential for identifying the band corresponding to the burn mark on the flank face. They were clamped to a tool holder of type DCLNR2525M12-JC with a coolant nozzle on the flank face, as shown in **Fig. 2**. The crescent or L-shaped area of the nozzle exit is 2.25 mm$^2$. The tool clearance angle in **Fig. 1** is magnified by more than twice the actual value of approximately 6° to highlight the film boiling area and position of the burn mark.

A soluble type of coolant was delivered to the tool tip through a nozzle on the tool flank face. This method of coolant supply will henceforth be referred to as jet cooling (JC). Coolant pressure varied widely from 0.1 to 0.5 MPa using a low-pressure coolant pump and from 1.0 to 20.0 MPa using a high-pressure coolant pump. The average cross-sectional flow velocity at the nozzle exit was calculated based on the exit area and flow rate, measured using a magnetic flow meter. This flow velocity is essential for estimating the coolant's penetration ability in the cutting area and its momentum, which could aid in chip breaking. However, previous studies [6, 7, 10] did not provide this value.

In this study, the coolant was supplied to the tool tip area only from the side of the flank face in both JC and flood cooling because the boundaries of the wedge-shaped space between the tool flank face and machined surface are well-defined, and the burn mark on the flank face is unlikely to be scratched by a produced chip. In contrast, the chip-leaving point on the rake face periodically changes during the chip-breaking process, accompanied by a change in the chip curl radius. Thus, the boiling area on the rake face may move with a change in the chip-leaving point, resulting in a broad and vague burn mark, and the damaged burn mark is further smeared and scratched by the produced chip.

The cutting conditions for SUS304 included cutting speeds of 300 and 500 m/min, a depth of cut of 1.0 mm, and a feed rate of 0.2 mm/rev. For Inconel 718, the conditions were a cutting speed of 150 m/min, a depth of cut of 0.3 mm, and a feed rate of 0.1 mm/rev. The cutting experiment persisted until the maximum width of flank wear $VB_{max}$ surpassed a critical value of 0.2 mm.

The widths of the boiling areas were measured using a digital microscope. In addition, mappings of certain elements in the burn marks were identified using electron probe microanalysis to confirm the origins of the burn mark components.

## 3. Results and Discussion

The relationship between the coolant velocity and coolant pressure is shown in **Fig. 3**. The coolant velocity was calculated to be 81.5 m/s from a flow rate of 11 L/min and the nozzle exit area at a coolant pressure of 20 MPa. This was very rapid, and continued to show an increasing trend. By contrast, it was 4.0 m/s for flood cooling at a coolant pressure of 0.5 MPa. This value was less than half of the coolant velocity at the crescent nozzle exit for

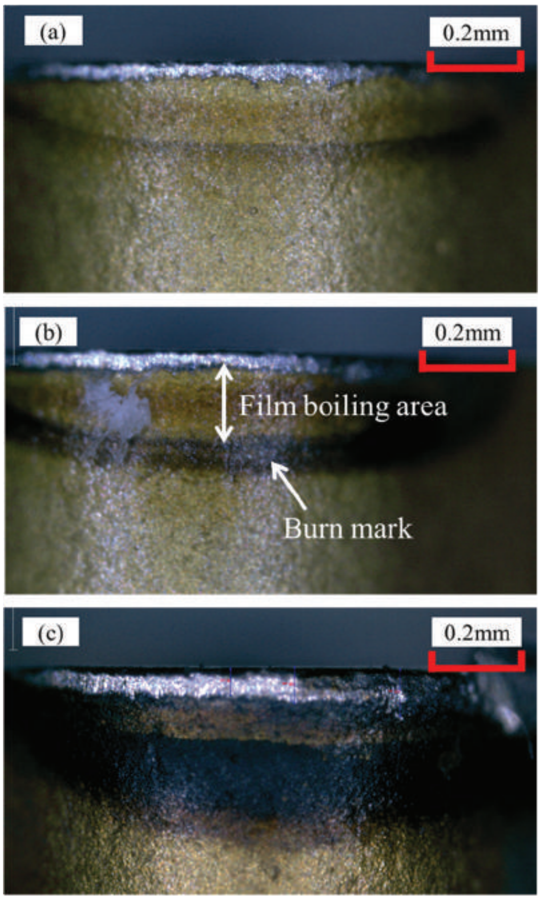


**Fig. 4.** Burn marks on the flank face at cutting lengths of (a) 25, (b) 100, and (c) 1000 m when machining SUS304 at cutting speed 300 m/min using JC at a coolant pressure of 0.5 MPa.

a coolant pressure of 0.1 MPa.

