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Wear Mechanism of an AlCrN-Coated Solid Carbide Endmill Cutter and Machined Surface Quality under Eco-Friendly Settings during Open Slot Milling of Tempered JIS SKD11 Steel

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Abstract: In the die and mold industry, tempered JIS SKD11 steel is selected to manufacture cold-forming dies that require an optimum balance of toughness, strength, and wear resistance. Therefore, the machinability of tempered JIS SKD11 in the milling machining process is challenging. The use of eco-friendly machining settings is intended to diminish tool wear and enhance the quality of the machined surface as well as the accuracy of the machined components. Adapting to the aforementioned factors for cold-forming dies is a pivotal issue. In this study, the machinability of tempered JIS SKD11 steel was analyzed under dry, MQL, cryogenic cooling with liquid nitrogen (LN_2), and liquid carbon dioxide (LCO_2) machining settings during open slot milling operations with varying input parameters, including cutting speeds and cutting feeds. An in-depth evaluation of output responses, including tool wear, surface roughness, cutting temperature in the cutting zone, and microhardness of the machined surface, was also conducted. The findings unveiled that the flank wear of the cutters and surface roughness of the machined surfaces obtained minimum values of 0.22 mm and 0.197 μm, respectively, during open slot milling operations at a cutting speed of 100 m/min and a cutting feed of 204 mm/min under cryogenic cooling with liquid carbon dioxide (LCO_2). The findings from this study suggest that employing cryogenic cooling with LCO_2 could serve as a viable substitute for dry, MQL, and cryogenic cooling with LN_2 methods to enhance the machinability of hardened JIS SKD11 steel.

Keywords: minimum quantity lubrication (MQL); cryogenic cooling; tool wear; microhardness; surface roughness

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1. Introduction

Hard machining generally refers to the process of shaping materials that possess a hardness level exceeding 45 HRC and is commonly applied to materials with hardness ratings ranging between 58 and 68 HRC. The types of materials typically processed include a variety of hard alloy steels, tool steels, case-hardened steels, superalloys, nitride irons, hard chrome-coated steels, and heat-treated powder metallurgical components. The primary objective of hard machining is to attain precise dimensions, shapes, and surface finishes, and it is predominantly used in the final or near-final stages of production. A variety of machining techniques such as turning, milling, boring, and broaching are applied to these materials. In recent years, there has been substantial growth in the mold and die sector globally. The distinct features of this industry have captured the interest of those involved in metal-cutting and machining processes. According to established machining methods, cores and cavities are machined from materials such as pre-hardened mold steel and hot-work chromium-molybdenum tool steel. These materials, known for their optimal balance of toughness, strength, and wear resistance, are initially machined in their hardened state and then processed through electrical discharge machining (EDM). In contemporary practice, however, these materials are directly machined using Computer-Aided Manufacturing (CAM) software in conjunction with Computer Numerical Control (CNC) machines to facilitate hard milling [1]. Kazuo Nakayama et al. [2] explored the intricacies of machining hard materials, a process distinct from conventional machining. Unlike traditional methods, hard machining requires a fresh perspective. To enhance machining technology for hard materials, understanding their unique characteristics is essential. Their study revealed that the machined surface profile of hardened steel closely mirrors that of the cutting tool; as long as the tool profile remains smooth, surface finish remains unaffected by tool wear. JIS SKD11 steel, with a hardness of 58–62 HRC, is widely used in the die and mold industry for applications such as cold-forming dies, die casting, plastics molding, the press tool components of automobiles, and various applications that require high wear resistance and a substantial reduction in cost [3–5]. In their empirical investigation, Tonshoff et al. [6] explored chip-removal mechanisms during hard cutting and examined the thermomechanical effects within the work area. They introduced and analyzed multiple models of chip removal in hard turning, summarizing metallurgical principles and offering insights into stress and temperature distribution. Their findings emphasized the significance of accounting for boundary conditions, such as machine tools and cutting materials, when assessing the workpiece quality and economic efficiency of hard cutting processes in comparison to grinding. Investigations into the machinability of JIS SKD11 steel, particularly after heat treatment to an average hardness of 58–62 HRC, are indeed significant due to the material's low thermal conductivity. This property can lead to high temperatures in the cutting zone, affecting both the tool–workpiece and tool–chip interfaces during the machining process. Wear mechanisms, diffusion, and cutting conditions affect the high accuracy, hardness, and surface roughness of the machined parts. This is a big challenge in the machining process [7–9]. Furthermore, there are many factors that affect the quality of the machined surface. These include the geometry of the cutter, oscillations in the machining process that cause phenomena such as built-up edges, and oscillations caused by surrounding machines in the workshop. Cutting conditions, which consist of depth of cut, feed rate, cutting speed, cutter coatings, and cutting fluids, also play a role. Wear on the cutter, particularly on the flank and rake faces, can lead to a decrease in the quality of the machined surface. Therefore, lubrication and cooling strategies in the machining process are pivotal techniques to reduce tool wear and simultaneously enhance the quality of the machined surface, achieving the smallest possible values. On the other hand, lubrication and cooling strategies also substantially decrease impacts on the health of operators in the workshop. Simultaneously, these strategies comply with environmental and ecological regulations, resulting in a substantial decrease in machining costs. Several literature reviews have identified cutting fluids that can meet these requirements, such as nanofluids, nanoparticles, and vegetables oils [10,11].

In their experimental study, Fox-Rabinovich et al. [12] investigated dry cutting conditions during the milling process of hardened H13 tool steel (with a hardness of HRC 52–55). They used ball nose end mill cutters coated with a TiAlCrSiYN/TiAlCrN nano-multilayer PVD coating. The study involved varying cutting speeds (500–700 m/min), a feed rate of 0.06 mm/tooth, an axial depth of 5 mm, and a radial depth of 0.6 mm. The researchers evaluated the coated tool's flank wear as an output response. Their findings suggested that the surface layer could achieve a robust non-equilibrium state, leading to stabilized interactions between the tool and the environment, resulting in low wear. Urbanski et al. [13] reported an experimental study on the use of high-speed machining in molds and dies manufacturing technologies. The investigation utilized independent variables including the coatings of the cutter (TiCN and TiAlCrYN), uncoated cermet, and cutting speed to identify the dependent variables consisting of tool wear, the quality of the machined surface, and cutting force during AISI H13 hot-work tool steel machining. The findings revealed that the solid carbide end mill had a tool life that was about 50% longer than that of the indexable insert end mill. The quality of the machined surface using the indexable insert end mill was slightly lower than that of the solid carbide end mill. Sebbe et al. [14] conducted an experimental study on the difficult-to-cut material Inconel 718. Their study used ISO 8688-2 to evaluate the wear mechanism on the cutter and the quality of the machined surface through SEM analysis. The analysis was based on the input parameters of the machining process, including cutting speed, feed rate, and the TiAlVN coating of the cutter during Inconel 718 milling. The findings revealed that higher cutting speeds led to enhanced tool wear. Additionally, increasing the input parameters of the milling process resulted in a poorer quality machined surface. Khetre et al. [15] revealed that an insignificant mistake, ranging from 1.27% to 3.44%, occurred in their experimental investigation based on Finite Element Simulation software. They utilized independent variables, including cutting speed, feed rate, and depth of cut, combined with a machining environment consisting of nano-cutting fluid and minimum quantity lubrication (MQL). They used a CBN-coated cutter during the turning of Inconel 718 to analyze the temperature of the cutter in the experimental process. Subsequently, they performed a comparison between the experimental results and those obtained from the Finite Element Simulation software based on computational fluid dynamics (CFD). The researchers concluded that there was a substantial reduction in the temperature of the cutter, which simultaneously improved tool life. Chauhan et al. [16] published a detailed study comparing machining settings between dry machining and cryogenic machining during the turning of Ti-6Al-4V alloy. Their study focused on tool wear, surface roughness, and power consumption. They revealed that the cryogenic technique, which utilized liquid carbon dioxide (CO_2), enhanced heat dissipation in the cutting zone more effectively than other techniques, such as dry machining and flood cooling. The effectiveness of cryogenic machining on Ti-6Al-4V was evident in the improved surface quality and mitigated heat-related harm. Gong et al. [17] optimized the cutting temperature and cutting force using the Response Surface Methodology (RSM) to create a mathematical paradigm. This paradigm served as a forecasting tool for comparing the outcomes of cutting temperature and cutting force with those obtained from a detailed study during the turning of Inconel 718. Their study explored various machining environments, including dry and cryogenic machining, as well as changes in cutting speed. The findings suggested that cutting temperature played a crucial role in determining the machinability of Inconel 718. Sap et al. [18] analyzed the advantages and drawbacks of various lubrication and cooling techniques on the tribological properties during the milling of hybrid composites. The study examined three different machining settings—dry, minimum quantity lubrication (MQL), and cryogenic (liquid nitrogen, LN_2). The parameters evaluated included tool wear, surface roughness, temperature, surface texture, and energy consumption. The results revealed that the cryogenic setting offered superior benefits by reducing temperature in the cutting zone, flank wear, and power consumption. Additionally, the findings indicated that the MQL technique was also an effective solution for improving tool life and surface quality. David Fernández et al. [19] developed an integrated cooling technique for the toolholder in conjunction with the cryogenic system for face milling difficult-to-cut materials such as Gamma TiAl, Inconel 718, and EA1N steel. The objective of their study was to extend the tool life of the cutter as well as improve machining performance. The experimental outcomes showed that the cryogenic machining method was effective and served as an environmentally friendly alternative to replace previous cooling techniques. Kaynak et al. [20] found that the wear mechanisms of the cutter during the turning of AISI 4140 varied under different machining settings, including dry, minimum quantity lubrication (MQL), liquid nitrogen (LN_2), carbon dioxide (CO_2), and the combination of MQL and CO_2. The study consistently maintained the input variables of cutting speed, feed rate, and depth of cut. The outcomes revealed that there was no contribution to tool wear reduction during the turning of AISI 4140 with the cooling and lubrication techniques (MQL + CO_2). Moreover, the built-up edge (BUE) phenomenon appeared with both cryogenic machining methods. On the other hand, dry machining resulted in dangerous chip flow that devastated the cutting edge. Dai et al. [21] asserted in an experimental study that the deformation behavior of workpiece material altered under various machining mediums, such as dry and cryogenic-aided machining, during the turning of Inconel 718. The outcomes of their study demonstrated that the depth of the stiffened coating beneath the machined surface reached 60 μm or more, which varied with different cutting speeds. Furthermore, the study found that cryogenic-aided machining with liquid nitrogen coolant (LN_2) had a significant advantage over dry machining. This advantage was due to the fact that the deeper cooling areas of the machined surface with cryogenic coolant enhanced the wear resistance of the product. Muhammad et al. [22] carried out detailed research using the Taguchi L9 orthogonal array and field-emission scanning electron microscopy (FESEM) to analyze the impact of cutting conditions and cutter coatings, including TiAlN and AlCrN, on the wear mechanism during the milling of AISI 4340. The study highlighted the significant impact of experimental outcomes, revealing that the deterioration of the coating on the rake face of the cutter occurred with the high input variables of the machining process. Furthermore, crater wear developed on the rake face due to the adhesion of the workpiece material. Another finding indicated that abrasion and adhesion were considered the main factors affecting the wear mechanism at the low input variables of the machining process. Wainstein et al. [23] conducted an extensive investigation into adaptive cutting coatings for high-speed dry cutting, covering the entire spectrum from the initial concept to the development of complex multilayer coatings specifically designed for processing tough metals. In the context of high-speed cutting, the intense energy and material flow typically cause damage to both tool materials and protective coatings through various mechanical and chemical processes, including oxidation. Surprisingly, these oxidation processes can actually enhance the lifespan of the tools; their study revealed that by promoting non-equilibrium processes during friction, protective tribo-ceramics form dominantly. These tribo-ceramics are based on sapphire-like, tungsten, and niobium polyvalent oxides, resulting in significantly improved wear performance. Iqbal et al. [24] presented a comparative study of three cooling and lubrication strategies during the milling of Ti-6Al-4V alloy. The study's outcomes, which included cutter failure, cutting force, power expenditure, operational expense, and machined surface quality, were based on the analysis of input parameters such as the orientation of the toolpath, cutting speed, and the helix angle of the endmill cutter. The results indicated that the micro-lubrication technique was more efficacious compared to the cooling strategies that used cryogenic coolants, including liquid nitrogen (LN_2) and carbon dioxide snow (CO_2), in affecting the aforementioned output responses.

