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Targeted Minimum Quantity Fluid Application in Machining

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Abstract: The surface integrity of a machined component is crucial for its service life part. One of the main final specifications that a machined part is inspected for is the surface integrity metrics, including surface residual stresses, surface microhardness, surface roughness, and microstructure. In this paper, the cutting fluid is strategically targeted to utilize heat energy effectively in the primary, secondary, and tertiary shear zones to positively affect the surface integrity metrics and machining mechanics. In this study, a lower quantity of the cutting fluids is targeted at the high-temperature zones to reduce the machining temperatures, thereby effectively simulating the effect of a 'flood coolant'. The cutting fluid is applied simultaneously as a targeted Minimum Quantity Fluid (MQF) on the cutting tool's flank and rake faces to improve the surface integrity metrics and chip formation. Also, this study analyzes the effect of the cutting fluid composition, the type of cutting fluid, and the amount of fluid quantities. The machining-induced surface integrity metrics are analyzed to understand the effects of targeted minimum quantity fluid application. The impact of the targeted application of cutting fluid on machining mechanics metrics, such as cutting forces and chip formation, is analyzed. Applying a targeted MQF application at the flank face of the cutting tool leads to higher compressive subsurface principal residual stresses. The results indicate that using MQF on both the flank and rake faces simultaneously enhances the surface integrity. The effect of a cutting fluid jet on the flank face is modeled to highlight the thermophysical properties that are crucial for selecting the appropriate cutting fluid to lower the machining-induced temperatures. With targeted MQF application, the fluid jet acts as a dynamic and external chip control mechanism. Overall, effectively managing temperatures in machining could enhance subsurface residual stresses and surface roughness using various cutting fluid combinations. Also, this paper presents a targeted cutting fluid application that improves the microstructural formation, enhancing chip control and producing machined surfaces and components with better surface integrity.

Keywords: surface integrity; residual stresses; surface roughness; machining; cutting fluid; minimum quantity fluid

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1. Introduction and Background

The quality of the machined surface and subsurface influences the service life of the component and its overall sustainability. The machined surfaces are subjected to high loads, temperatures, and stresses and may face harsh environments [1]. Recent emphasis on sustainability and the circular economy has sparked renewed interest in extending the manufactured part's service life [2]. Therefore, greater attention and focus are required on the machining-induced surface and subsurface integrity. To achieve the desired surface

integrity, the machined components undergo post-machining surface modifications and heat treatments for a wide range of applications. In contrast, this study attempts to facilitate planned in situ surface enhancement/treatment, such as cooling during machining, to minimize the necessity for costly post-processing treatments aimed at achieving the desired surface integrity. Thus, reducing manufacturing costs, saving time, improving product quality, and enhancing overall sustainability.

The machined component's surface integrity is an important quality measure, which includes surface roughness, surface (and subsurface) residual stresses, microhardness, and surface (and subsurface) microstructure. To minimize costly surface enhancements like low plasticity burnishing and shot peening, post-machining processes must incorporate surface integrity as a design input in the process planning, as shown in Figure 1 [3,4]. Surface integrity is defined as 'the inherent or enhanced surface condition resulting from a machining process'. [5]. B211.1–1986, the ANSI standard [6]., provides detailed metrics for surface integrity and a standard for depicting residual stress profiles. As per the standard, the four key parameters for analyzing the residual stress profiles are (1) surface residual stress (the stress value at zero depth), (2) peak residual stress (either tensile or compressive), (3) crossover depth (crossover of the residual stress profile from compressive to tensile or vice versa) and (4) depth of the residual stress underneath the surface [6]. Also, according to the same ANSI standard, the minimum data set to define surface integrity includes (a) surface texture (such as surface roughness, surface lay, etc.), (b) macrostructure (10× or less), (c) microstructure (1000×), and (d) microhardness. Furthermore, the standard data set used to define surface integrity consists of the minimum data set, residual stress profile, and fatigue test.

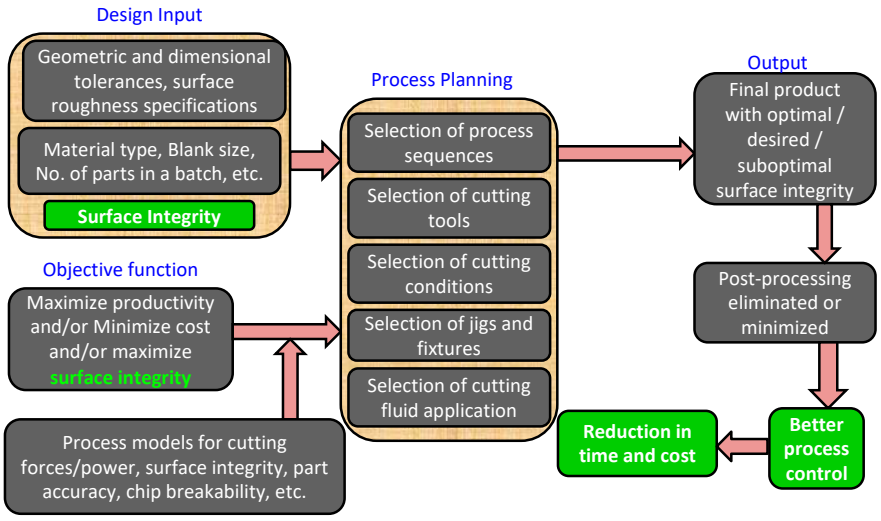


Figure 1. Process plan schematic including surface integrity as a design input (adapted from [3]).

A review of the studies on machining-induced residual stresses suggests that mechanical loads generate compressive stresses, whereas thermal loads produce tensile residual stresses [7,8]. Okushima and Kakino, in their work from 1971, computed the machining-induced residual stresses as a combination of mechanical stresses (due to the force applied by the cutting tool edge on the workpiece) and thermal stresses produced by the heat energy from metal cutting [9]. Tsuchida et al.'s 1975 research on the effects of cutting conditions on machining-induced residual stresses indicates that the feed rate typically moves the residual stress profile toward higher tensile stress, while the depth of cut has little impact on residual stresses [10]. Their research has shown that using cutting oil as a cutting fluid during machining produces higher compressive residual stresses compared to machining

without cutting fluid (dry machining). The higher feed rate and dry machining raise the machining temperatures, consequently increasing thermal stresses and, in turn, tensile residual stresses. Outeiro et al. investigated the impact of coated and uncoated cemented carbide cutting tools on machining-induced residual stresses when machining AISI 1045 steel and 316L stainless steel [11]. Their work concluded that coated tools induced higher surface residual stresses than uncoated tools. This was due to the coated tools' thermal barrier, which increased the likelihood of thermal energy being transferred to the machined surface, ultimately impacting the surface residual stresses.

Effectively using the heat energy generated during the machining process could help improve surface quality. Both the machining industry and academic researchers have utilized cutting fluid to control/manage machining temperatures. The cutting fluid is mainly applied as a flood coolant, which involves a high quantity of (cutting) fluid. It is also applied as a Minimum Quantity Fluid (MQF) or a Minimum Quantity Lubricant (MQL). Generally, these methods aim to reduce heat energy to enhance tool life and surface integrity metrics. However, flood coolant (as cutting fluid) application can have negative environmental, health, and economic impacts [12,13]. In general, the flood coolant application in machining is applied on the primary shear zone (also referred to as the top of the chip), lowering machining temperatures (reducing the thermal softening) and adversely affecting the cutting tool life [14]. Additionally, the flood coolant minimizes thermal softening in the primary shear zone, resulting in increased machining-induced tensile residual stress [15].

However, traditional MQL is both cost-effective and environmentally friendly, and it also has its own benefits and limitations. The traditional use of MQL as a lubricant has limited success because it cannot penetrate the tool–chip interface [14]. Thus, controlling tool wear using MQL could be challenging due to its application location, that is, on the upper side (or top) of the chip surface rather than along the tool–chip interface (tool rake face), and limited cutting fluid near the tool flank face. Additionally, a lubricant alone is not specifically designed for cooling or reducing machining temperatures. To counter that, Diniz and Micaroni researched the effects of targeting a high quantity and pressure (jet) cutting fluid on cutting flank and rake faces. The targeted application enhanced the cutting life by reducing tool wear while machining AISI 1054 steel. They attributed the decrease in tool wear to the higher flow rate on the cutting tool [14]. Leppert (2011) used a small quantity of vegetable oil as a lubricant (MQL) on the rake and flank faces to research the effect of cutting parameters on surface texture properties such as surface roughness [16]. Recently, researchers have used different nano lubricants such as Al_2O_3 with oil, and CuO with oil as an MQL for machining AISI 4340 steel to investigate the surface roughness and tool wear. The results showed improvement in surface roughness and tool wear [17]. Researchers have utilized MQL as a cutting fluid for machining AISI D2 steel to investigate its effects on machining vibration and cutting temperatures and, subsequently, on surface roughness. The results indicated that the MQL application improved surface roughness and reduced cutting vibrations when compared to dry machining results [18]. Similarly, research has compared MQL, flood coolant, and dry milling Inconel 800 to comprehend the effects of different cutting fluid applications for surface properties and cutting forces. The results showed that the surface roughness and cutting forces were reduced due to the usage of MQL [19]. However, these researchers did not study the influence of targeting the cutting fluid onto the tool flank face and the tool rake face on machining-induced surface integrity metrics.