The burn mark became wider and thicker on the flank face as the cutting length increased, as shown in **Fig. 4**. **Figs. 4(a)–(c)** show the marks at cutting lengths of 25, 100, and 1000 m, respectively, when SUS304 was machined at a cutting speed of 300 m/min with JC at a coolant pressure 0.5 MPa. The film-boiling area spread to both ends of the cutting edge engaged in cutting; thus, its length along the cutting edge did not change with the coolant pressure. In contrast, its width in the cutting direction, or the distance from the flank wear land to the band of the burn mark, changed along the cutting edge and was likely proportional to the local undeformed chip thickness at the point of the cutting edge. Because the boiling area changed little as the cutting length increased from 25 to 100 m, its maximum value, which is simply referred to as the width of the boiling area below, was measured once at an early stage of cutting.

The results of electron probe microanalysis of the elements on the flank face with thick and wide bands of burn marks are shown in **Fig. 5**. **Fig. 5(a)** shows a micrograph of the burn mark on the flank face, and **Figs. 5(b)–(f)** show maps of carbon, phosphorus, sulfur, oxygen, and iron. The work material was SUS304, and the cutting conditions

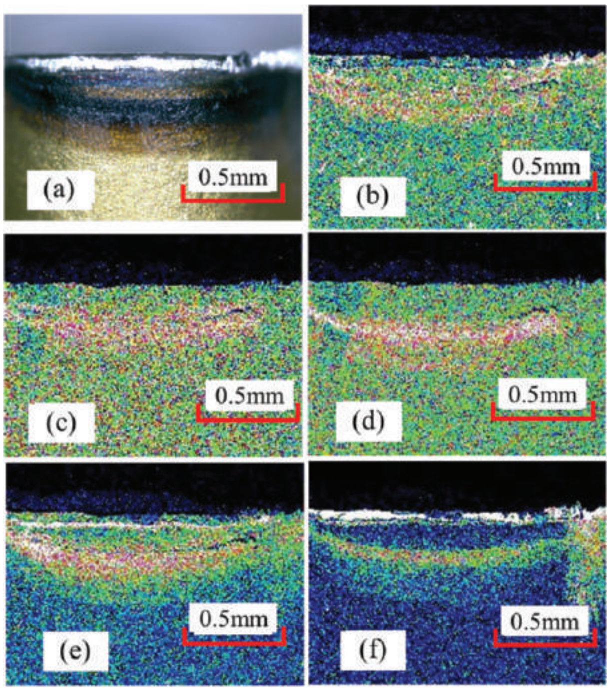


**Fig. 5.** Results of electron probe microanalysis of the flank face with a burn mark after machining 800 m of SUS304 at a cutting speed of 300 m/min using JC at a coolant pressure of 0.5 MPa. (a) Micrograph of the burn mark on the flank face and mappings of (b) carbon, (c) phosphorus, (d) sulfur, (e) oxygen, and (f) iron.

were a cutting speed of 300 m/min, a cutting length of 800 m, and JC at a coolant pressure of 0.5 MPa.

High concentrations of carbon, phosphorus, sulfur, and oxygen in the burn mark area indicated that the coolant was the source of the burn mark. Intense boiling of the coolant occurred in the narrow wedge-shaped space between the tool flank face and the machined surface, leading to the formation of the burn mark at the boundary zone between the liquid and gas phases of the coolant during film boiling. Additionally, a high iron concentration was found in the burn mark area, with even higher iron concentrations detected on the flank wear land. This suggests that the boiling was extremely severe because the particles of the work material worn down by friction against the tool flank wear surface, initially carried onto the finished surface, became firmly adhered to the position of the burn mark on the tool.