Shah et al. [25] indicated that the cryogenic cooling technique offered superior advantages in titanium alloy drilling operations compared to dry and flood cooling methods. The research outcomes revealed that cryogenic cooling techniques, which involved liquid nitrogen (LN_2) and liquid carbon dioxide (CO_2), contributed to the improvement of machining efficiency and the surface roughness of the machined material. Additionally, the wear mechanism of the cutter was also improved. Danish et al. [26] established a hybrid technique for an experimental study on the turning machining process of Inconel 718. The study employed various machining settings, including dry, MQL (Minimum Quantity Lubrication), cryogenic, and cryogenic-MQL. The analysis of the input parameters revealed that the Cryo-MQL setting was more effective at improving the output responses, particularly in terms of machined surface quality, cutting temperature, and tool wear. Moreover, the grain structure of the machined surface produced in the Cryo-MQL medium was finer than that under other conditions. Danish et al. [27] employed scanning electron microscopy (SEM) and X-ray diffraction (XRD) techniques to assess tool wear, in accordance with ISO 3685:1993 [28], and the quality of the machined surface during the milling of SS 316L using four different cooling and lubrication mediums. The findings indicated that cryogenic cooling resulted in a surface finish enhancement of 43%–46% compared to the dry medium, 33%–36% compared to the flood medium, and 15%–17% compared to the MQL medium.

Umbrello et al. [29] compared the impact of a cryogenic machining medium with that of a dry machining setting on the turning process of AISI 52100 steel. They used a cutter with a CBN coating at various cutting speeds to assess machined surface quality, residual stresses, and metallurgical characteristics. The research revealed that the cryogenic technique was more effective in prolonging tool life and enhancing the quality of the machined surface. Abu Bakar et al. [30] demonstrated that the cutting edge radius of an uncoated solid carbide endmill was a significant factor affecting the wear mechanism of the cutter during the milling of AISI H13. The examination compared the impact of various cutting-edge radii in two different machining mediums, including a dry medium and a cryogenic cooling setting with liquid nitrogen (LN_2). The input parameters of the cutting conditions were kept at constant values. The study revealed that the cryogenic technique combined with the cutting-edge radius improved the phenomena of adhesive and abrasive wear on the cutter. Simultaneously, tool life was extended by approximately 55% compared to the dry medium. Pereira et al. [31] demonstrated the superior traits of the hybrid machining technique, which combined minimum quantity lubrication with cryogenic cooling in the turning process of AISI 304 compared to other near-dry machining techniques. The final findings showed that integrating the Cryo-MQL technique in the turning process not only prolonged tool life but also increased cutting speed by more than 50% and 30%, respectively, compared to the dry medium. Furthermore, an additional perspective confirmed that the Cryo-MQL technique supported a balance between ecological considerations and industrial specifications. Chetan et al. [32] pointed out that the cryogenic technique has many advantages over the nanoparticle-based minimum quantity lubrication (nMQL) technique. The cryogenic technique protects the ecological system and avoids dangerous risks for operators. On the other hand, the cryogenic technique helps eliminate the formation of grooves and peeling flaws in the coating on the cutter. Albertelli et al. [33] confirmed that the cryogenic medium utilized in machining operations is considered a significant contribution to eliminating or reducing the temperature and tribological phenomena at the cutting zone, tool–chip interface, and tool–workpiece interface. Their research used a 3D Finite Element simulation paradigm to interpret the aforementioned issues. Wang et al. [34] examined a cryogenic medium with a liquid nitrogen coolant (LN_2) and the Cryo-MQL setting with the integration of minimum quantity lubrication and carbon dioxide (CO_2) as the main factors affecting chip formation in the machining process and the wear mechanism of the cutter during turning of tantalum–tungsten alloy. Their research revealed that the shavings produced during the machining of the high-plasticity Ta-2.5W alloy exhibited a morphology reminiscent of the texture of pomelo pulp, characterized by irregular and aperiodic wrinkling. Wu et al. [35] indicated the different significant points of view in experimental research when using various machining environments during the high-speed milling of hardened steel. The study compared the impact of three machining mediums including minimum quantity lubrication, cryogenic cooling with liquid nitrogen (LN2), and the integration of Cryo-MQL (LN_2–MQL). The conclusive results revealed that the Cryo-MQL paradigm was more efficacious in prolonging tool life. Furthermore, both the Cryo-MQL paradigm and the cryogenic standalone paradigm did not alter the mechanical and physical characteristics of the workpiece. Llanos et al. [36] described an in-house cooling system with cryogenic coolant to continuously supply a steady flow rate to the cutting zone during the turning of AISI 52100 steel. Their findings demonstrated that the innovative cooling system for supplying cryogenic coolant—including the mixture of liquid carbon dioxide (LCO_2) and gaseous carbon dioxide (CO_2)—had superior advantages compared to direct supply systems. Simultaneously, the reduction in tool wear and the improvement of surface roughness for semi-finishing machining were better than those achieved with dry and flood-cooling mediums. Iqbal et al. [37] highlighted the individual advantages of various machining settings. A notable advancement in cooling and lubrication techniques was the simultaneous integration of cryogenic coolant with micro-lubrication. Their study explored five distinct machining settings during the milling of Incoloy 825 using TiN- and TiAlN-coated solid carbide end mills. The findings indicated an enhancement in the machinability of the nickel-based superalloy when subjected to a combination of micro-lubrication and cryogenic mediums.

In the realm of machining, achieving optimal cutting conditions significantly impacts the quality of machined components. While existing research has extensively investigated cooling and lubrication strategies for hard-to-machine materials, a critical gap remains—the specific impact of cryogenic cooling techniques on alloys like JIS SKD11. Our study aims to address this gap by evaluating JIS SKD11 machinability under different cooling conditions, including dry, minimum quantity lubrication (MQL), and cryogenic cooling. By analyzing cutting temperature, tool wear, surface roughness, and microhardness, we aim to identify optimal settings and cutting parameters. Ultimately, our research contributes to the advancement of machining technology and provides practical insights for manufacturers.

2. Materials, Cutters, Machine, and Methodology for the Probing Trials

2.1. Trial Preparation

The open slot milling tests were implemented on JIS SKD11 rectangle blocks with a width of 60 mm, a length of 200 mm, and a height of 20 mm. These blocks were tempered with the mean hardness ranging from 58 to 60 HRC. JIS SKD11, a high-carbon, high-chromium tool steel, is well-suited for low-speed machining due to specific material properties. Notably, JIS SKD11 excels in wear resistance, making it ideal for slower cutting operations; it withstands abrasive wear from workpiece contact. Additionally, with a typical hardness of 58–62 HRC, JIS SKD11 steel maintains tool life and prevents premature wear at low speeds. Despite its hardness, JIS SKD11 remains tough, handling mechanical shocks during machining. Moreover, it exhibits excellent heat resistance, retaining hardness even at elevated temperatures, minimizing the risk of softening. Finally, during machining, JIS SKD11 resists deformation and maintains shape, especially under intermittent cutting forces. The cutter for the open slot milling operation was a SECO TOOLS (Fagersta, Sweden) coated solid carbide with the following designation: 554100Z4.0-SIRON-A. This endmill cutter had the following technical parameters: an AlCrN coating applied with the Physical Vapor Deposition (PVD) coating process, a peripheral cutting edge count of four flutes, a diameter of 10 mm, a shank diameter of 10 mm, a maximum depth of cut on the feed direction side of 22 mm, an overall length of 70 mm, a corner chamfer width of 0.125 mm, a helix angle of 48°, and a rake angle of 8°. In this experimental investigation, the SK40-Q6Z440 tool holder was utilized. We chose an endmill with an AlCrN PVD coating for three reasons: Firstly, multiple studies suggest that PVD (physical vapor deposition) coatings applied to cutting tools, such as CrN, AlCrN, and AlTiN, enhance tool-chip friction, reduce tool oxidation wear, abrasive wear, and diffusion wear, and thereby prolong the overall lifespan of the cutting tool. Secondly, the durable coatings applied to the cutting tool surface for high-speed machining are produced using vapor deposition (PVD). PVD offers distinct advantages over chemical vapor deposition (CVD) coating methods. Specifically, PVD operates at lower process temperatures (<500 °C), whereas CVD typically requires temperatures of 1000–1200 °C. Furthermore, PVD coatings conform more closely to the cutting edge geometry of the tools. Additionally, this method introduces beneficial compressive stresses within the coatings and prevents substrate reaction. Finally, other studies have investigated adaptive PVD (physical vapor deposited) coatings, exemplified by the TiAlCrSiYN/TiAlCrN nano-multilayer PVD coating. This adaptive coating efficiently withstands severe operating conditions typical of dry machining of hard-to-cut materials [12,23,38–41].

The open slot milling trials were carried out on an EMCOMAT FB 450 MC (Hallein, Austria) vertical milling machine with the following specification parameters: a motor capacity of 10 kW; a maximum spindle speed of 5000 rev/min; and a table of dimensions 800 × 400 mm, capable of withstanding a work-part material of 150 kg. Two dissimilar cutting speeds and two dissimilar cutting feeds were identified as the input parameters that affect machining efficiency. Additionally, the depth of cut was kept constant. In practice, based on previous research on turning and milling processes [11,16,32,36,37,42], cutting speed and cutting feed are the most significant factors influencing tool wear. Moreover, advancements in cutting methods and tools, including ultrasonic-vibration-assisted cutting, cryogenic cutting, MQL cutting, and micro-textured tools, have significantly impacted the friction and wear behavior of cutting tools. Research indicates that minimum quantity lubrication (MQL) could be a more sustainable choice, maintaining tool life and dimensional accuracy while reducing environmental impact. Considering factors such as energy consumption, tool life, and surface integrity, cryogenic CO_2 and liquid nitrogen (LN_2) are suitable coolants for challenging-to-machine materials [43–45]. Therefore, the open slot milling trials were conducted with cutting speeds of 80 and 100 m/min, cutting feeds of 204 and 318.5 mm/min, and a constant depth of cut of 0.1 mm under dry, MQL, and cryogenic cooling mediums. Each trial was performed three times to ensure an accurate open slot milling cycle and to avoid the inconsistent experimental mistakes that occur during the derivation of mean values. The preparation for the experimental process is shown in Figure 1.