Sharma et al. (2015) reviewed the literature on MQL application in machining processes such as turning, milling, drilling, and grinding difficult-to-cut materials like nickel-based alloys and titanium alloys [20]. The paper concluded that by applying MQL, the

cutting temperatures could be reduced. Similar review papers on MQL application in machining have shown that cutting temperatures can be reduced using the MQL application [21,22]. The review papers have shown that most studies have applied the MQL onto the top of the chip or the primary shear zone. At the same time, little focus has been placed on studying the effect of targeting cutting fluid to reduce the temperature along the rake and flank surfaces. Based on the review papers mentioned above, one of the research areas that has been least researched in the sustainable machining process has been the effects of applying targeted minimum quantity cutting fluid as a coolant (as opposed to mainly using the cutting fluid as a lubricant) along the rake and flank faces.

A recent review of the cutting fluid application of the post-processing of additively manufactured parts has recommended an in-depth study on the effects of targeted cutting fluid on machining AM parts [23]. Nunna's work on machining AISI 1045 steel has demonstrated the effects of applying cutting fluid on the cutting tool flank face and cutting tool rake face on the surface integrity [24]. Targeting the cutting fluid on the cutting tool flank face produced compressive subsurface principal residual stresses by reducing machining temperatures. For steels, this can lead to a phase transformation from austenitic to martensitic, generally accompanied by a localized increase in volume [25]. This localized increase in the volume restrains/constrains the subsurface, causing residual compression. However, the effects of targeting different cutting fluids and their quantities on the machining performance have not been reported in the literature.

Thus, this paper strategically targets the MQF on the tool flank face and the tool rake face to 'control the produced heat energy' and enhance the surface integrity metrics. It investigates the possibility of inducing compressive subsurface residual stresses in the workpiece by rapidly reducing the temperature produced during machining. Figure 2 shows the primary, secondary, and tertiary shear zones, which are generally high-temperature zones in machining. The primary shear zone (or Zone 1) is a high-temperature area, which, when reduced in temperature, can lead to higher cutting forces and higher tensile residual stresses due to lower thermal softening. In this study, cutting fluid is not applied in this zone. The machining temperatures in the secondary shear zone along the rake face can influence chip formation and tool life. As shown in Figure 2, the temperatures in this zone are reduced by applying the cutting fluid directly beneath the chip. Using cutting fluid in this area can change machining mechanics and affect surface integrity metrics. However, the effects of changes in the chip formation and the tool's tribological properties on surface integrity metrics have yet to be explored. The tertiary shear zone, a high-temperature zone along the just machined subsurface near the flank face, and its temperatures influence the surface integrity metrics, especially surface residual stresses and the subsurface microstructure. Energy transfer from the primary and secondary shear zones impacts temperatures in this zone. In this study, as shown in Figure 2, the temperatures are reduced using different cutting fluids at different flow rates to understand their effect on the surface integrity metrics. The temperature in these heat-affected zones can be lowered by using different combinations of cutting fluids, adjusting the volume flow rates, and aiming the cutting fluid more strategically. The effect of this cooling process on machining tribology and machining temperatures, and consequently on the surface integrity metrics, has largely been unexplored. Overall, in this work, a variety of cutting fluids with different amounts are strategically targeted to (a) not affect the primary shear zone temperatures (the cutting fluid is not applied in the primary shear zone), (b) reduce the temperatures in the secondary shear zone, and (c) use the temperature generated in the tertiary shear zone to locally quench, and alter the machining mechanics, thereby improving the integrity of the just machined subsurface.

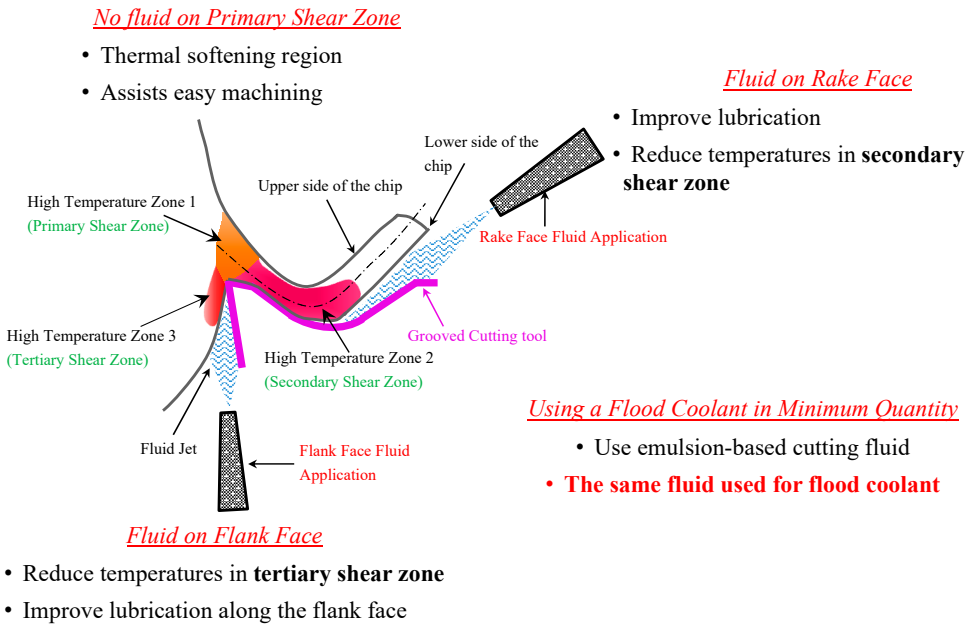


Figure 2. An illustration of the targeted application of MQF in machining (adapted from [4]).

2. Experimental Setup and Method

In this study, face-turning experiments are conducted to investigate the impact of targeted cutting fluid application on chip formation, and machining mechanics, and their effects on the machining-induced surface integrity. The experimental plan used in this study is detailed in Table 1. The workpiece material (114.3 mm diameter) is annealed before machining experiments to eliminate residual stresses and assist the microstructural analysis. A generic grooved (CNMG-432) CVD-coated cemented tungsten carbide cutting tool is used to machine the annealed AISI 1045. The cutting conditions and cutting fluid selected for this study are as per the recommendation of the cutting tool industry for machining annealed AISI 1045. The tool holder that dispenses cutting fluid onto the rake face (PCLNR 124 BHP) is used in this study to investigate the effects of targeting cutting fluid.

This study uses a semi-synthetic fluid (TRIM® MicroSol® 585 XT) as the cutting fluid. Generally, semi-synthetic cutting fluids are known for their ability to reduce heat while also providing decent lubrication properties [26]. To minimize the effects of hard water and potential contamination, the cutting fluid is mixed with distilled water. To minimize foam formation and follow the cutting fluid supplier's recommendation, the cutting fluid is mixed at a ratio of 1:9. In practice, this combination of cutting fluid (1:9 semi-synthetic to water) is used for flood (cutting) fluid application when machining steels. One unique aspect of this study is the use of this cutting fluid combination for both the High Quantity Fluid (HQF) and MQF applications. The effects of using the same cutting fluid composition for the minimum quantity fluid application and for the industry-standard flood coolant application on the surface integrity have rarely been studied. The reason for using the same cutting fluid composition is to reduce the machining temperatures (i.e., as coolant) apart from any lubrication effects and also to compare the MQF and HQF results with flood application. MQL is designed to enhance lubrication, while the purpose of using the cutting fluid in this study is to regulate the machining temperatures. Thus, instead of using traditional MQLs for a minimum quantity application, a combination of flood fluid application (MicroSol® 585 XT and distilled water at a 1:9 ratio) is employed in this study. To investigate the impact of targeted cutting fluid application, dry machining is compared to targeted MQF and HQF (simulating flood fluid) applications for machining annealed AISI 1045 steel.

Table 1. Cutting fluid variation along with the experimental plan.

Targeted Cutting Quantity Fluid Application **Cutting Fluid (CF) = Semi-Synthetic Fluid (Oil) 10% + Water 90%** **Water =Distilled Water** **CA = Compressed Air @ 0.689 MPa**				
No	**Name**	**Cutting Fluid Application**		**Variation**
		Cutting Tool Rake Face	**Cutting Tool Flank Face**	
1	Dry	None	None	Fluid quantity on the rake face.
2	HQF on Rake	CF @ 600 mL/min	None	
3	MQF on Rake	CF @ 300 mL/h + CA	None	
4	Water + Oil cooling	CF @ 300 mL/h + CA	CF @ 300 mL/h + CA	Cooling the just machined surface with different fluids.
5	Water cooling	CF @ 300 mL/h + CA	Water @ 300 mL/h + CA	
6	Air cooling	CF @ 300 mL/h + CA	CA	
Experimental details: Workpiece material: AISI 1045 steel–fully annealed (Pearlite + Proeutectoid Ferrite), pre-machining HRB 78 Cutting tool and coating: CNMG 432 CVD coated (TiN/Al_2O_3/TiCN). Tool holder: PCLNR 124 BHP—tool holder that dispenses cutting fluid onto the rake face. Cutting conditions: Cutting speed = 225 m/min; feed = 0.1 mm/rev; depth of cut = 1.2 mm				

After the machining experiments are completed, the machining-induced residual stresses are measured using the hole-drilling strain-gage method using ASTM E 837-08 standard [27]. Face-turning is used as a machining process in this study since a flat surface is recommended for better approximating the residual stresses when using the hole-drilling method. As shown in Figure 3, the cutting fluid is strategically applied to the rake face to examine the effect of reducing the secondary shear zone temperatures on subsurface residual stresses and overall machining performance. Also, to investigate the impact of the cutting fluid quantity, various amounts of cutting fluid are applied on the rake face dry, 600 mL/min (HQF) and 300 mL/h (MQF). As seen from the experimental plan, no cutting fluid is applied on the cutting tool flank face in the first set of experiments (No. 1-3). In the second set of experiments (No. 4–6), the cutting fluid with various compositions is targeted on the cutting tool flank face to investigate its cooling effect on temperature rise in the tertiary shear zone (i.e., just machined surface near the cutting tool flank face). By using various cutting fluid compositions, the tertiary zone heat energy is naturally controlled (dry condition), with compressed air (at 0.689 MPa), water (at 300 mL/h), and cutting fluid (at 300 mL/h). For this set of experiments, cutting fluid at 300 mL/h is applied on the cutting tool rake face to manage secondary shear zone temperatures.