The relationship between the width of the film boiling area and coolant pressure obtained for the turning of SUS304 using JC at a cutting speed of 300 m/min is shown in **Fig. 6**. Two or three burn marks appeared on the flank face at coolant pressures of 1–7 MPa. Because a high-pressure pump with discharge pressures of up to 20 MPa was designed for a range of pressures much higher than 7 MPa, a large reduction in coolant pressure using a pressure control valve often causes a large pressure pulsation, which must have resulted in multiple burn marks.

The boiling areas for pressures of 0.5 MPa and lower were wider than 0.2 mm, the feed of one revolution. They

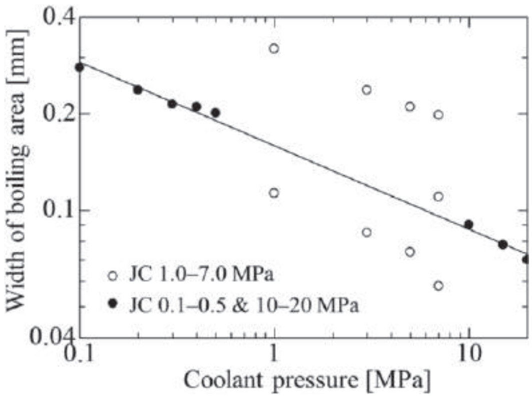


**Fig. 6.** Relationship between the width of the film boiling area and coolant pressure when machining SUS304 using JC at a cutting speed of 300 m/min.

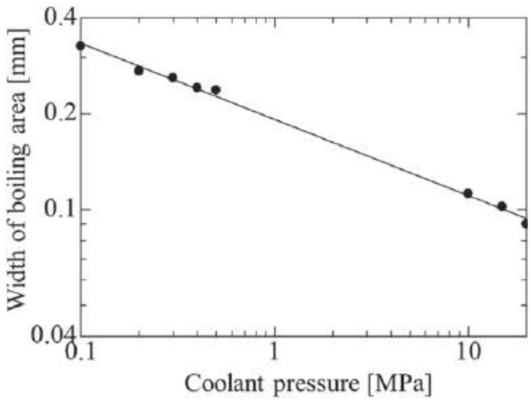


**Fig. 8.** Relationship between the width of the film boiling area and coolant pressure when machining SUS304 using JC at a cutting speed of 500 m/min.

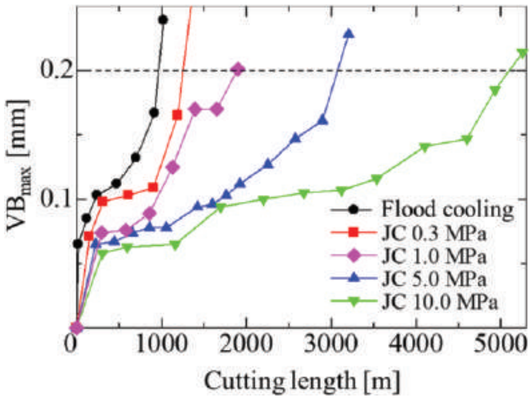


**Fig. 7.** Effect of coolant pressure on the development of the maximum width of flank wear when machining SUS304 using JC at a cutting speed of 300 m/min.

would be even wider in flood cooling because the coolant speed in flood cooling is much slower than that in JC at a coolant pressure of 0.1 MPa. This suggests that cooling of the hottest areas of the tool flank face was significantly reduced by coolant boiling when low-pressure coolant was supplied to the cutting area. This is because the heat transfer coefficients from solid to gas were approximately two to three orders of magnitude lower than those from solid to liquid.

In contrast, the width of the boiling area decreased by a factor of 4.0 as the coolant pressure increased from 0.1 to 20 MPa, whereas it decreased by a factor of 2.9 as the pressure increased from 0.5 to 20 MPa. The above results show that a high-pressure coolant can enhance the cooling ability in the cutting processes by not only increasing the flow speed, but also changing the heat transfer mechanisms in the hottest area of the flank face.