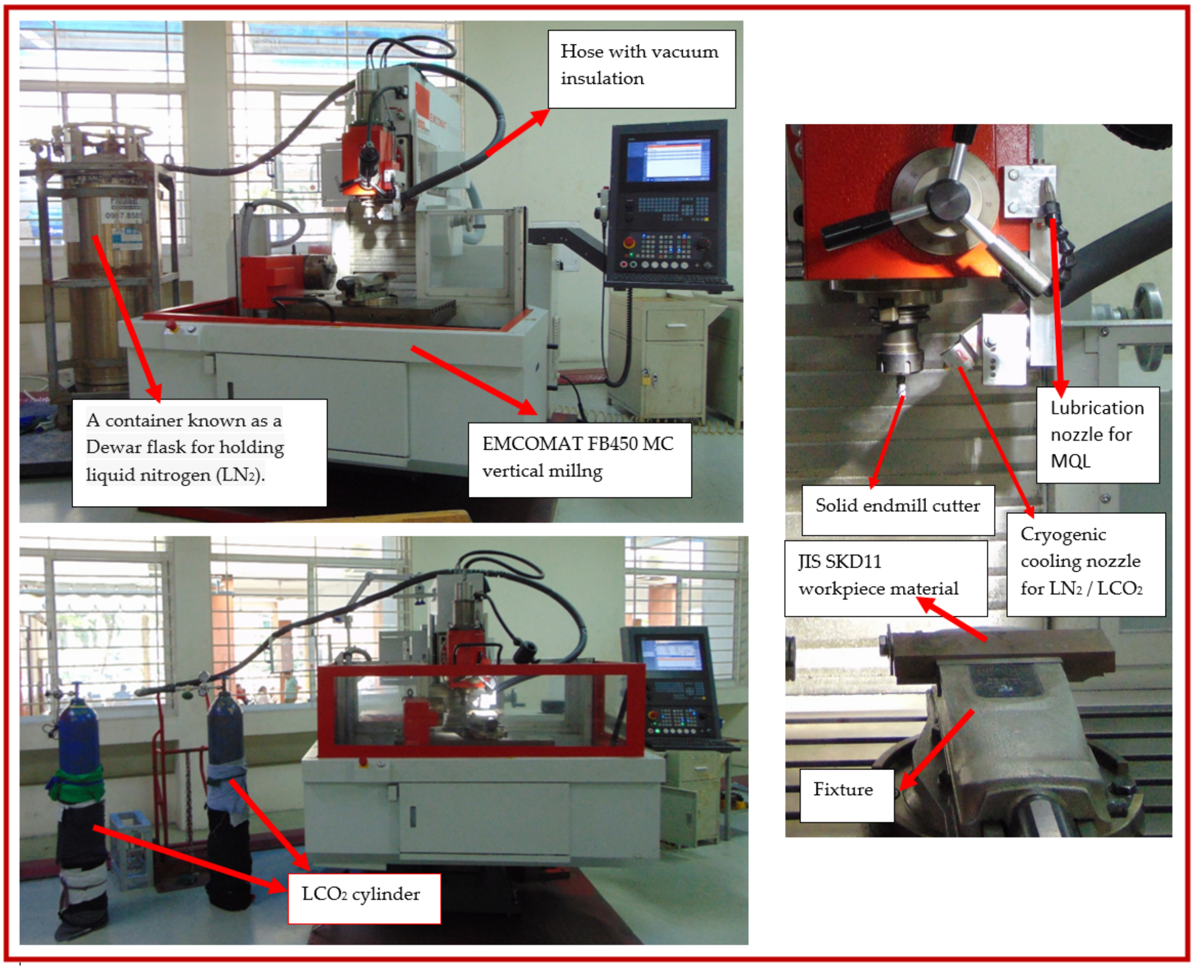

Figure 1. Test arrangement with the liquid nitrogen (LN_2), liquid carbon dioxide (LCO_2), and minimum quantity lubrication (MQL) delivery systems.

2.2. Thermal and Lubricant Mediums

2.2.1. Dry Medium

Dry machining is a method whose operation is conducted completely without the use of coolant. It is considered a sustainable machining method because it entirely eliminates the application of coolant [46]. Dry machining is regarded as the most cost-effective and environmentally friendly technique as it operates without any cutting fluid. Nonetheless, its drawbacks include a subpar surface finish and accelerated tool degradation, which diminish its overall productivity. The absence of a cooling or lubricating medium in the cutting area results in elevated temperatures, thereby constraining the process parameters and reducing productivity [16]. In this work, the machining process of an open slot milling, shown with a dry medium, is depicted in Figure 2.

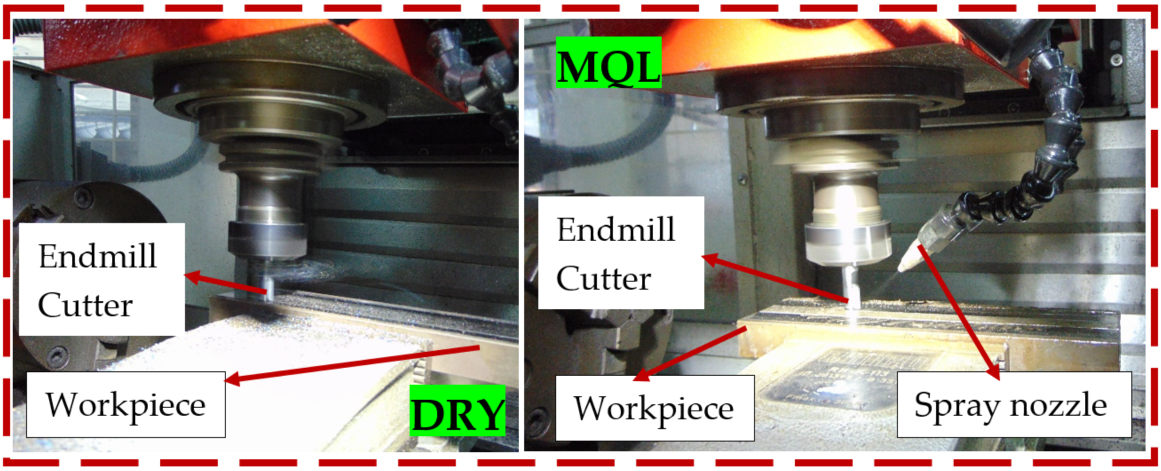

Figure 2. Open slot milling using both dry and MQL mediums.

2.2.2. Minimum Quantity Lubrication Medium

In the MQL process, a slight volume of oil is amalgamated with the compressed air that is delivered to the cutting zone. This oil functions as a lubricant, while the compressed air serves as a coolant [46]. In this study, the apparatus came with a flood cooling system and an external MQL system designed for milling tasks. The external MQL system was composed of several specific components—an air-pressure control valve that could be adjusted from 1 to 4 bar, a pair of lubricant flow rate control valves that could be set from 1 mL/min to 10 mL/min, a reservoir that could contain up to 500 mL of mineral oil, and two external spray nozzles. The cutting fluid used in the MQL system consisted of original mineral oil and additives, which were supplied directly into the cutting zone by a 2 mm MQL nozzle without being diluted in water. The MQL system functioned at a pressure setting of 3 bar, and the delivery rate of the MQL fluid was maintained at 60 mL/h. The nozzle was positioned about 50 mm away from the cutting zone and was angled at 45 degrees. Figure 2 presents the machining process of open slot milling, demonstrated with an MQL medium.

2.2.3. Cryogenic Cooling Medium with Liquid Nitrogen (LN_2)

Liquid nitrogen (LN_2) serves as a cryogenic coolant in machining processes, effectively removing heat from the cutting area. Employing LN_2 for this purpose is more environmentally friendly compared to traditional oil-based coolants. To utilize liquid nitrogen (LN_2) as a coolant in machining, it is kept under high pressure in insulated containers. When exposed to atmospheric conditions, LN_2 begins to boil at −196 °C, drawing away the heat generated in the cutting area and vaporizing, thus leaving no residue on either the workpiece or the cutting instrument [47]. In this work, liquid nitrogen functioned as the cryogenic coolant. To prevent heat dissipation, LN_2 from a Taylor Wharton XL-45 nitrogen tank (Beijing, China) with a working pressure of 2.88 MPa was channeled through a vacuum hose. The cryo-spraying device featured a nozzle with a 3 mm diameter. This nozzle was positioned roughly 50 mm away from the cutting area at a 45 degree angle. The LN_2 was dispensed at a flow rate of 0.38 kg/min, propelled by a spraying pressure of 5 bar. An open slot milling operation with liquid nitrogen (LN_2) cryogenic cooling is presented in Figure 3.

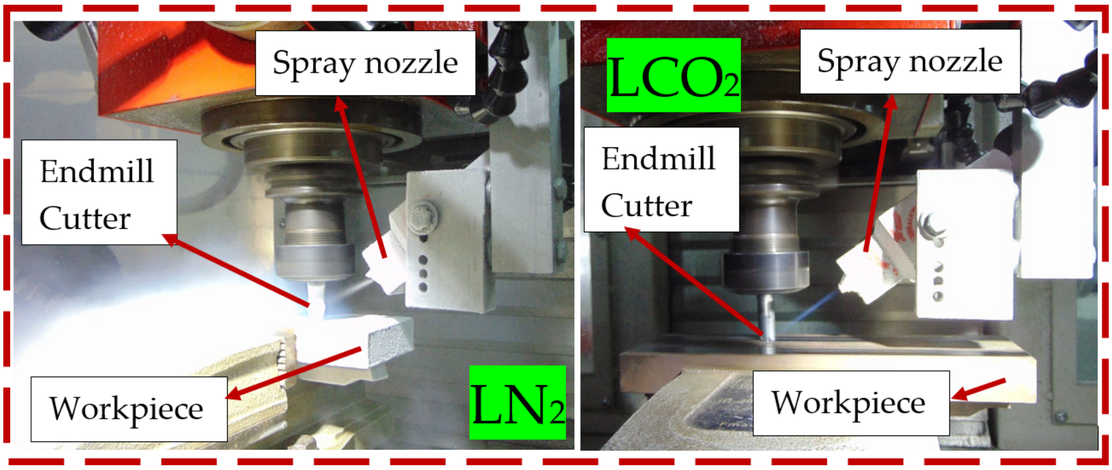

Figure 3. Open slot milling using both cryogenic cooling with liquid nitrogen (LN_2) and liquid carbon dioxide (LCO_2) mediums.

2.2.4. Cryogenic Cooling Medium with Liquid Carbon Dioxide (LCO_2)

Liquid carbon dioxide (LCO_2) has been receiving recognition as a potential cryogenic cutting fluid, offering an alternative option to liquid nitrogen (LN_2). On occasion, LCO_2 may not be classified as a cryogenic fluid due to its marginally elevated boiling point compared to typical cryogenic substance. Nevertheless, it is sufficiently chilled to remove heat from the cutting area effectively [47]. In this work, an LCO_2 cylinder was utilized to supply LCO_2 to the cutting zone through a hose with vacuum insulation, leading to a nozzle with a 3 mm diameter. A pressure regulator was installed between the LCO_2 cylinder and the nozzle to maintain a stable pressure of 5 bar. This nozzle was positioned approximately 50 mm away from the cutting area at a 45 degree angle. An open slot milling operation with liquid carbon dioxide (LCO_2) cryogenic cooling is presented in Figure 3.

2.2.5. Input Variables and Levels for the Probing Trials

During the trials, each solid endmill cutter achieved a depth of cut identified at 0.1 mm for each open slot milling cycle. Each cutter was iterated thrice until the total depth of cut reached 0.3 mm. The open slot milling cycle was executed using SIMEN software version 828 V 02.60.44.00 (EMCO GmbH, Hallein, Austria) with a down-cut single position strategy and base-finishing. The input variables and details used for the experimental process are displayed in Table 1. The input variables and levels employed in the experimental process of tempered JIS SKD11 steel are presented in Table 2.

Table 1. Input variables used for the experimental process.

Input Variables	Details
Workpiece material	JIS SKD11, HRC 58–60, 200 × 60 × 20 mm
Cutter	PVD coated solid carbide endmill with an AlCrN coating, 554100Z4.0-SIRON-A, SECO TOOLS
Cutting speed (m/min)	80, 100 m/min
Cutting feed (mm/min)	204, 318.5 mm/min
Depth of cut (mm)	0.1 mm
Machining medium	Dry, MQL, cryogenic cooling with liquid nitrogen (LN_2), cryogenic cooling with liquid carbon dioxide (LCO_2)
Machining dimensions of an open slot milling operation (mm)	200 × 50 × 0.3 mm

Table 2. Input variables and levels employed in the experimental process.

No.	Cutting Speed (m/min)	Cutting Feed (mm/min)	Machining Medium
1	80	204	Dry
2	80	318.5	Dry
3	100	204	Dry
4	100	318.5	Dry
5	80	204	MQL
6	80	318.5	MQL
7	100	204	MQL
8	100	318.5	MQL
9	80	204	Cryogenic cooling with liquid nitrogen (LN_2)
10	80	318.5	Cryogenic cooling with liquid nitrogen (LN_2)
11	100	204	Cryogenic cooling with liquid nitrogen (LN_2)
12	100	318.5	Cryogenic cooling with liquid nitrogen (LN_2)
13	80	204	Cryogenic cooling with liquid carbon dioxide (LCO_2)
14	80	318.5	Cryogenic cooling with liquid carbon dioxide (LCO_2)
15	100	204	Cryogenic cooling with liquid carbon dioxide (LCO_2)
16	100	318.5	Cryogenic cooling with liquid carbon dioxide (LCO_2)

2.3. Techniques for Measuring the Output Responses

First, while performing open slot milling, the cutter executed the final cycle (the third pass), achieving a depth of cut of 0.3 mm, the cutting temperature in the zone was measured. Positioned 300 mm from the machined surface, the TG275 Flir thermal camera (Taipei City, Taiwan) boasts a thermal resolution of 19,200 pixels, a temperature range of between −25 °C and 550 °C, and an image resolution of 320 × 240 pixels. Consequently, it produced a thermal image by reliably and instantaneously measuring the temperature during the open slot milling process. Figure 4a presents the position where the cutting temperature in the cutting zone was measured.