For this study, face-turning machining experiments are conducted on a HAAS® SL-20 turning center. A Raytek® Pi20 Infrared Radiation (IR) camera is used to measure the machining temperatures. To measure machining temperatures with the IR camera, an emissivity of 0.75 is applied to machining the workpiece at 400 mm from the work surface. The machining surface roughness is measured on the Zygo® Newview profilometer, Middlefield, USA. This study considers the surface roughness *Ra* to evaluate the surface integrity metrics per the ANSI B211.1-1986. As previously mentioned, the machining-induced residual stresses were measured using the hole-drilling method in accordance with the ASTM E837-08 standard [27]. Residual stresses for all the machined parts were measured precisely at the same radial distance from the center of the workpiece to ensure measurement consistency and to have a uniform reference for plotting the data. The machining cutting forces are measured for every experiment using a Kistler® three-component piezoelectric dynamometer. The microstructural analysis is carried out using a FEI Quanta

600 FEG SEM, Hillsboro, USA. The microhardness is measured for every experimental condition using a Shimadzu MV microhardness tester with a 100 g load and 15 s dwell time.

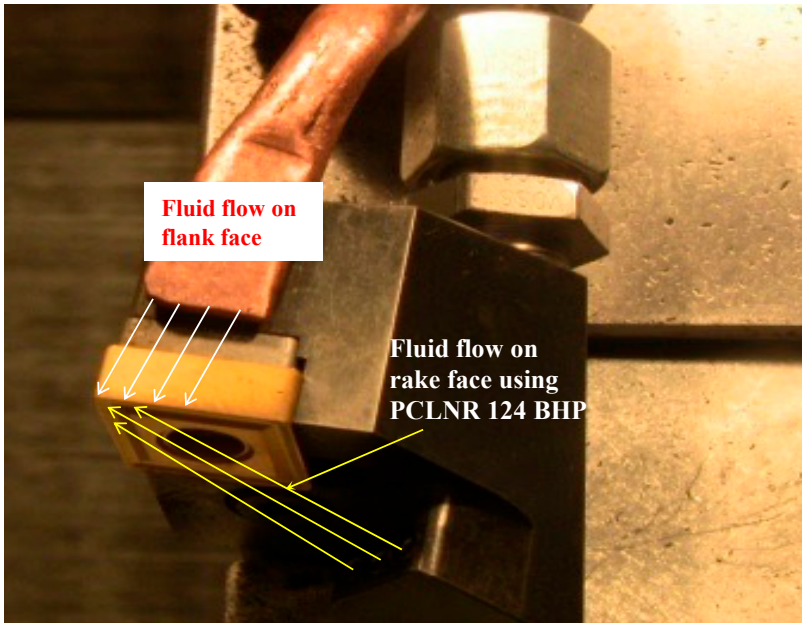


Figure 3. Experimental setup: strategically targeting the cutting fluid onto the rake and flank faces [28].

3. Results and Discussion

This section details the impact of the targeting cutting fluid on machining mechanics (cutting forces, chip formation) and surface integrity metrics (machining-induced residual stresses, surface roughness, microhardness, and microstructural analysis).

3.1. Residual Stresses Due to Targeted Cutting Fluid Application

3.1.1. Varied Cutting Fluid Application on the Cutting Tool Rake Face and No Cutting Fluid on the Cutting Tool Flank Face

Researchers in academia and industry have used the hole-drilling method for measuring the machining-induced surface (and subsurface up to 2 mm in depth [29]) residual stresses because of the method's measurement accuracy [30] and ease of implementation [29]. Figure 4 illustrates the maximum principal residual stresses induced by machining by directing the cutting fluid onto the cutting tool rake face. The results show that dry machining produced 509.9 MPa of surface and peak residual stresses at 0.005 mm from the surface. The MQF application produced 244.6 MPa tensile surface residual stresses, while a high quantity fluid application HQF produced −145.5 MPa of compressive surface residual stresses. According to the results, dry machining typically generated higher tensile residual stress, consistent with previous studies on machining steel [10,28,31]. Using an MQF for the same process reduced the level of surface residual stress [31]. As the quantity of fluid increases, the residual stresses decreased even more significantly. The increased quantity of cutting fluid reduced the machining temperatures, reducing the surface residual stresses. The reduction in the IR camera-measured temperatures (181 °C for dry machining, 155 °C for MQF, and 95 °C for HQF) at the tooltip, as seen in Table 2.

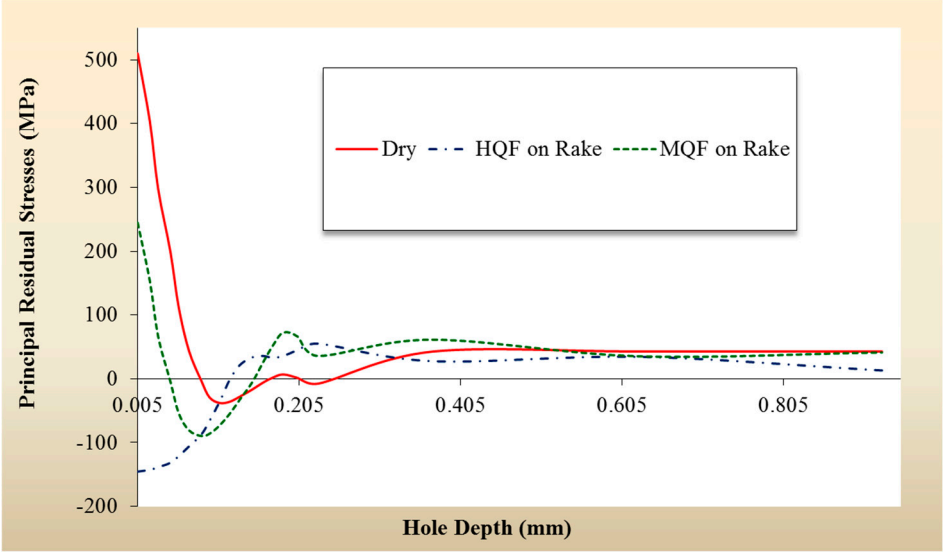


Figure 4. The effect of targeted cutting fluid application on the rake face and no fluid application on the flank face on maximum principal residual stress (MPa).

Table 2. IR camera-measured machining temperatures at the tooltip (CF application on rake face).

Cutting Fluid Application on the Tool Rake Face	Cutting Fluid Application on the Tool Flank Face	Measured Machining Temperatures at the Tooltip by the IR Camera	Variation
None	None	181 °C	Fluid quantity on the rake face.
HQF on the Rake	None	95 °C	
MQF on Rake	None	155 °C	

Applying more cutting fluid onto the rake face lowered the secondary shear zone temperatures, thus reducing the heat energy transferred to the tertiary zone, or just machined subsurface. This effectively reduced the thermal residual stresses and, consequently, the total residual stresses in the subsurface. Machining residual stresses are a combination of compressive stresses induced by mechanical load and tensile stresses induced by the temperature [7,32]. By applying a high quantity of cutting fluid, some of the cutting fluid applied onto the cutting tool rake face splashes onto the cutting tool flank face, potentially lowering temperatures in the just machined subsurface. This effect can be observed in the temperature maps from the IR camera, as illustrated in Figure 5.

Machining an annealed medium carbon steel produced long, continuous chips, even with the use of a standard chip-breaker geometry study. As we targeted the cutting fluid beneath the chip, the lower surface of the chip was considerably cooled. This temperature change on the chip's lower side changed the chip curl mechanism [33]. Further analysis to quantify this chip formation is discussed later in this paper. The thermal images from the IR camera indicated that a significantly high-temperature 'chip nest' formed during dry machining. In contrast, applying cutting fluid to the rake face did not form a 'chip nest'; instead, long chips were broken, as seen in Figure 5. 'Chip nest' formation leads to a high ambient temperature after machining, potentially damaging the just machined subsurface. This also contributes to subsurface residual stresses' tensile nature [34].