The influence of the coolant pressure on the development of the maximum flank wear width when machining SUS304 at a cutting speed of 300 m/min is shown in **Fig. 7**. In addition to the data for JC with coolant pressures ranging from 0.3 to 10 MPa, data for flood cooling were also plotted. The cutting distance at the maximum width of the flank wear $VB_{max}$ = 0.2 mm was the shortest for flood cooling and constantly increased with a coolant pressure of up to 10 MPa for JC. It was three and five times longer for JC at coolant pressures of 5 and 10 MPa, respectively, than for flood cooling. This indicated that JC using a high-pressure coolant was favorable for the high-speed machining of stainless steel SUS304.

The relationship between the width of the film boiling area and coolant pressure for JC at an even higher cutting speed of 500 m/min is depicted in **Fig. 8**. Comparing this with **Fig. 6** reveals that the increase in cutting speed resulted in a wider boiling area. The coolant must flow into the narrow wedge-shaped space between the tool flank face and the machined surface, opposing the movement of the machined surface in the opposite direction and the associated boundary layers, which may cause countercurrents. Given that the height of the space at the position of the burn mark is approximately one-tenth the width of the boiling area, the coolant velocity significantly decreases before reaching the boiling area. Therefore, the increase in cutting speed or the moving velocity of the machined surface from 300 m/min (5.0 m/s) to 500 m/min (8.3 m/s) would have a noticeable impact on the starting position of boiling.

The change in the width of the boiling area with cutting speed when machining SUS304 using JC at the lowest coolant pressure of 0.1 MPa is shown in **Fig. 9**. The boiling area increased monotonically with the cutting speed. However, the cutting speed has a smaller influence on the width than the coolant pressure.

The relationship between the width of the film boiling area and the coolant pressure for turning Inconel 718 using JC at a cutting speed of 150 m/min is depicted in **Fig. 10**. As the feed rate of 0.1 mm/rev for Inconel 718 is half that of SUS304, the width of the boiling area of Inconel 718 is approximately half that of SUS304. However, the effect of the coolant pressure on narrowing the boiling area appears to diminish, as indicated by the smaller slope of the line in **Fig. 10** compared to that in **Fig. 6**. With an increase in coolant pressure from 0.5 to 20 MPa, the width of the

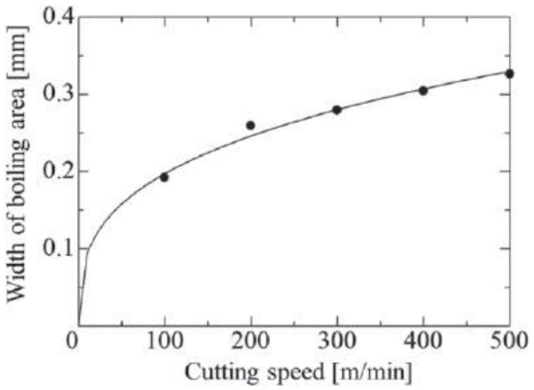


**Fig. 9.** Relationship between the width of the film boiling area and the cutting speed when machining SUS304 using JC at a coolant pressure of 0.1 MPa.

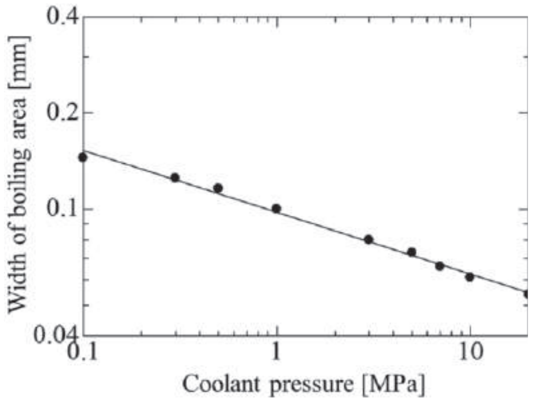


**Fig. 10.** Relationship between the width of the film boiling area and the coolant pressure when machining Inconel 718 using JC at a cutting speed of 150 m/min.