Second, surface roughness significantly influences the tribological behavior of surfaces. Factors such as wear rates, friction coefficients, crack formation, and adhesion are all impacted by surface roughness. Out of the different roughness metrics, the average surface roughness (expressed as Ra in micrometers) is commonly used to assess surface roughness. Surface roughness on the machined area was evaluated using a Mitutoyo SJ-210 instrument (Kawasaki, Japan), capable of measuring up to 360 µm with a speed of 0.5 mm/s. Following the guidelines of ISO 1997 [48], we established the cutoff and evaluation lengths at 0.8 mm and 4 mm. The roughness data were collected at four distinct points across the machined surface, and the computed mean of these values served as the basis for comparison. Figure 4b shows where surface roughness was measured.

Third, a Wire-cut Electrical Discharge Machine (WEDM) was utilized to cut solid carbide endmill cutters, preparing the samples for flank wear analysis. Detailed images of the wear mechanisms were obtained using a HITACHI SU 8010 Field Emission Scanning Electron Microscope (FE-SEM, Tokyo, Japan) with magnifications ranging from 100× to 300,000×. Additionally, the value of the flank wear was also identified based on the FE-SEM data using ISO 8688:1989 criteria. Figure 4c illustrates how the cutters were fabricated using a Wire-cut Electrical Discharge Machine prior to conducting the FE-SEM analysis.

Finally, utilizing a STCMC device from China, the microhardness (HV) of a machined surface was assessed. The device exerted a uniform force of 100 kgf (980 N) for a duration of 10 s. Measurements were taken at intervals of 100 mm. The microhardness was gauged perpendicular to the machined surface, and an average value was derived from two distinct points. Figure 4d depicts the measurement process of microhardness (HV).

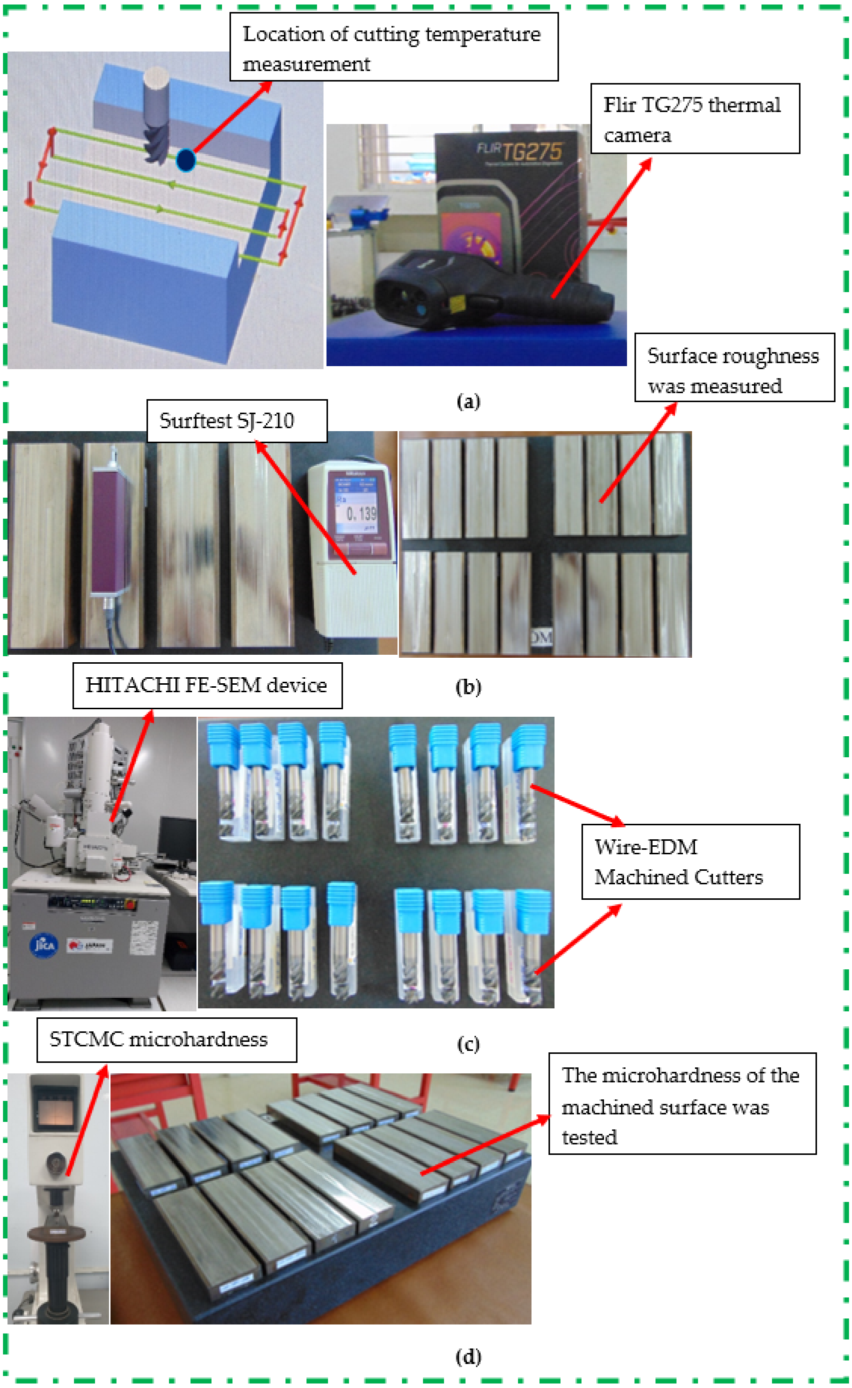

Figure 4. Devices employed in experimental response measurement (**a**–**d**).

3. Results and Discussion

This research aims to evaluate the effectiveness of dry, minimum quantity lubrication (MQL), cryogenic cooling with LN_2, and LCO_2 machining settings in the machining of tempered JIS SKD11 steel (HRC 58–60). The study applied this cutting-edge lubrication and cooling strategy during open slot milling processes to assess its ecological and technical viability. A comparative analysis with alternative near-to-dry or dry machining methods was also conducted, focusing on various aspects that affect output responses including thermal conditions during cutting, tool wear, surface texture, and material hardness.

3.1. Dissection of Cutting Temperature

In the machining process, the temperature in the cutting area is a crucial factor because it causes phenomena such as chip shrinkage, built-up edge (BUE), and stiffening of the machined surface after machining. In hard machining, the high temperature frequently derived from the cutting zone directly affects the quality of the machined surface, the geometric parameters of the cutter, tool wear, and dimensional accuracy, etc. Over the past few years, many researchers have explored various cooling and lubrication techniques in machining processes, such as turning, milling, and drilling, in order to find an optimum solution for cooling and lubrication methods in the cutting region. The goal is to reduce or eliminate the entire heat generated. In this study, we employed several techniques to achieve this, including Minimum Quantity Lubrication (MQL), cryogenic cooling with liquid nitrogen ($LN_{2)}$, and liquid carbon dioxide (LCO_2). Figure 5 illustrates the variation in temperature during open slot milling under dry, MQL, and cryogenic cooling conditions with the LN_2 and LCO_2 settings.

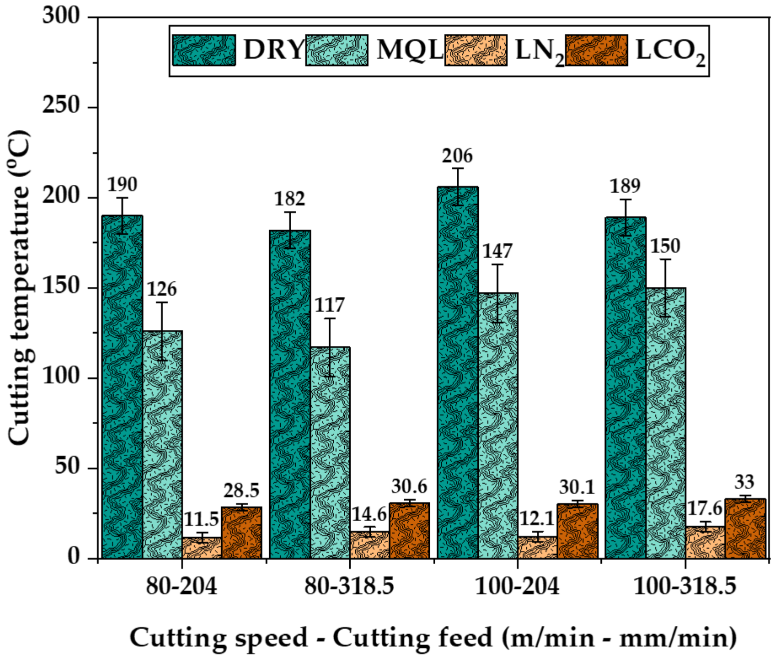

Figure 5. Variation in temperature during open slot milling under dry, MQL, and cryogenic cooling conditions with LN_2 and LCO_2.

Opting for dry machining is recognized as the most cost-effective and environmentally friendly method since it eliminates the use of cutting fluids. Elevated temperatures noted during such conditions indicate the necessity for a cooling system to be integrated into the machining process. Nonetheless, this increase in temperature is due to the escalated friction at the interface of the cutting tool and the chip, resulting in intense thermal conditions within the cutting zone. The lack of lubrication at the point of contact between the chip and tool causes a drastic temperature surge, leading to inferior surface quality and accelerated tool degradation, thereby reducing overall productivity. The absence of a cooling or lubricating agent contributes to the generation of excessive heat, constraining the operational parameters and the efficiency of the machining process [16,27].

As shown in Figure 5, increasing the cutting speeds from 80 m/min to 100 m/min, while maintaining a constant cutting feed of 204 mm/min and a consistent machining time of 70 min, enabled open slot milling to achieve the total depth of cut of 0.3 mm. The temperature of the cutting zone was measured on the third cutting pass, at which point the depth of cut had reached 0.3 mm. The data indicated that the maximum temperature value occurred during dry machining, with a temperature of 206 °C at a cutting speed of

100 m/min. Conversely, the minimum temperature value was observed during cryogenic cooling with the LN_2 medium, with a temperature of 12.1 °C, also at a cutting speed of 100 m/min. Compared to the dry environment, the percentage contributions to heat elimination in the cutting region for MQL and cryogenic cooling with LN_2 and LCO_2 were 28.6%, 94.2%, and 85.4%, respectively. Similarly, in the open slot machining process, adjusting the cutting speeds from 80 m/min to 100 m/min, while keeping the cutting feed steady at 318.5 mm/min and the machining duration fixed at 46 min, facilitated the attainment of a total depth of cut of 0.3 mm through open slot milling. The thermal conditions within the cutting zone were monitored during the third pass, coinciding with the moment the depth of cut reached 0.3 mm. Observations revealed that the peak temperature was recorded during dry machining, hitting 189 °C at the elevated cutting speed of 100 m/min. In stark contrast, the lowest temperature was recorded when employing cryogenic cooling with LN_2, registering at 17.6 °C, at the same cutting speed of 100 m/min. When compared to a dry machining environment, the contributions to thermal dissipation in the cutting area by MQL, LN_2 cryogenic cooling, and LCO_2 cooling were significant, with percentages of 20.7%, 90.7%, and 82.6%, respectively.