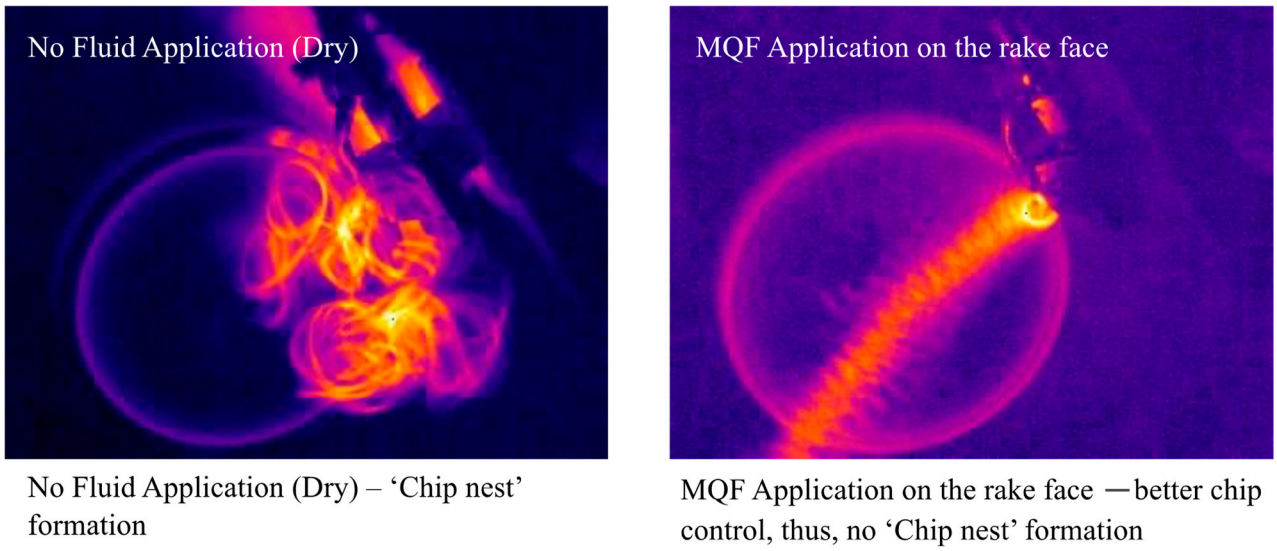


Figure 5. Temperature maps showing the effect of targeted MQF on chip formation.

3.1.2. MQF Application on the Cutting Tool Rake Face and Varied Cutting Fluid Application on the Cutting Tool Flank Face

In the second set of experiments, varied amounts and types of cutting fluid are targeted onto the flank face, while the MQF application is targeted onto the tool rake face. The maximum principal residual stresses induced by machining, achieved by strategically targeting the cutting fluid onto the tool flank face, are shown in Figure 6. The impact of strategically targeting the cutting fluid on measured temperatures at the tooltip by the IR camera is provided in Table 3. Applying the mixture of water and oil (semi-synthetic fluid) to quench the tertiary shear zone temperature generated a surface residual stress of −81.3 MPa. Applying water as a quenchant onto the flank face generated compressive surface residual stress of −251.5 MPa. A jet air as a quenchant for cooling the just machined surface generated compressive surface residual stress of −78.5 MPa. The surface residual stresses were measured at 0.005 mm depth from the surface.

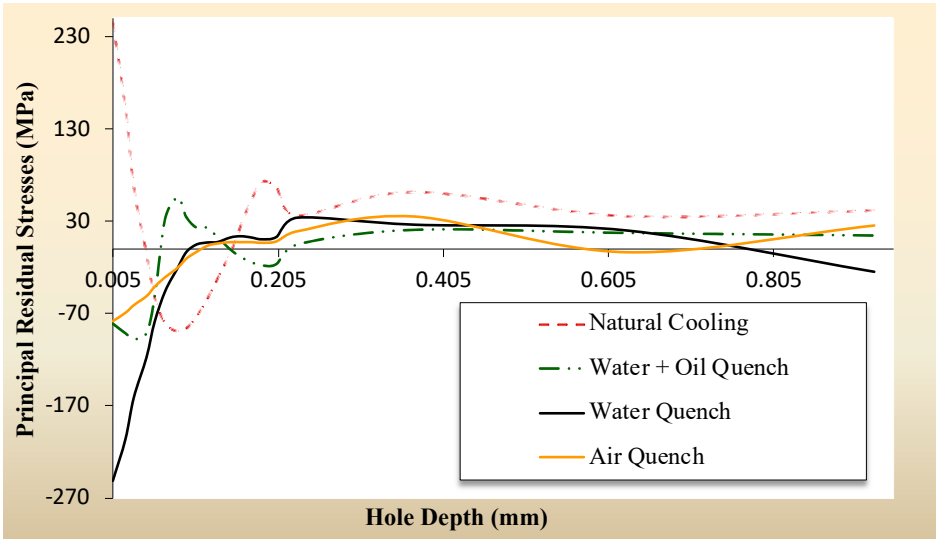


Figure 6. The effect of targeted cutting fluid application on the flank face and MQF application on the rake face on maximum principal residual stress (MPa).

Table 3. IR camera-measured machining temperatures at the tooltip (CF application on flank face).

Cutting Fluid Application on Rake Face	Cutting Fluid Application on Flank Face	Cooling Method	Measured Machining Temperatures at the Tooltip by the IR Camera	Variation
MQF on Rake	None	Natural	155 °C	Cooling the just machined surface with different cutting fluids.
MQF on Rake	MQF on Flank face	Water + oil cooling	142 °C	
MQF on Rake	Water cooling	Water cooling	117 °C	
MQF on Rake	Air cooling	Air cooling	140 °C	

As explained earlier, no cutting fluid was applied to the tertiary shear zone (along the cutting tool flank face), while the application of MQF on the rake face resulted in tensile residual stresses. In this setup, a mixture of water and oil (a cutting fluid, flood cutting fluid composition) was applied as a minimum quantity of cutting fluid onto the just machined surface, serving as a cooling agent. This resulted in a rapid decrease in temperature at the tertiary shear zone. The targeted MQF (cooling) of the just machined work surface' resulted in reduced thermal residual stresses and, consequently, lower overall residual stresses in the machined subsurface. When using water as the sole cutting fluid, temperatures decrease more rapidly, leading to the creation of more compressive residual stresses, which is beneficial for improved surface integrity. The residual stress distribution profile indicates that water is one of the most effective natural coolants, with a higher cooling rate compared to cutting fluid (water + oil) and compressed air. The cutting fluid with water as the main ingredient (cooling) produced the highest peak compressive principal residual stresses (−251.5 MPa). Figure 6 shows that employing water as a cutting fluid produced a crossover depth of 0.093 mm. These high compressive stresses partly arise from microstructural changes in the machined subsurface caused by the (targeted) cooling effect of the cutting fluid, which is explained further in the later sections of this paper. Although the surface residual stresses are similar for water + oil-based cutting fluids compared to air-based cutting fluids, a difference is observed in the crossover depth. Air-based cutting fluid has the highest crossover depth (0.112 mm) compared to cutting fluid (water + oil) (0.074 mm) and pure water (as cutting fluid) cooling (0.093 mm). Air from the flank fluid jet penetrates closer to the tooltip/cutting edge than the other two cutting fluids, resulting in a slight increase in quenching time and crossover depth. It is possible to increase the magnitude and depth of compressive residual stress and depth by increasing cutting fluid volume, jet velocity, and, consequently, the cooling rate. However, a higher cooling rate at the tooltip can increase the percentage of martensite in the machined subsurface, resulting in the formation of a white layer and part distortion (which may cause surface inaccuracies and a reduction in surface integrity in some cases). This topic will be elaborated on in a future section of this paper. Hence, a balanced approach between a cooling rate that is too high and a cooling rate that is too low needs to be further investigated.

3.2. Surface Roughness

Machining-generated surface roughness values were measured using a cutoff value of 0.8 mm, as recommended in the literature [35]. The average surface roughness (Ra) values were obtained at three different surface locations and plotted, as shown in Figure 7. Results from Figure 7 show that dry machining produced the highest surface roughness values. For targeted cutting fluid application, the surface roughness produced by targeting the MQF on the flank and the rake face (0.588 μm) is better than the surface roughness produced by dry machining (0.720 μm). Cutting fluid application reduces the machining temperatures,

thereby improving the generated surface; the same can be seen in the results in this paper as well. A similar observation of minimum quantity cutting fluid reducing the machining temperatures and thereby reducing the surface roughness was made by the researchers machining weld flash of spring steels [36]. Also, the dry machining process produced a 'chip nest', as shown in Figure 5, negatively affecting the machining surface roughness. The surface roughness produced by applying HQF onto the rake face was 0.689 µm, while the surface roughness produced by applying MQF onto the rake face was 0.679 µm. The quantity of the cutting fluid on the rake face alone did not affect the machining surface roughness values, as reported in the literature [24]. Targeting the cutting fluid on the rake affects the tool–chip tribology, and thereby the chip formation, and tool–chip contact length; however, it does not influence the surface roughness values [24].