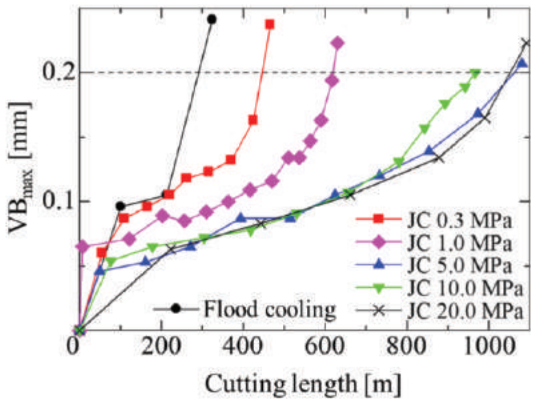


**Fig. 11.** Effect of coolant pressure on the development of the maximum width of flank wear when machining Inconel 718 using JC at a cutting speed of 150 m/min.

boiling area decreased by factors of 2.7 and 2.1 in **Figs. 6** and **10**, respectively.

Based on computational fluid dynamic analysis of coolant flow in turning [11, 12], there exists a limit to the coolant's reach in the narrow wedge-shaped space between the tool flank face and the machined surface, even without considering coolant boiling. This limit is dependent on coolant pressure, velocity, cutting speed, tool clearance angle, and viscosity. It is likely situated tens of micrometers away from the end of the flank wear-land, allowing only the gas-phase coolant [14] to flow beyond it.

The influence of the coolant pressure on the development of the maximum width of the flank wear when turning Inconel 718 at a cutting speed of 150 m/min is shown in **Fig. 11**. In addition to the data for JC with coolant pressures ranging from 0.3 to 20 MPa, data for flood cooling were also plotted. The cutting distance at $VB_{max} = 0.2$ mm was the shortest for flood cooling, which is similar to the results for SUS304 shown in **Fig. 7**. It increased with the coolant pressure up to 5.0 MPa for JC. This was four times longer for JC at a coolant pressure of 5 MPa than for flood cooling. However, it did not change slightly when the coolant pressure was increased from 5 to 20 MPa. One of the main reasons for this unexpected result is explained in [6] from the perspective of the deposition of trace coolant elements on the flank face under high-pressure conditions. This result indicates that JC using high pressure is not always effective in reducing flank wear. Studies in this area have started recently [6]. Further research is required to better understand machining using high-pressure coolants.

From **Figs. 6** and **10**, the relationships between the coolant pressure $p_L$ and the width of boiling area $w$ for SUS304 and Inconel 718 are expressed as $w = 0.160{p_L}^{-0.259}$ and $w = 0.0985{p_L}^{-0.192}$, respectively. Rearrangement of these equations results in $w^{3.86}p_L = 0.000845$ and $w^{5.21}p_L = 5.72 \times 10^{-6}$, respectively. Using the relationship between the coolant velocity $v_L$ and coolant pressure in **Fig. 3**, that is, $v_L = 23.8{p_L}^{0.411}$, the above equations become $w^{1.59}v_L = C_1$ and $w^{2.14}v_L = C_2$, where $C_1$ and $C_2$ are constants. However, because the volume of the gas-phase coolant in the wedge-shaped space is proportional to $w^2$, Boyle–Charles' law is expressed as $w^2 p_V = C$, where $p_V$ is the pressure of the gas-phase coolant, and $C$ is a constant. A comparison of the form of $w^2 p_V = C$ and the other equations led to the conclusion that the pressure of the gas-phase coolant, $p_V$ is dependent on the coolant velocity rather than the coolant pressure.

## 4. Conclusions

The film boiling of the coolant as a cooling inhibitor in a narrow wedge-shaped space between the tool flank face and the machined surface of a workpiece during the high-speed turning of SUS304 and Inconel 718 was investigated. The following conclusions were drawn:

1) The band of burn mark on the tool flank face was identified as a boundary zone between the liquid- and gas-phases of coolant boiling.

2) The width of boiling area in JC significantly decreased with increasing coolant pressure from 0.1 to 20 MPa and increased with cutting speed.

3) The maximum width of the flake wear decreased with increasing coolant pressure, resulting in a significant increase in the cutting length in machining SUS304, whereas an increase in the cutting length was limited in a range of very high coolant pressures in machining Inconel 718.

4) Applying the Boyle–Charles' law to film boiling suggested that the pressure of the gas-phase coolant is directly dependent on the coolant velocity and not on the coolant pressure.

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