Albertelli et al. performed an extensive examination of thermal factors within the cutting zone. They presented temperature maps for all simulated test cases. Notably, the use of cryogenic cooling with liquid nitrogen (LN_2) resulted in an average reduction of the maximum cutting temperature from 150 °C to 200 °C compared to dry cutting [33]. On the other hand, thanks to its efficient spray mechanism, convective heat transfer during cryogenic chilling facilitates effective heat dispersion from the cutting zone. When compared to dry and minimum quantity lubrication (MQL) methods, cryogenic cooling consistently achieves lower cutting temperatures across various cutting speeds. The ultra-low temperature of cryo-CO_2 enables rapid heat absorption from the machining area [46]. Moreover, observations indicate that the cryogenic medium's effectiveness is consistent across all aspects. Nonetheless, the dry medium records the highest temperatures during cutting, underscoring the importance of selecting an appropriate lubrication and cooling method. Further analysis contrasts the two approaches, revealing the superior ability of the cryogenic medium to reduce temperatures more than the MQL medium. Established research confirms that cryogenic coolants, due to their lower freezing points, are notably more effective at cooling than MQL coolants. However, the lubrication capacity of cryogenic solutions is considerably limited, which greatly reduces their application in precision machining that requires strict accuracy [26]. When analyzing the correlation between cutting temperature and cutting speed, we observed that as cutting speed increases, so does the cutting temperature. The highest cutting temperature occurred at a cutting speed of 100 m/min. As discussed earlier, excessive cutting temperatures lead to tool damage, negatively impacting machining quality and accuracy. Therefore, the pivotal issue here is avoiding excessively high cutting temperatures. To analyze the relevance and significance of temperature, we note the following characteristics in our analysis: First, the thermal images depict a gradient of temperatures. Second, the varying colors in the images represent different temperature levels in specific regions. Third, warmer areas (such as those shown in red or white) may indicate excessive heat, while cooler areas (likely in blue) likely represent cool spots. Understanding this visualization helps assess tool wear and performance implications. Finally, by comparing the temperature patterns, we identified uniform regions and localized peaks. These insights are crucial for assessing process reliability. Figures 6 and 7 depict the temperature variations across four distinct machining settings, considering different cutting speeds and cutting feeds, as obtained using the thermal camera data.

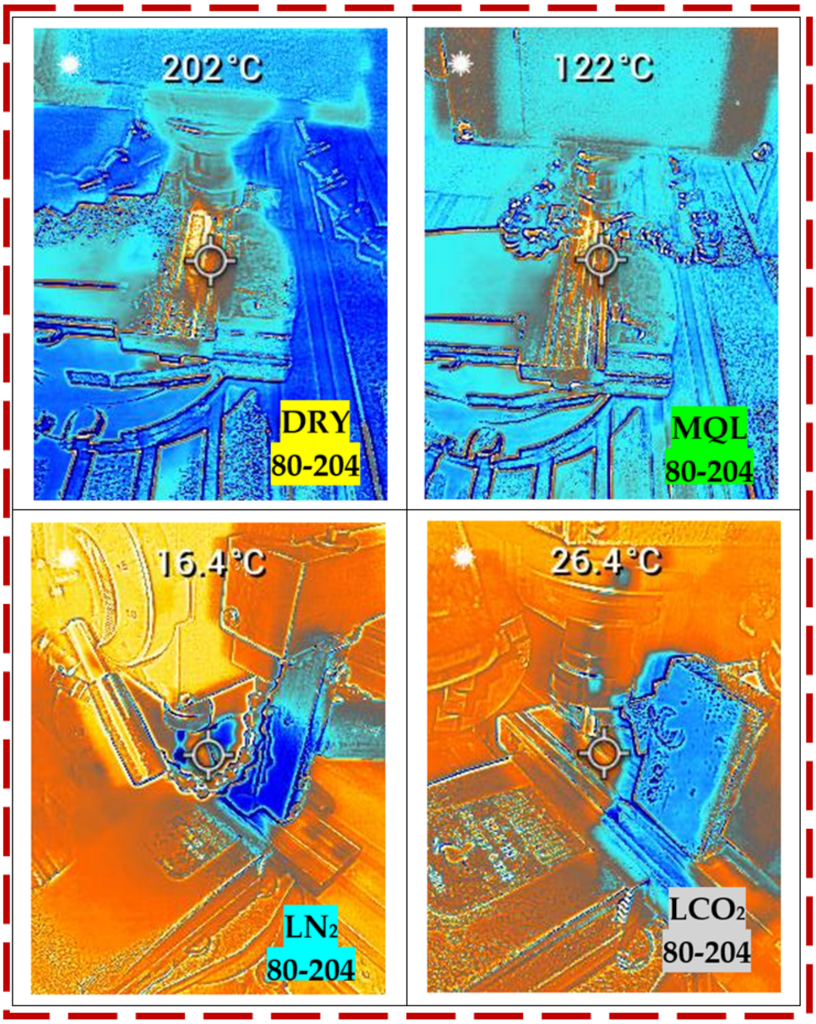

Figure 6. Temperature variations in the cutting zone under four distinct machining settings with a cutting speed of 80 m/min and a cutting feed of 204 mm/min.

3.2. Tool Degradation Patterns

According to ISO 8688 criteria [1,49], there are several different wear patterns that occur in the milling machining process. These include flank wear (VB), rake wear (KT), chipping (CH), flaking (FL), and catastrophic failure (CF). Flank wear, in particular, exhibits specific wear patterns such as consistent flank wear, inconsistent flank wear, and specific flank wear. Similarly, chipping can also manifest in two wear patterns—consistent chipping and inconsistent chipping. Regarding the tool life criterion, wear is often associated with the average flank wear. This means that a substantial change in tool dimensions can lead to alterations in the size of the machined component. In practical terms, the largest acceptable value for flank wear in the machining process typically falls within the range of 0.3 to 0.5 mm; the lower end of this range is suitable for finishing operations, while the upper end is more applicable for roughing processes. The susceptibility of materials to being machined plays a crucial role in the occurrence of flank wear. Varied materials demonstrate unique responses during mechanical and thermochemical processes, which primarily contributes to the onset of the flank wear [16]. In our study, research was conducted on the wear along the flank of AlCrN-coated solid carbide endmill cutters during open slot milling operations on tempered JIS SKD11 steel. By varying cutting speeds and cutting feeds and utilizing eco-friendly mediums, we aimed to elucidate the patterns of damage sustained by the cutters. The trials carried out a consistent open slot milling cycle under four eco-friendly mediums, maintaining uniform depth of cut and machining time, with a material removal rate that matched the predetermined cutting speed and cutting feed. Figure 8 illustrates the location of a solid carbide endmill with four flutes coated in AlCrN. The wear patterns are also shown.

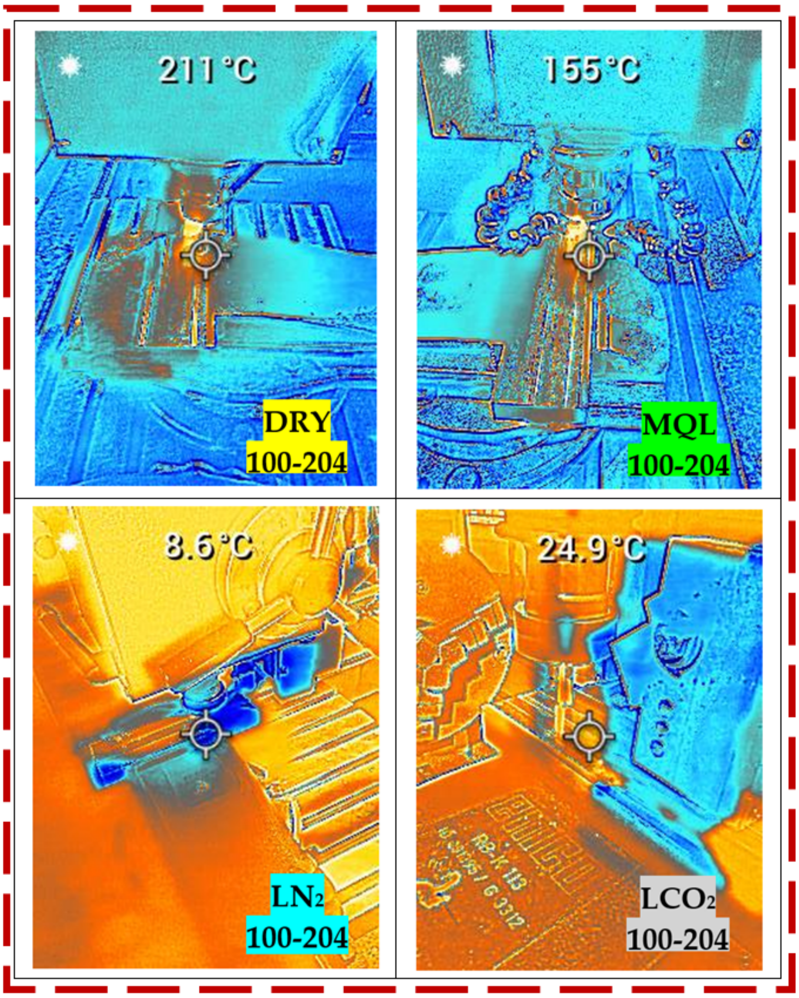

Figure 7. Temperature variations in the cutting zone under four distinct machining settings with a cutting speed of 100 m/min and a cutting feed of 204 mm/min.

The variations in flank wear and rake wear of the AlCrN-coated solid carbide endmill cutters during the open slot machining process at a cutting speed of 80 m/min and with a cutting feed of 204 mm/min under four distinct machining settings were analyzed through FE-SEM images, as illustrated in Figures 9 and 10, respectively. To facilitate a fair comparison of the worn surfaces, the analysis of these figures was conducted through FE-SEM with varying scales of magnification, namely 1 mm, 500 µm, 200 µm, and 100 µm. In a similar manner, Figures 11 and 12 depict the changes in flank wear and rake wear of the AlCrN-coated solid carbide endmill cutters. During the process of open slot machining for SKD11, wear mechanisms may manifest in four distinct stages, which can be categorized as follows: First, abrasive mechanisms often introduce hard particles, managing the progression of flank wear. Second, adhesive mechanisms occur in soft materials, leading to skyrocketing temperatures and the formation of a build-up edge. Third, diffusion mechanisms intensify on the cutter's rake face, causing rake wear. Finally, oxidative wear may occur on the back region of the primary cutting edge, resulting in notch wear. Under the MQL medium, signs of wear, such as abrasion and adhesion, were prominently observed in the flank and rake wear regions, with rake wear being particularly severe. Figures 9 and 11 illustrate that the MQL approach yielded remarkable outcomes, characterized by the absence of build-up edge formation [18].

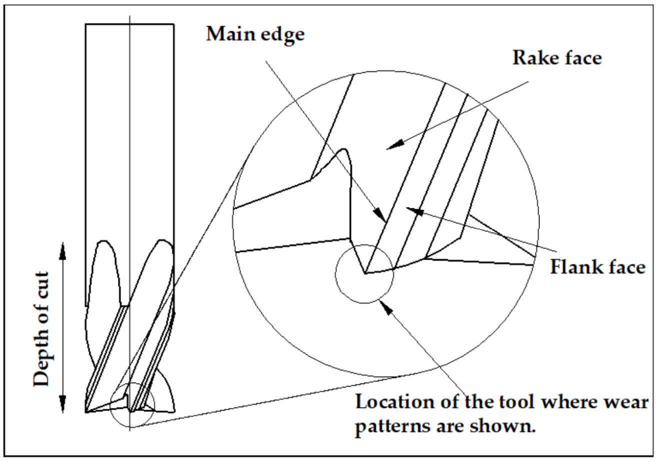

Figure 8. Solid carbide endmill coated with AlCrN highlighting the cutter's location where wear patterns occur.