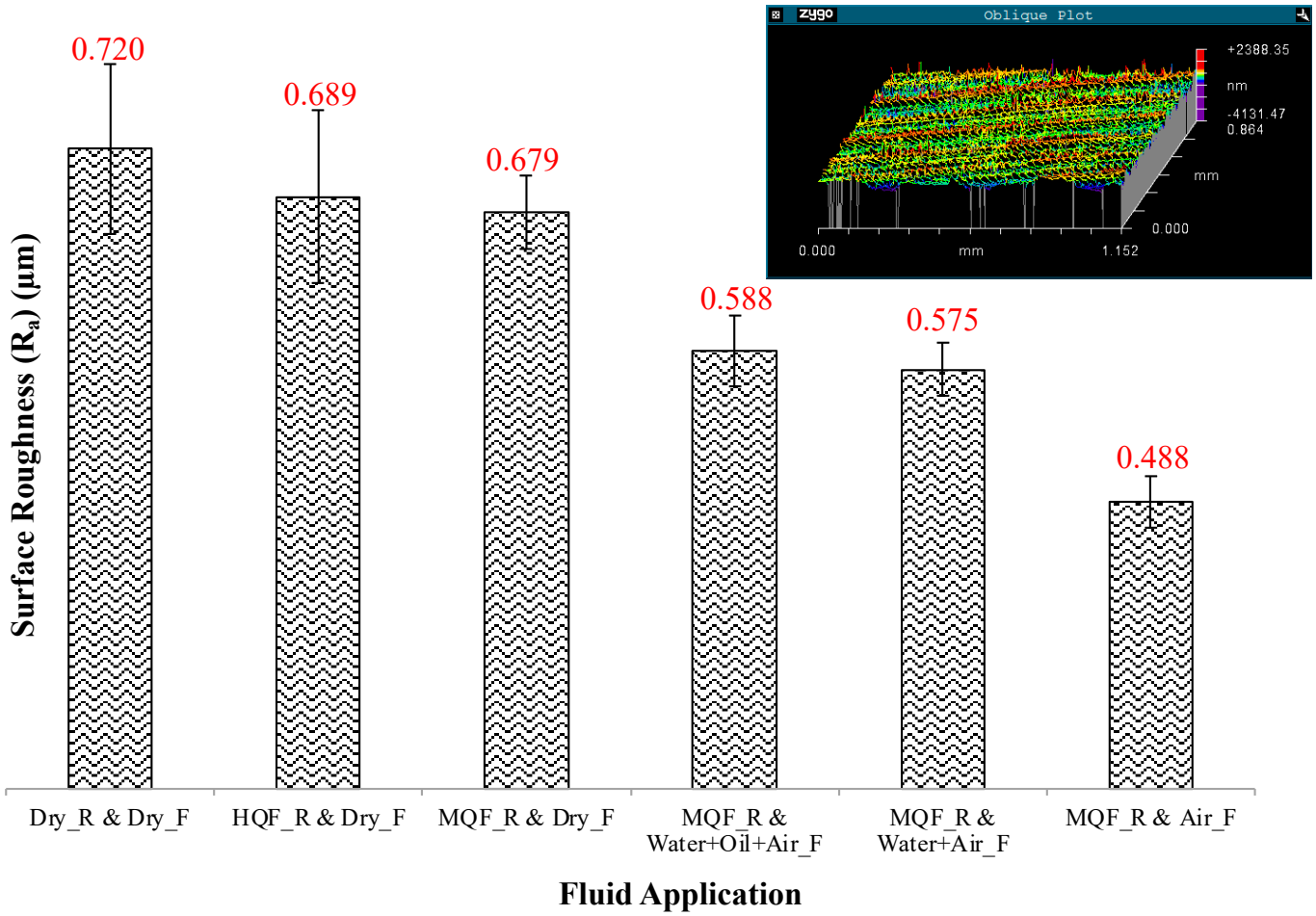


Figure 7. Effect of targeted cutting fluid application on surface roughness (*Ra*) (Insert: surface profile to measure Ra).

Machining surface roughness is mainly affected by the cutting conditions, tool geometry, and machining temperatures. With cutting conditions and the tool geometry remaining constant in this study, the variance in the machining temperatures caused the variation in surface roughness values. As the frictional coefficient decreased, the machined surface roughness decreased [37]. With the cutting fluid application on the rake and flank faces, the friction along the contact areas decreased, decreasing the surface roughness values. Another reason to explain the targeted MQF (TMQF) effect on the surface roughness values is the material side flow effect. The material side flow and its influence on surface roughness values are explained in the following sections.

3.3. Cutting Force

Cutting forces for every experimental condition are measured using a Kistler® three-component piezoelectric dynamometer. The measured forces (*Fz*, *Fy*, and *Fx*) for each case are plotted, as shown in Figure 8. The main cutting force (*Fz*) produced by the dry machining was 381 N, by applying HQF on the rake face was 369 N, by applying MQF on the rake face was 366 N, by applying MQF on the rake and the flank face was 341 N, by applying MQF on the rake face and water on the flank face was 356 N, and by applying MQF on the rake face and air on the flank face was 353 N. The results show that TMQF had a statistically insignificant effect on the cutting forces compared to dry (or no fluid) machining. The differences in the measured forces were within a standard deviation. With the application of the TMQF on the rake face, the tool–chip frictional performance was enhanced. However, this effect did not appear on the forces due to the cutting fluid jet force acting on the tool [24]. The cutting fluid jet was targeted underneath the chip to improve its frictional performance. The cutting fluid jet acted as a dynamic chip-breaking tool, the details of which will be explained in later sections. The additional force from the cutting fluid jet acting on the tool also skewed the measured forces. TMQF application has shown a profound effect on the surface integrity measures but a very minimal effect on produced/measured cutting forces. Researchers have reported that cutting fluids are known to have a minimal impact on the cutting forces when machining AISI 1045 steel [38].

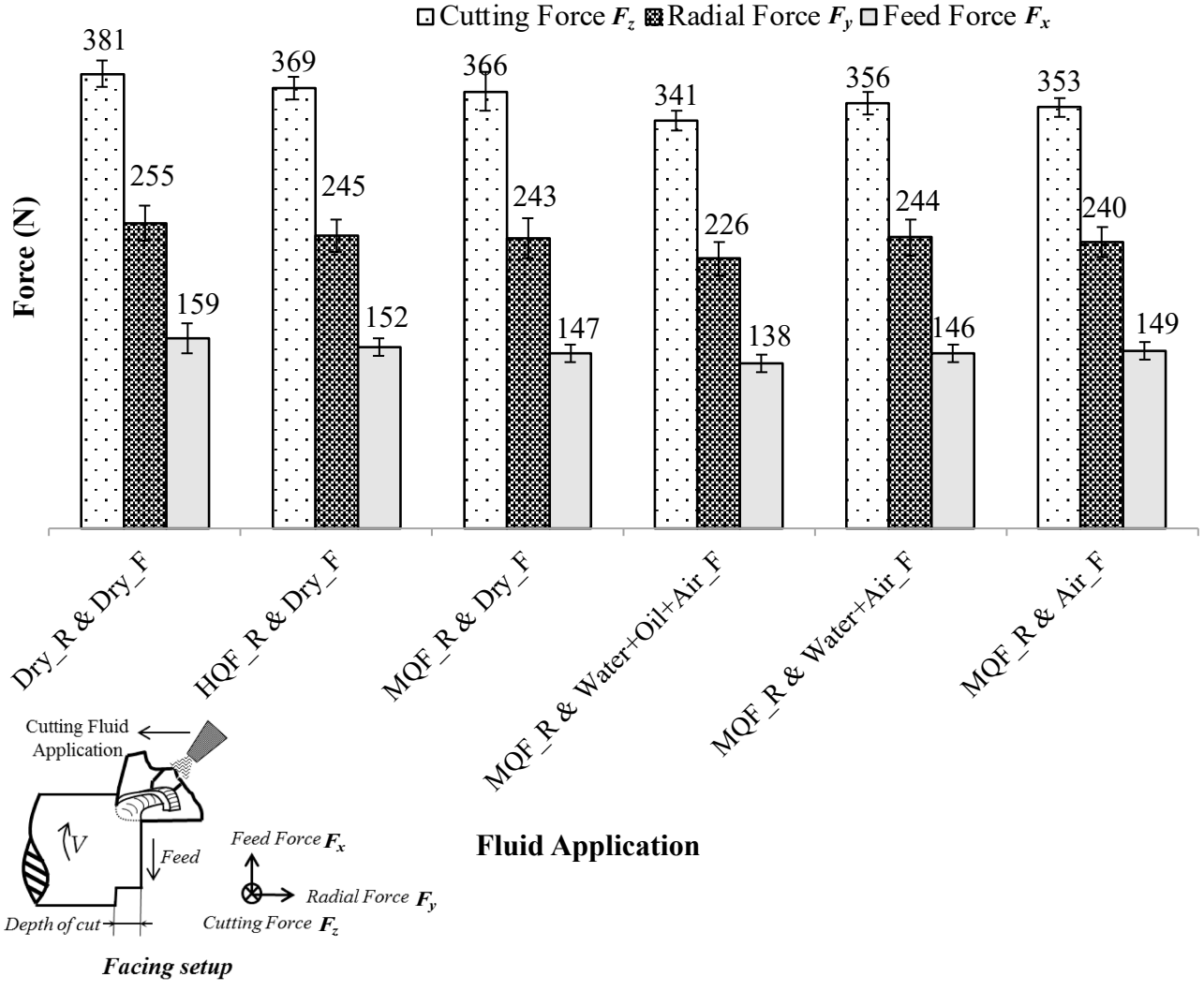


Figure 8. Targeted cutting fluid application effect on cutting forces when machining annealed AISI 1045 steel with coated CVD carbide cutting tool.

3.4. Chip Formation

For post-processing analysis, the produced chips from each experiment—which serve as an excellent measure of the material deformation undergone in complex machining processes—are collected and arranged, as shown in Figure 9. As mentioned earlier, the TMQF application assisted the chip-breaking process, which typically improves the overall machining performance. The chip morphology shows that the chip-breaker geometry is ineffective for dry machining. The selected tool is recommended for finish machining; even then, the dry machining chips are long and continuous. The effect of a long (and high temperature) machining 'chip nest' on surface integrity has been addressed earlier in Section 3.1. With the TMQF application, the cutting fluid jet acted as a dynamic and external chip control mechanism. Along with small chips, the TMQF application produced chips at lower temperatures. The collected IR temperature maps showed that for TMQF application, the temperatures along the chip surfaces are smaller compared to dry machining. The chip surface temperatures are lowest when the cutting fluid is targeted upon the rake and flank faces. This occurs due to the TMQF application on targeted surfaces reducing the machining temperatures and, thereby, the overall chip temperatures.