As shown in Figures 9–12, during the open slot milling operation, an increase in cutting speed from 80 m/min to 100 m/min, while maintaining a constant cutting feed of 204 mm/min, cryogenic cooling techniques using LN_2 and LCO_2 were more effective compared to the dry and MQL techniques. These data indicate that, when operating at a high cutting speed of 100 m/min coupled with a steady cutting feed of 204 mm/min, the use of LN_2 and LCO_2 as cryogenic mediums outperforms other techniques. As the cutting speed escalated, the tools deteriorated swiftly due to the intense friction at the contact point between the tool and workpiece, leading to the tool's edge crumbling or breaking off, and, ultimately, the tool's failure. The heightened levels of wear and tear, both abrasive and adhesive, along with the crumbling and breaking observed during dry machining, were linked to the reduced resilience and strength of the material, which became more pliable at elevated temperatures. This caused the material to be drawn into the tool's notch area, causing it to crumble or break off, and the tool to fail. On the other hand, when machining under cryogenic settings, the wear on the tool's side was minimal and even [16]. The distinction between machining with the aid of liquid nitrogen (LN_2) and that with liquid carbon dioxide (LCO_2) was also clear. Common knowledge dictates that the low temperatures of cryogenics inhibit the softening of cutting tools, thereby reducing their wear rate. As a result, cutting tools cooled cryogenically exhibit markedly enhanced performance. Support for this assertion is found in scholarly articles, which have indicated that the application of cryogenic cooling is effective at diminishing tool wear during the machining of diverse materials. This is attributed to its ability to lower the temperature at the tool–chip interface, which in turn prevents the cutting tool from becoming soft [20]. The workpiece material, containing iron (Fe), tends to stick to the TiAlN/AlCrN coating on the tool's surface. If this coating were to come off, it would expose the underlying carbide material of the tool. The material typically adheres to the tool's flank and rake face due to the intense stress and high temperatures at these contact points. This adherence continues on both the newly exposed surfaces and those already covered, leading to a gradual increase in the thickness of adhered layer. As the workpiece moves or as chips are formed, this layer is subjected to mechanical forces that may pull on it [22]. Similar to the observations made during the tests conducted at 75 m/min, the trials at 100 m/min also exhibited signs of abrasive wear, accumulation of material, and layer separation. Additionally, certain conditions revealed the presence of bubbles and fissures within the coating, which are indicative of impending layer separation, along with instances of fractures or defects in the base material of the cutting tool [14]. Climb milling, also referred to as down-milling, typically resulted in less wear on the tool compared to conventional up-milling. This difference was particularly noticeable when milling was performed using liquid nitrogen (LN_2). In climb milling, the chip thickness gradually reduced to zero towards the end of the cut, which helped avoid any friction and polishing action by the cutting edge and the side of the tool against the workpiece. This absence of friction during cutting is why climb milling exhibited reduced flank wear. Regarding the impact of cutting speed, higher speeds were associated with increased tool wear, though this correlation was not strongly significant [24].

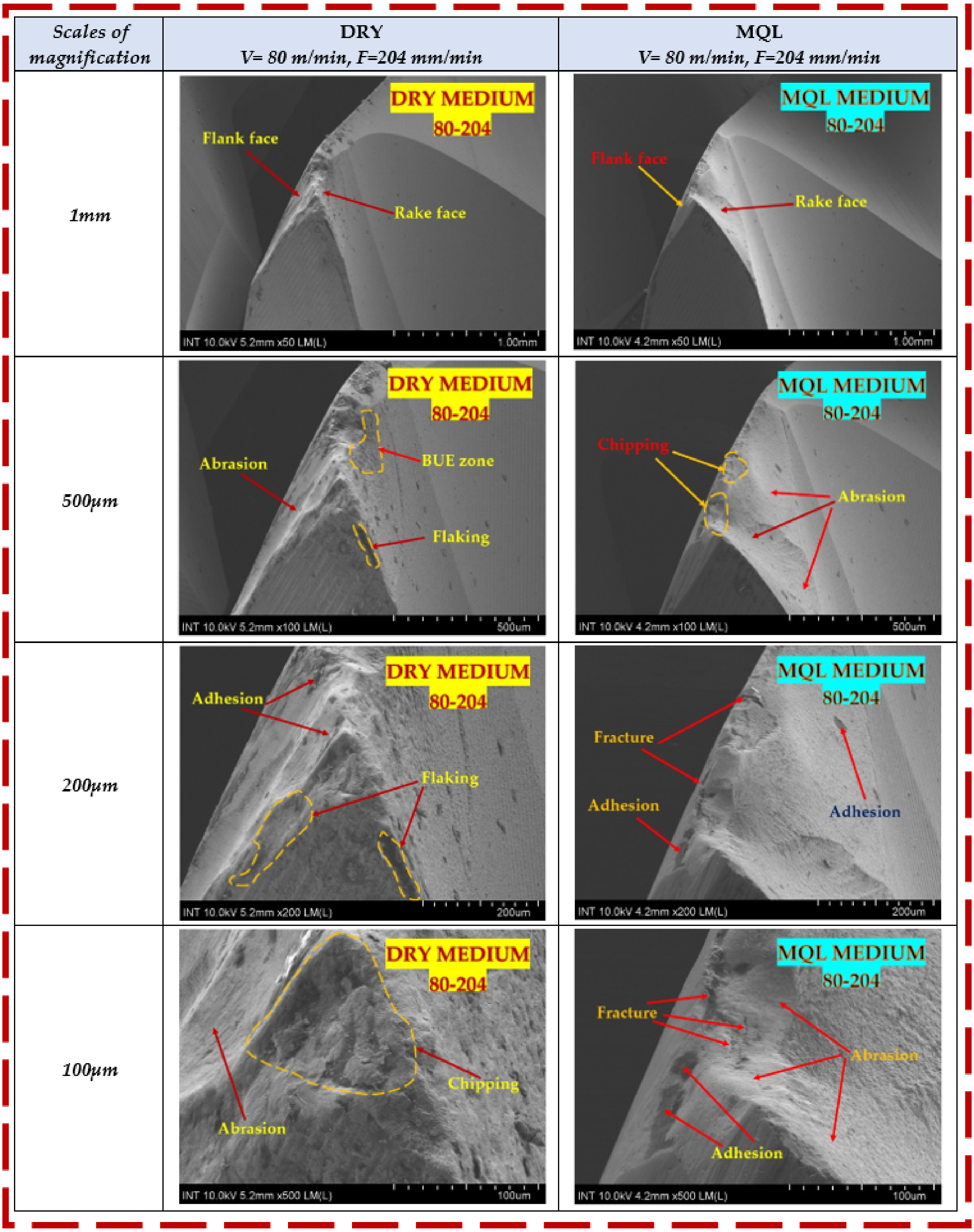

Figure 9. Illustrates the variation in flank wear and rake wear under dry and MQL machining settings at a cutting speed of 80 m/min and a cutting feed of 204 mm/min.

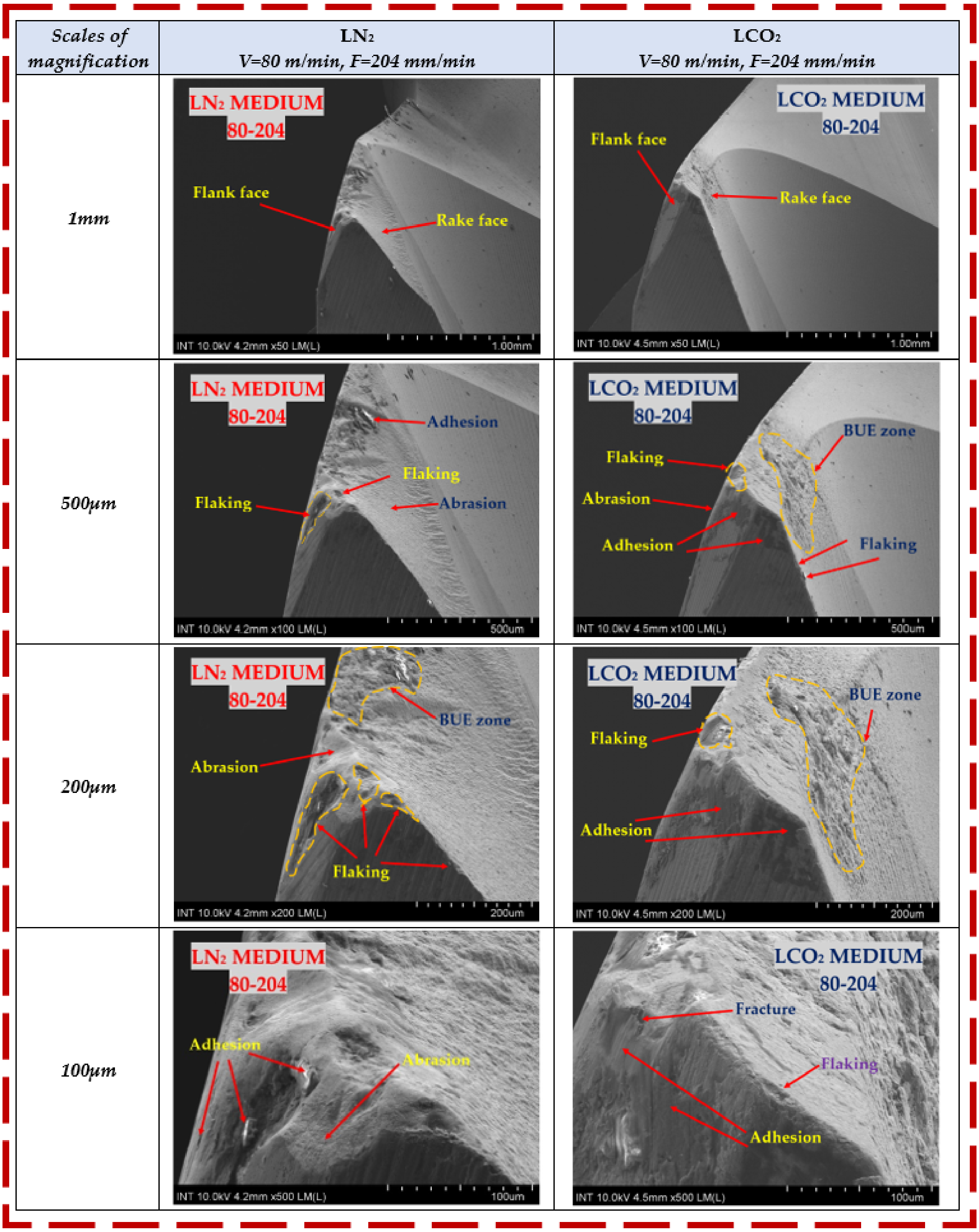

Figure 10. Variations in flank wear and rake wear under LN_2 and LCO_2 machining settings at a cutting speed of 80 m/min and a cutting feed of 204 mm/min.

As shown in Figures 13 and 14, during the open slot milling operation, an increase in cutting speed from 80 m/min to 100 m/min was implemented while maintaining a constant cutting feed of 318.5 mm/min. It was observed that flank and rake wear were significantly stronger and predominantly focused on notch wear in the cryogenic cooling environment with LN_2 compared to the LCO_2 medium. The wear mechanism mainly involved notch abrasion and adhesion. Additionally, the presence of the built-up edge was noted in both cryogenic cooling machining mediums; however, flaking and fracture were more apparent with the LCO_2 medium than with the LN_2 medium. The flank wear with the LN_2 medium exhibited a U-shape, whereas in the LCO_2 medium, it had a V-shape. Notably, the temperature in the cutting zone with cryogenic cooling in the LN_2 environment was lower than that in the LCO_2 medium. The diminished flank wear observed in the LCO_2 environment relative to the LN_2 conditions can be attributed to the greater degree of material brittleness induced by LN_2 than by LCO_2 [25]. Figure 15 depicts the advancement of flank wear across various cutting speeds and cutting feeds, as observed under dry, MQL, and cryogenic cooling conditions during machining.

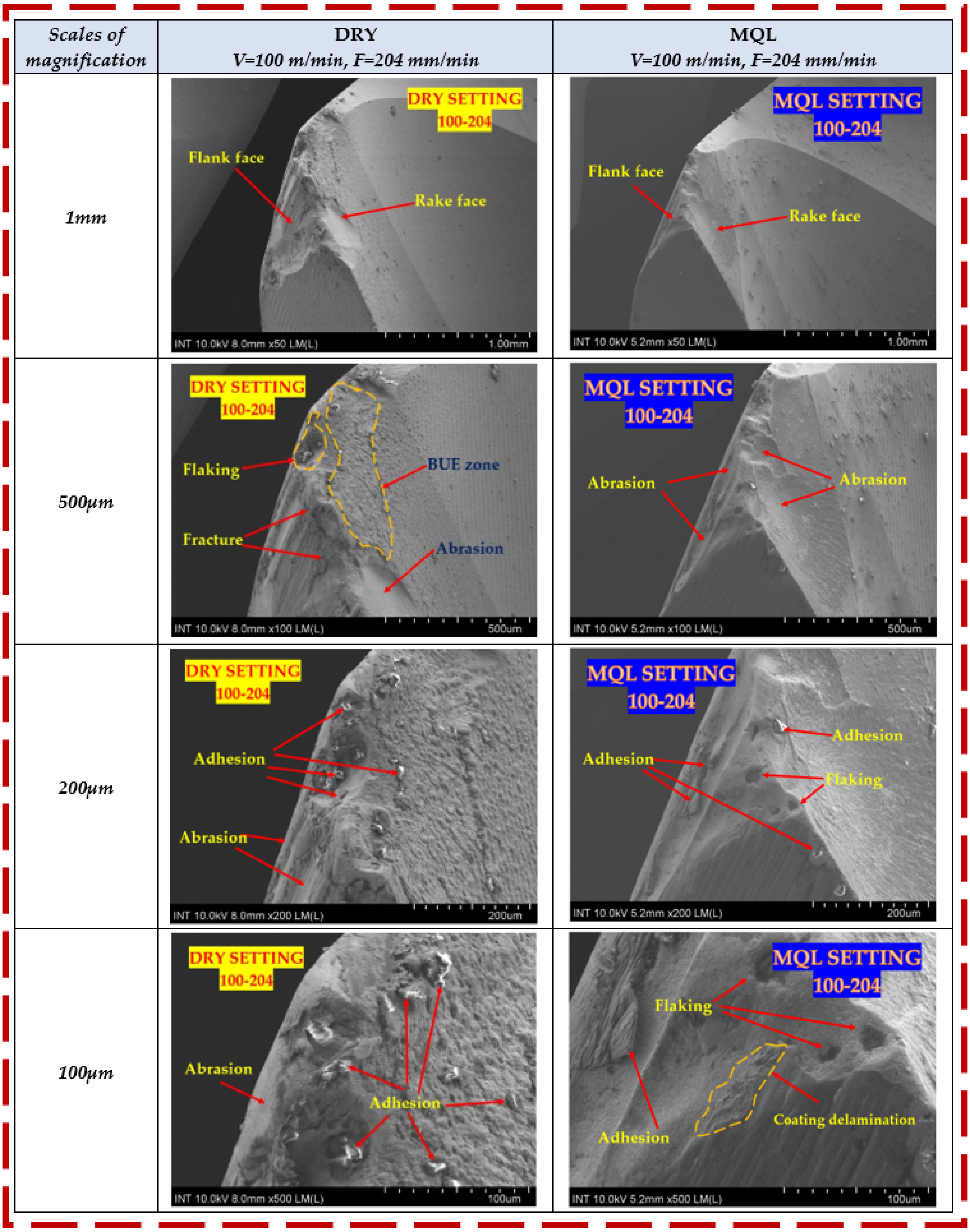

Figure 11. Variation in flank wear and rake wear under dry and MQL machining settings at a cutting speed of 100 m/min and a cutting feed of 204 mm/min.

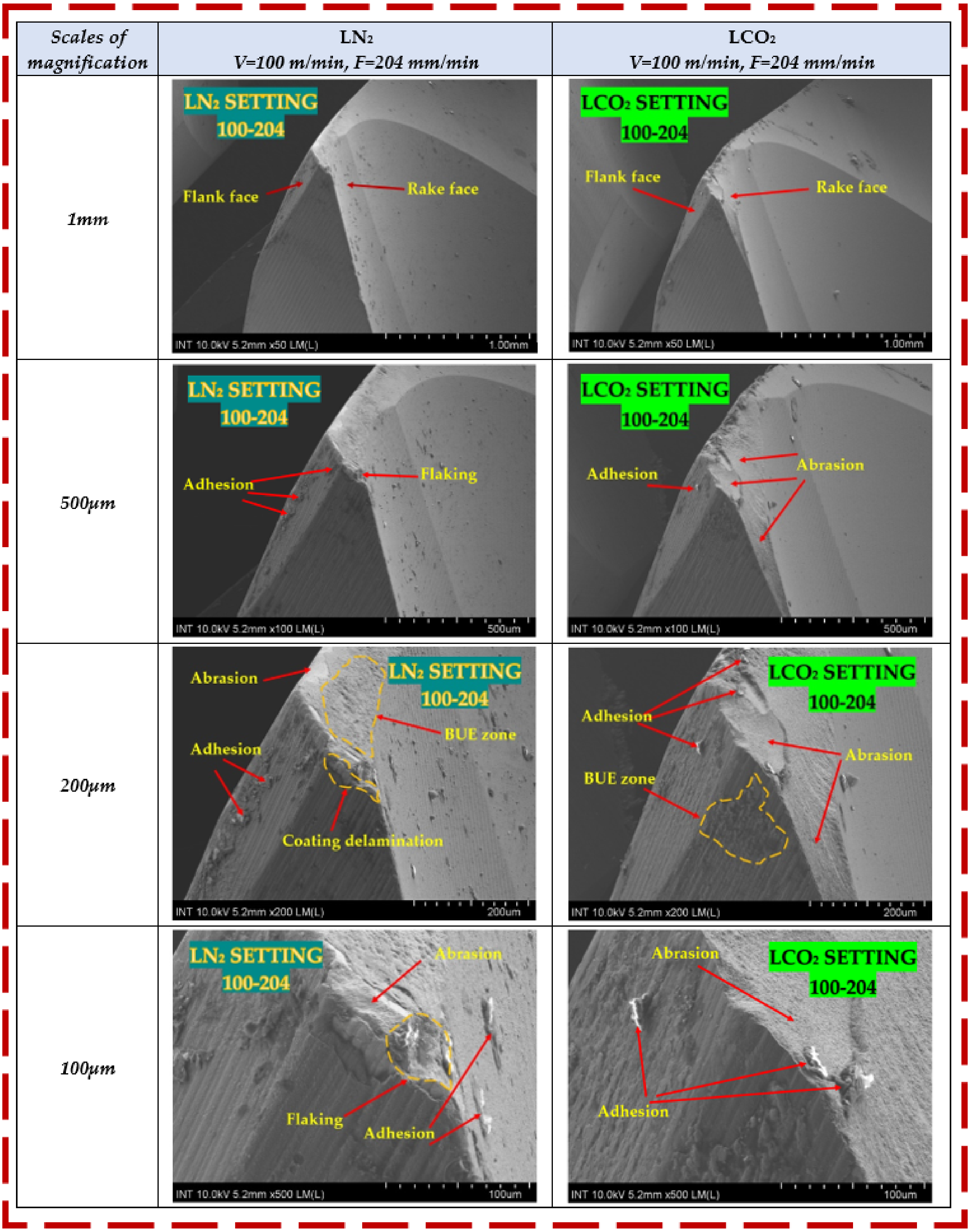

Figure 12. Variation in flank wear and rake wear under LN_2 and LCO_2 machining settings at a cutting speed of 100 m/min and a cutting feed of 204 mm/min.

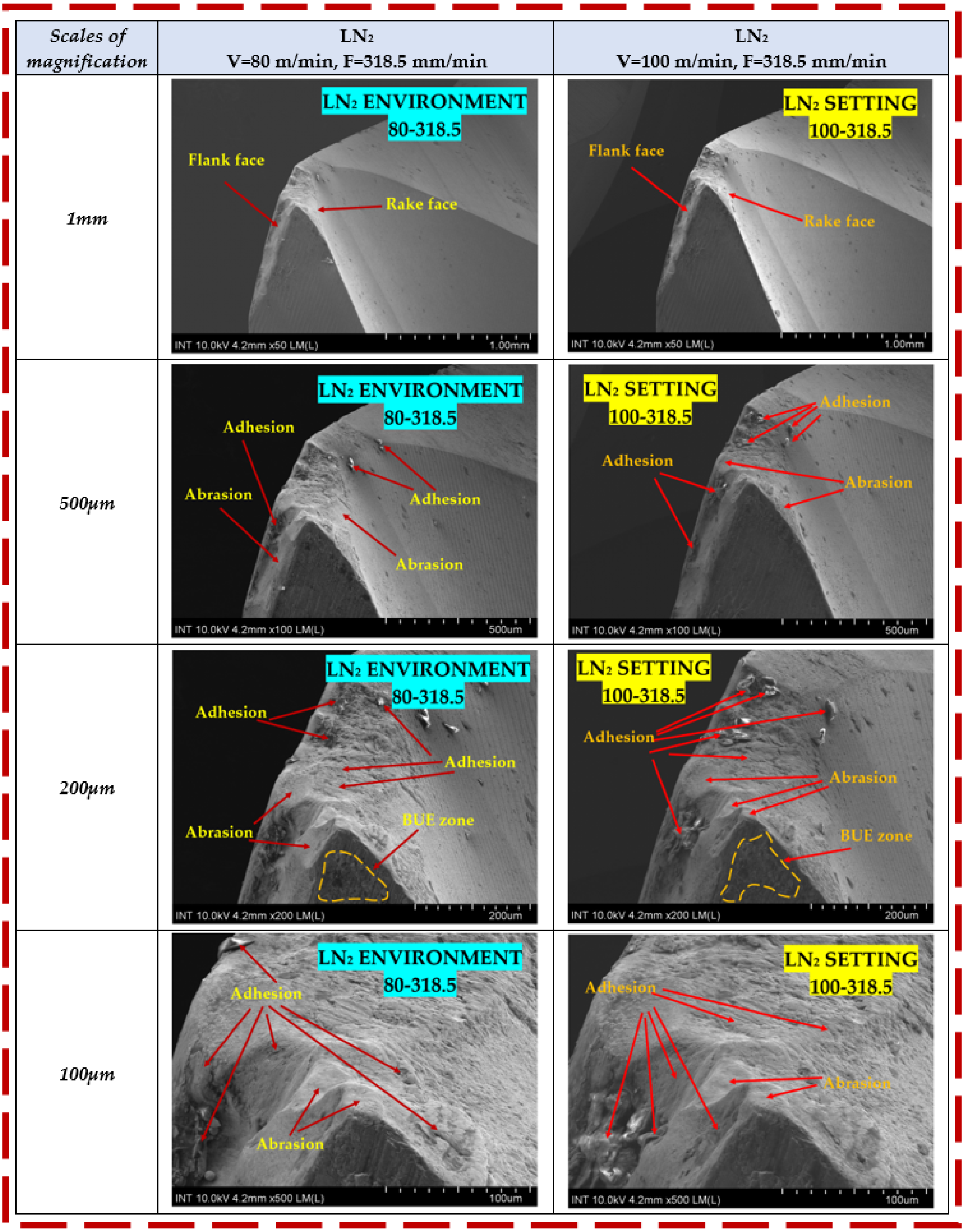

Figure 13. Variation in flank wear and rake wear under LN_2 machining settings at a cutting speed ranging from 80 m/min to 100 m/min and at a constant cutting feed of 318.5 mm/min.