Chips produced in this study are prepared for photo-micrographic analysis using an optical microscope. Chip bottom surfaces (or lower part of the chip) are slightly polished and etched (using 5% Nital etchant solution) to obtain the micrographic images shown in Figure 10. The images show that the frictional resistance is typically reduced with TMQF application. The plastic striations on the chip surface for dry machining are severely stretched. In contrast, the plastic striations due to the TMQF are moderately severe, indicating lower plastic strains along the tool–chip interface. The plastic strains on the chip's lower surface indicate the variable and complex frictional behavior at the tool–chip interface and within the heavily strained chip [33].

Another interesting phenomenon observed from optical images is the chip side flow. At high temperatures, the cutting tool's edge displaces material in the high-temperature zone to the side of the cutting edge, causing side flow [39]. A multiple-coated CVD tool has a rounded edge, which produces higher temperatures due to the local negative rake angles at small undeformed chip thicknesses (leading to the size effect in machining). With (local) negative rake angles leading to increased temperatures, the material beneath the cutting edge undergoes plastic deformation. It behaves like a viscous liquid, pushing the material out of the cutting-edge area as a side flow [39]. This mechanism increases the surface roughness. From Figure 10, it is observed that there is considerable side flow for the dry machining condition, thereby increasing the corresponding measured surface roughness. However, with TMQF application, the machining temperatures are reduced, thus reducing the chances of squeezing the material near the cutting edge as side flow (as seen in Figure 10) and resulting in better (lower) surface roughness values when compared to no fluid (dry) application.

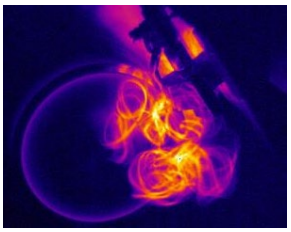
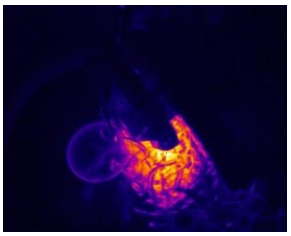
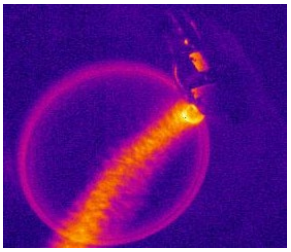
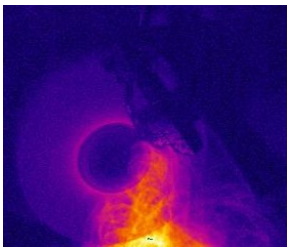
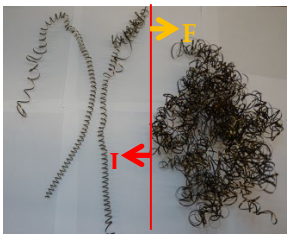
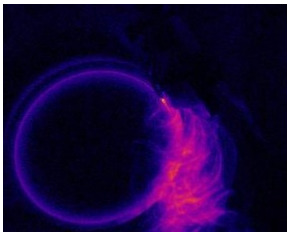
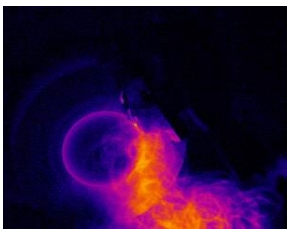
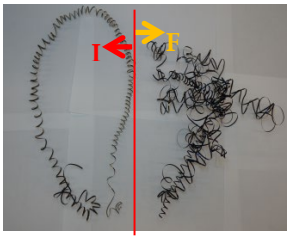
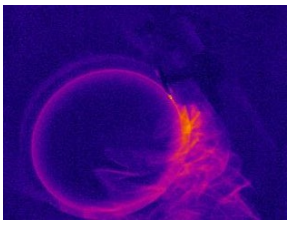
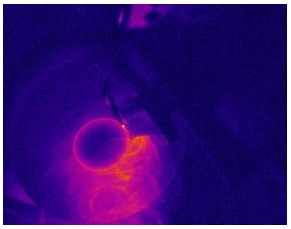
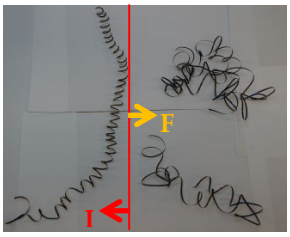
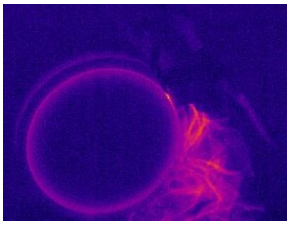
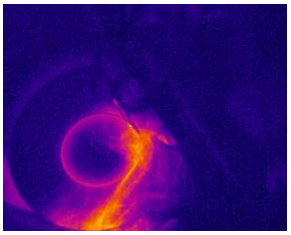
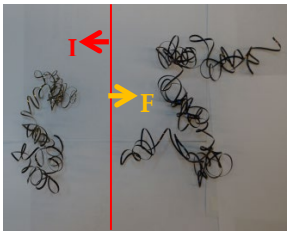
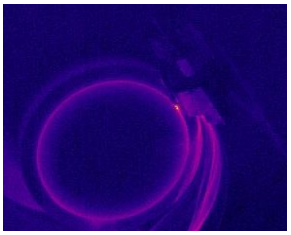
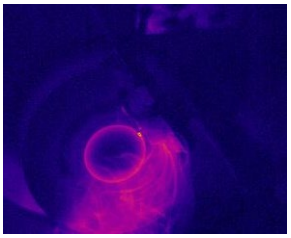
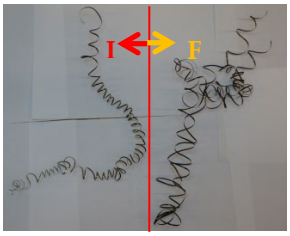
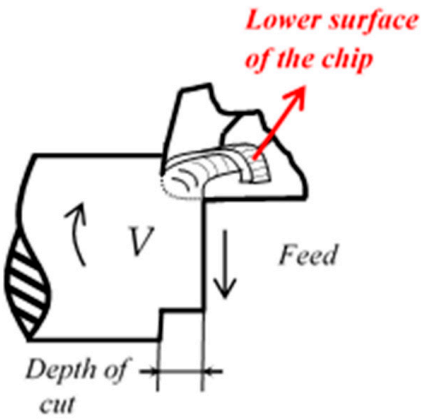
Cutting Fluid Application	IR image at Initial stage	IR image at Final stage	Photographic evidence*
Dry on Rake Face & Dry on Flank Face			
HQF on Rake Face & Dry on Flank Face			
MQF on Rake Face & Dry on Flank Face			
MQF on Rake Face & Water + oil + Air on Flank Face			
MQF on Rake Face & Water + Air on Flank Face			
MQF on Rake Face & Air on Flank Face			

Figure 9. Effect of cutting fluid application on chip morphology. * Left side of the chip from Initial (I) stages of the process and right side of the chip from Final (F) stages of the process.



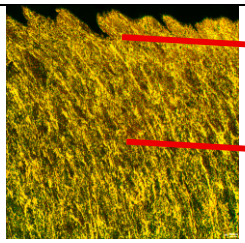
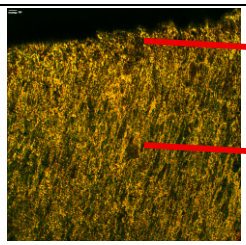
Photomicrograph of 'lower surface of the chip' (200X)	
Dry on Rake and Dry on Flank	 *Chip side flow* *Heavy plastic strain*
MQF on Rake and MQF on Flank	 *Reduced Chip side flow* *Reduced plastic strain*

Figure 10. Effect of cutting fluid application on chip side flow.

3.5. Modeling Heat Transfer Effect of Cutting Fluid

The targeted cutting fluid acts similarly to jet impingement in high-temperature zones in machining. Therefore, the heat transfer from the workpiece using a targeted cutting fluid can be assumed to be by forced convection. One method for quantifying the cooling impact of targeted fluid jets is to determine their heat transfer coefficients using the Nusselt number correlation. Researchers assumed the flank face cutting fluid was an impinging jet parallel to the flank face and the just machined surface [40]. Thus, the Nusselt number (Nu) correlation for the cooling can be used as follows [41],

$$\mathrm{Nu} = 0.644\mathrm{Pr}^{1/3}\mathrm{Re}^{1/2} \tag{1}$$

where Re is the Reynolds number and Pr is the Prandtl number. Researchers like Li [40] have used the correlation mentioned above to evaluate the cooling effectiveness of cutting fluid on the flank face during turning operations. Similarly, Ramesh et al. [42] used the correlation for cutting fluid impingement when grinding. However, the correlation's effectiveness and accuracy rely on the precise computation of the fluid jet's Reynolds number. The cutting fluid is aimed at the flank face using a fluid jet applied to a rotating workpiece through a V-shaped channel, as shown in Figure 11. Obikawa et al. modeled the Reynolds number (Re) for the fluid flowing through V-shaped channel geometry, such as a fluid jet onto the flank face as given in Equation (2) [43],

$$\mathrm{Re} = \frac{\rho v_0 \tan\alpha}{\mu}\left[1 - \exp\left(\frac{-l}{m}\right)\right]l \tag{2}$$

The Reynolds number calculation accounts for the rotation of the workpiece and the velocity of the cutting fluid jet (v_0). The rotation of the workpiece counters the cutting fluid velocity jet, which is incidentally reduced to zero at the tooltip. The density of the cuttingfluid is given by ρ, the dynamic viscosity of the cutting fluid is denoted by μ, and

the flank clearance angle of the cutting tool is given by α. The distance from the tooltip is represented by l, while m serves as an exponent (m = 5 mm). The Prandtl number is presented in Equation (3),

$$\mathrm{Pr} = \mu C_p / k \tag{3}$$

where C_p and k represent the specific heat and thermal conductivity of the cutting fluid, respectively. Using Equations (1)–(3), along with the properties of the cutting fluids from Table 4, the Reynolds and Nusselt numbers are calculated along the flank face. This study solely examines the cooling effect of the cutting fluid, excluding the interplay between air and fluid. In the context of water cooling, only water is regarded as the fluid, disregarding the effects of air mixing. This assumption is only made for the initial analysis. The modeling of the cooling effect of a fluid jet on the flank face primarily aims to emphasize the essential thermophysical properties for selecting an appropriate cutting fluid.

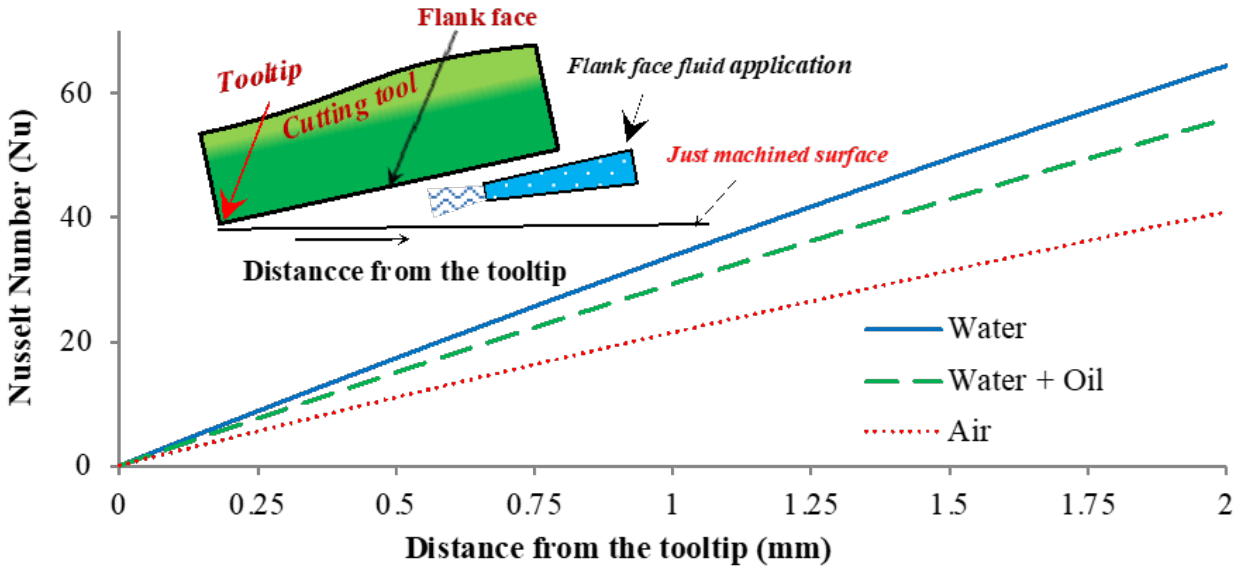


Figure 11. Nusselt number (Nu) for different cutting fluids from the tooltip on the flank face.

Table 4. Cutting fluid properties [4,44].

Cutting Fluid Application on Rake Face	Cutting Fluid Application on Flank Face	Cooling Method	Properties			
			ρ (Kg/m^3)	μ (cP)	C_p (J/Kg-K)	k (W/m-K)
MQF on Rake	MQF on Flank face	Water (90%) + oil (10%) cooling	999.2	2.68	4118	0.554
MQF on Rake	Water cooling	Water cooling	1000	1	4183	0.5984
MQF on Rake	Air cooling	Air cooling	1.2	0.02	1000.5	0.0257

The air-based cutting fluid medium has a higher Reynolds number than the other cutting fluids due to its lower viscosity. Lower viscosity and density of the air medium could allow it to reach the tooltip at a higher velocity, thereby enhancing the cooling effect. The impact of increased velocity can be observed in the crossover depth. As seen in Figure 6, the targeted air cooling (onto the flank face) has a higher crossover depth (0.112 mm), followed by water cooling (0.093 mm) and then by water + oil cooling (0.074 mm). A similar trend is evident in the viscosity of these cutting fluids and their corresponding Reynolds numbers. The Nusselt number indicates the heat transfer capability of the cutting fluids. As shown in Figure 8, water media exhibit a superior heat transfer rate, followed by water + oil-cooling

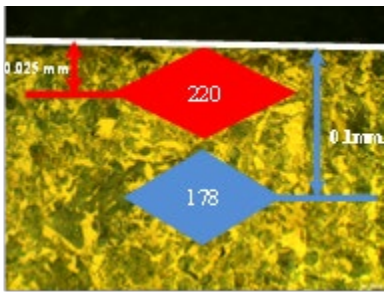
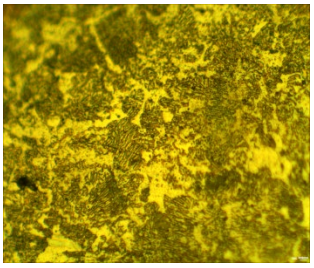
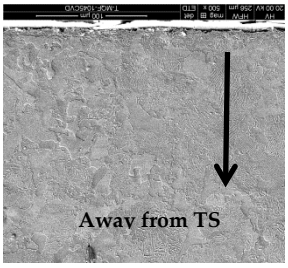
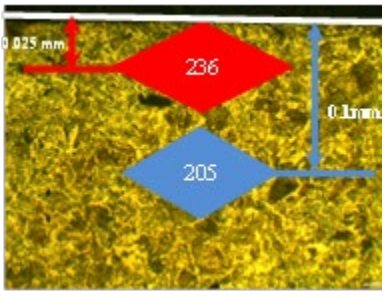
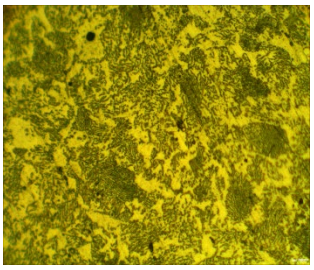
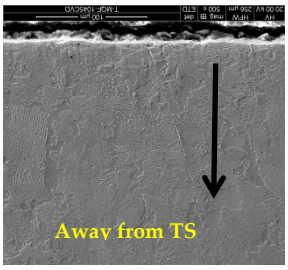
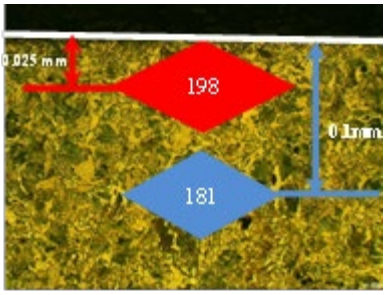
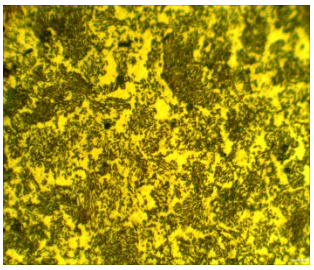
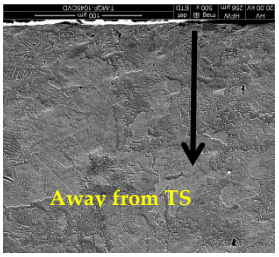
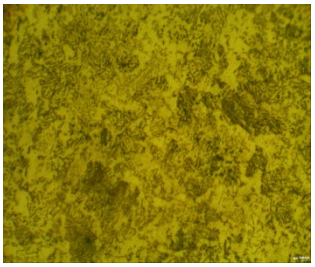
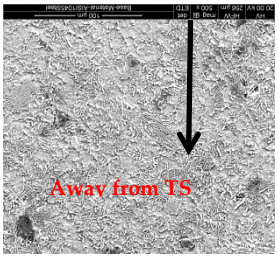
media and then air-cooling media. A similar trend can be observed for the peak residual stresses induced in Figure 6. Water cooling achieves a higher Nusselt number along the just machined surface, resulting in a greater reduction in machining temperature and, consequently, a lower machining-induced residual stress in the newly machined surface and subsurface, which leads to improved surface integrity of the machined component. Thus, for sustainable industrial usage, using a water + oil-based cutting fluid with high-pressure jet application on the flank face improves the machining-induced surface integrity.

3.6. Microstructure and Microhardness

The surface integrity of a machined subsurface encompasses microcracks, tears, surface phase transformations, residual stresses, surface roughness, etc., [5]. As per ANSI B211.1-1986, the microstructure (top surface and cross-section) and microhardness are measures of surface integrity. In order to completely understand the TMQF effect on machining surface integrity, a detailed microstructural analysis is conducted. A cubical piece is cut from the machined AISI 1045 steel surface, as shown in Figure 12. The top surface (machined surface) and the cross-section surface (in the feed direction) are polished and etched with 3% Nital solution. The surface's (top and cross-sectional) micrographical images are collected from optical and scanning electron microscopes (SEMs). The collected images are shown in Figures 12 and 13, along with the associated microhardness values. Microhardness values are measured using a Shimadzu MV microhardness tester with a 100 g load and 15 s dwell time.

A glance at the machined AISI 1045 steel microscopical images rules out the possibility of martensitic formation, which was mentioned as a possibility in the earlier sections of this paper. The base material (before machining) is an annealed AISI 1045 steel, and its microscopical images are seen in Figure 12. The base material, as expected, consists of evenly distributed pearlite and ferrite colonies. Machining the annealed surface without cutting fluid application created larger pearlitic colonies near the subsurface. However, with HQF (600 mL/min) application, finer pearlitic colonies were observed near the subsurface (as suggested by rapid cooling). Due to the finer grains, the microhardness value slightly increased (from 220 HK (from dry machining) to 236 HK). With the decrease in the flow rate of cutting fluid application, the number of pearlite colonies decreased, and thus, the microhardness decreased as well (to 198 HK). An observation from Figure 13 is that very fine pearlite colonies formed near the subsurface due to the cooling of the flank fluid jet. The distance between the pearlite can establish the cooling rate effect on the microstructural formation. Further analysis to quantify this cooling rate effect is recommended to model and optimize the TMQF application further.

With a cutting fluid jet near the just machined surface, the possibility of white layer formation has been investigated. The combined effects of the pressures and temperatures during carbon steel machining could be sufficient to trigger the transformation from pearlite to austenite at a much lower temperature than normal [45]. Therefore, martensite formation is observed if the machining-induced temperatures are rapidly cooled. Martensite has a negative thermal coefficient of expansion, resulting in a local volume increase and inducing compressive residual stresses in the subsurface [25,46]. The results show no white layer formation along the machined subsurface, as the cutting fluid jet on the tool rake face lowered the overall machining temperatures in the primary shear zone. As these temperatures are lower than the austenitizing temperatures of AISI 1045 steel, white layer formation and any of its negative effects on surface integrity are avoided.

Cutting Fluid Application	Cross-section images (500x) with microhardness values	Top-section (TS) images (500x)	Cross-section SEM images (500x)
Dry on Rake Face & **Dry** on Flank Face			
HQF on Rake Face & **Dry** on Flank Face			
MQF on Rake Face & **Dry** on Flank Face			
Base Material			

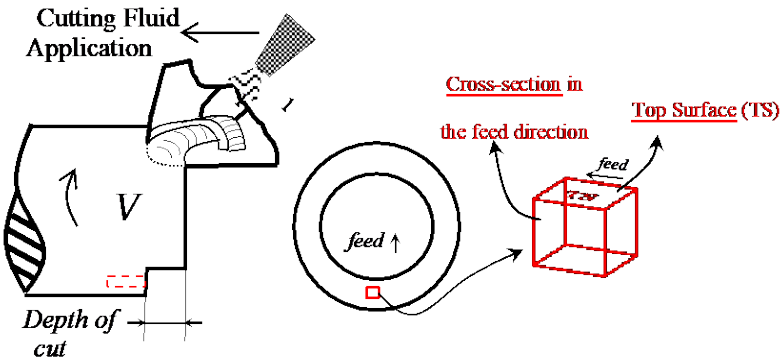


Figure 12. Microstructural analysis using an optical microscope and SEM images for conditions with no fluid application on the flank face (Microhardness values are in Knoop microhardness (HK)).

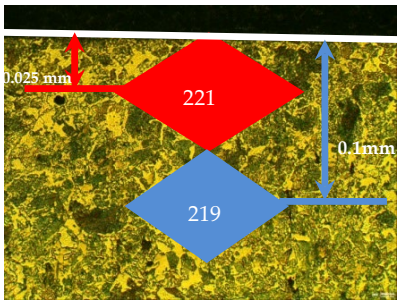
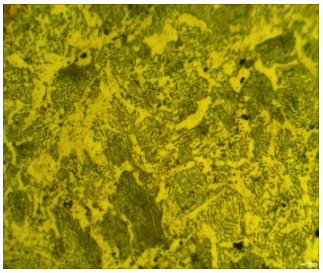
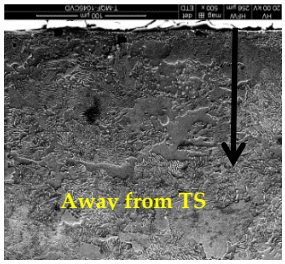
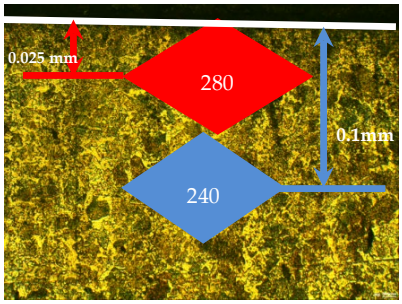
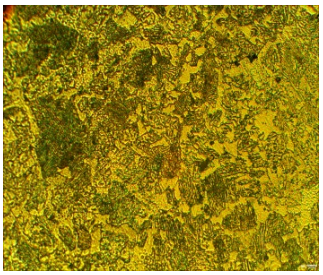
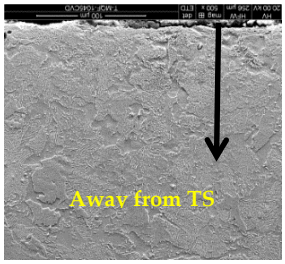
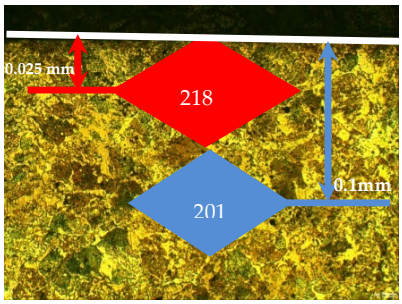
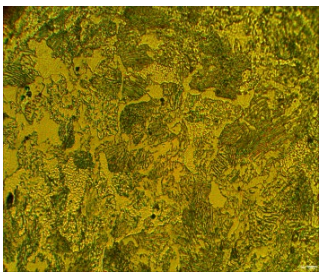
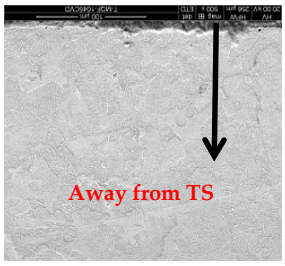
Cutting Fluid Application	Cross-section images (500x) with microhardness values	Top-section (TS) images (500x)	Cross-section SEM images (500x)
MQF on Rake Face & **Water + oil + Air** on Flank Face			
MQF on Rake Face & **Water + Air** on Flank Face			
MQF on Rake Face & **Air** on Flank Face			

Figure 13. Microstructural analysis using an optical microscope and SEM images for conditions with targeted cutting fluid application on the flank face (Microhardness values are in HK).

4. Conclusions

In this study, the effects of strategically targeting varied amounts and varied types of cutting fluid to reduce the machining temperature and improve the surface integrity metrics, chip formation, and cutting forces have been investigated. The combination of workpiece and cutting tool for this study was an annealed AISI 1045 steel paired with a CVD multicoated carbide tool. Machining experiments were performed to understand the effects of the targeted cutting fluid, resulting in the following findings:

1. Applying cutting fluids to the tool rake face reduced the temperatures along the cutting edge and lowered the surface residual stresses on the machined surface compared to dry (no fluid application) machining. When a higher amount of targeted cutting fluid is applied along the tool rake face, the residual stresses are lower (or more compressive). Higher compressive stresses suggest improved surface and subsurface quality and integrity.
2. A targeted MQF application at the tool flank face rapidly cooled the temperatures at the just machined subsurface, resulting in compressive subsurface principal residual stresses. Effectively targeting MQF on the rake and flank faces substantially improved

subsurface integrity. Therefore, a higher quantity of fluid application on the rake face can be eliminated, enhancing sustainable manufacturing in machining operations within the industry.

3. The surface roughness values show that the TMQF application effectively improved the quality of the machined surface. The decrease in machining temperatures and the improved chip control mechanism were crucial in achieving better surface quality.
4. The chip morphology shows that the chip-breaker geometry was ineffective for dry machining, and the chips were long, continuous, and formed 'chip nests'. With the TMQF application, the fluid jet acted as a dynamic and external chip control mechanism. In addition to being small, the TMQF application produced chips at lower temperatures.
5. The microstructural analysis shows that white layer formation can be safely avoided, and TMQF application creates finer pearlitic colonies to improve the local surface hardening in the machined subsurface.
6. The cutting fluid's viscosity and density influence the crossover depth of the residual stress profile. Lower viscosity and density result in an increase in the velocity of the cutting fluid striking the surface, thereby enhancing the ability to reduce surface temperatures. In contrast, the thermal properties of the cutting fluid influence the magnitude of the peak subsurface principal residual stress.

Overall, the main idea of effectively controlling temperatures in machining with different cutting fluid types, quantities, and application locations to enhance surface integrity metrics has been studied. The higher the cooling rate of the cutting fluid on the cutting tool flank face, the lower the subsurface principal residual stresses. By strategically applying the cutting fluid, this paper highlights improvements the industry could use to enhance chip control and create machined surfaces and components with better surface integrity.

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