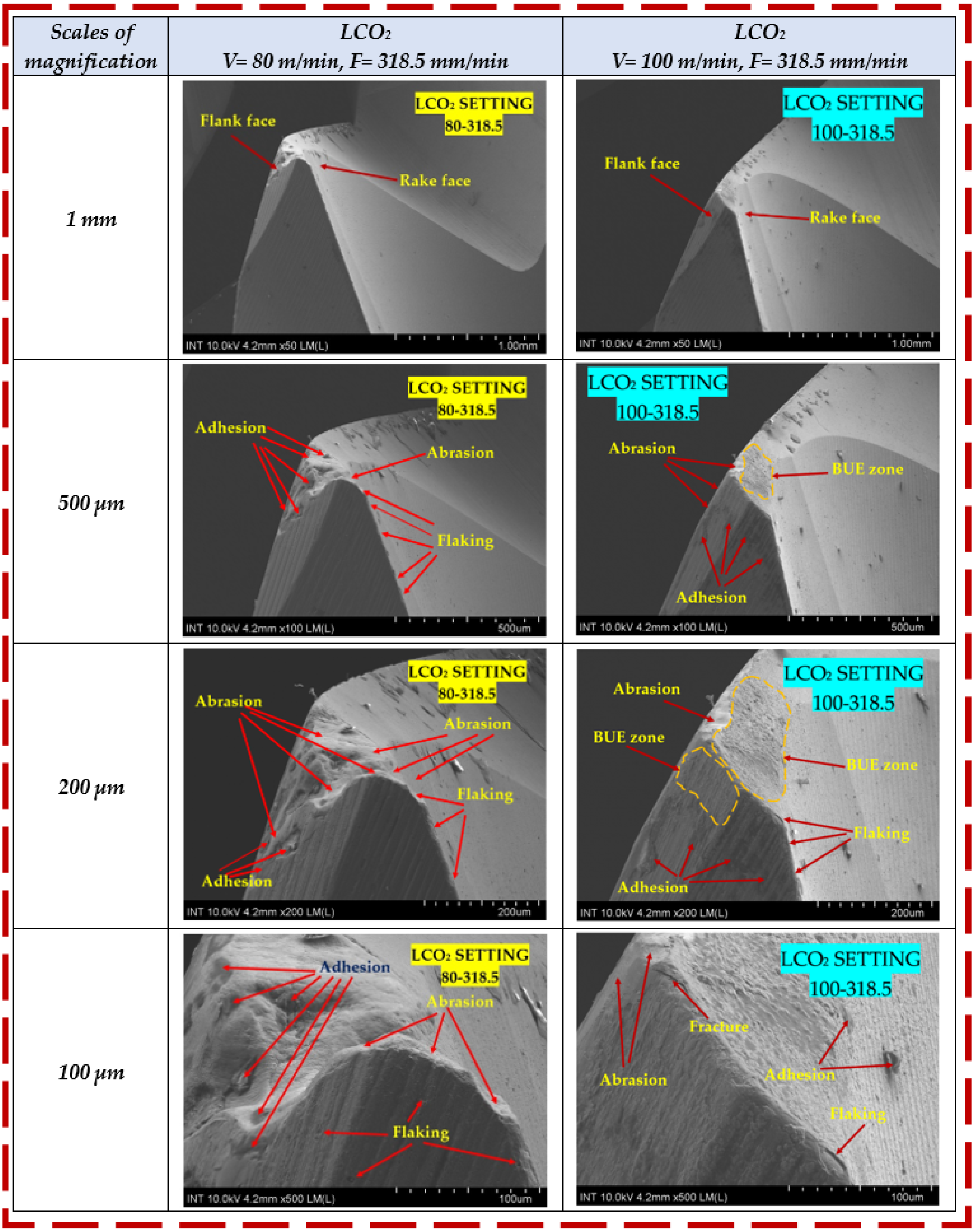

Figure 14. Variations in flank wear and rake wear under LCO_2 machining settings at cuttings speed ranging from 80 m/min to 100 m/min and a constant cutting feed of 318.5 mm/min.

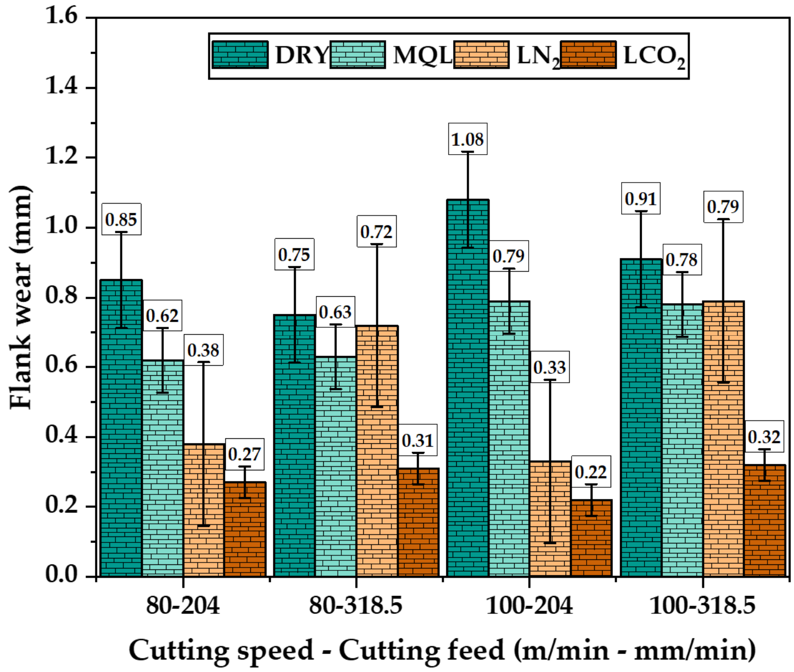

Figure 15. Progression of flank wear observed during the open slot milling process when employing dry, MQL, and cryogenic cooling techniques using LN_2 and LCO_2.

As shown in Figure 15, the flank wear value was measured during the open slot machining process at various cutting speeds and cutting feeds, under four distinct cooling and lubrication environments. For instance, at a cutting speed of 100 m/min and a cutting feed of 204 mm/min, with a machining time of 70 min, each cutter performed the open slot milling cycle three times to achieve a total depth of cut of 0.3 mm. Measurements indicated that the flank wear in the dry machining process reached a maximum value of 1.08 mm, while the flank wear value with cryogenic cooling with liquid carbon dioxide (LCO_2) reached a maximum value of 0.22 mm. In comparison to the dry environment, the contributions of MQL and cryogenic cooling with LN_2 and LCO_2 to the improvement of flank wear were 26.8%, 69.4%, and 79.6%, respectively. In a comparable scenario, utilizing a cutting speed of 80 m/min and a cutting feed of 204 mm/min over a period of 70 min, the maximum flank wear observed during the dry machining process was 0.85 mm in contrast to a significantly lower value of 0.27 mm when employing cryogenic cooling with liquid carbon dioxide (LCO_2). When evaluated against the dry environment, it was noted that the use of MQL and cryogenic cooling with LN_2 and LCO_2 contributed flank wear reductions of 27.1%, 55.3%, and 68.3%, respectively.

Conversely, as depicted in Figure 15, at a cutting speed of 100 m/min and a cutting feed of 318.5 mm/min, the cutters completed the open slot milling cycle three times within 46 min to attain a cumulative depth of cut of 0.3 mm. Observations showed that under dry machining, flank wear peaked at 0.91 mm whereas it reached only 0.32 mm when using cryogenic cooling with liquid carbon dioxide (LCO_2). Relative to dry conditions, the enhancements in flank wear due to MQL and cryogenic cooling with LN_2 and LCO_2 were 14.3%, 13.2% and 64.8%, respectively. In a similar experiment, with a cutting speed of 80 m/min and a cutting feed of 318.5 mm/min over 46 min, the maximum flank wear under the dry machining condition was 0.75 mm compared to a much lower 0.31 mm when using cryogenic cooling with liquid carbon dioxide (LCO_2). Against the dry machining benchmark, the application of MQL and cryogenic cooling with LN_2 and LCO_2 resulted in flank wear reductions of 16%, 4%, and 58.7%, respectively.

3.3. Surface Finish Quality

During the manufacturing phase, prioritizing cost is essential when determining product quality. It is equally crucial to minimize labor time wastage caused by additional reworking and product refusals. As such, the surface roughness that results from machining processes is often regarded as a key indicator for assessing the quality of the machined surface. This study examined surface roughness (R_a) across various cutting speeds and cutting feeds within the context for four environmentally conscious machining conditions. Figure 16 depicts the fluctuations in surface roughness observed when employing different cutting speeds and feed rates, conducted under dry, MQL, and cryogenic cooling conditions using LN_2 and LCO_2, respectively.

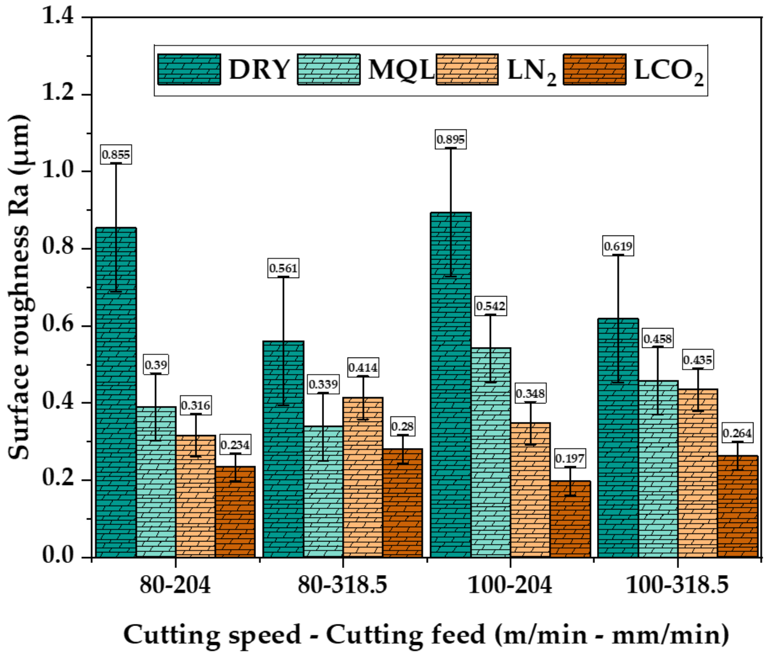

Figure 16. Variations in surface finish quality at various cutting speeds and cutting feeds under dry, MQL, and cryogenic cooling with LN_2 and LCO_2 in open slot milling.

As shown in Figure 16, an increase in cutting speeds from 80 m/min to 100 m/min with a constant cutting feed of 204 mm/min and a consistent machining time of 70 min for an open slot milling operation at a total depth of 0.3 mm led to varied effects on surface roughness. Specifically, surface roughness increased under the dry, MQL, and cryogenic cooling with LN_2 conditions but, in contrast, decreased under cryogenic cooling with the LCO_2 medium. The smallest surface roughness value was 0.895 µm under dry machining conditions, while the lowest value with cryogenic cooling with LCO_2 was 0.197 µm. Compared to the dry condition, surface roughness improvements were 39.5% for MQL, 61.1% for cryogenic cooling with LN_2, and an impressive 78% when using LCO_2.

In a similar experiment, elevating the cutting speed to 100 m/min while maintaining a cutting feed of 318.5 mm/min and a steady machining duration of 46 min resulted in diverse impacts on surface roughness. Notably, surface roughness showed an uptick under the conditions involving dry machining, MQL, and cryogenic cooling with LN_2. On the flip side, surface roughness showed a reduction with cryogenic cooling using LCO_2. The minimal surface roughness recorded was 0.619 µm under the dry condition, whereas the most significant reduction (to 0.264 µm) occurred with cryogenic cooling using LCO_2. When measured against dry conditions, the enhancements in surface roughness with MQL and cryogenic cooling with LN_2 and LCO_2 were 26.1%, 29.7%, and 57.4%, respectively.

Shown in Figure 16, surface roughness in a cryogenic cooling environment with liquid carbon dioxide (LCO_2) increased from 0.197 µm to 0.28 µm when the cutting speed was raised from 80 m/min to 100 m/min and the cutting feed was raised from 204 mm/min to 318.5 mm/min. Concurrently, the use of cryogenic cooling with LCO_2 resulted in less tool wear compared to the dry, MQL, and LN_2 cryogenic cooling methods, which in turn yielded a smoother surface finish [25,27]. Therefore, cryogenic cooling with liquid carbon dioxide (LCO_2) is suitable for open slot milling operations on tempered JIS SKD11 steel.

3.4. Microhardness (HV)

Surface hardness plays a critical role in material behavior, especially when subjected to various cutting conditions and machining environments. When we machine a workpiece, stress is generated and the temperature rises. These factors significantly impact the hardness of the machined surface and the layers beneath it. Notably, cutting speed is a pivotal parameter that creates a strongly concentrated heat zone in the cutting region. As a result, the workpiece becomes harder due to a combination of strain hardening and resistance to thermal softening. Temperature emerges as the primary factor influencing hardness changes in the material. To enhance this process, it is crucial to establish a suitable machining environment that efficiently controls heat in the cutting area [27]. Figure 17 describes the variation in microhardness (HV) at various cutting speeds and cutting feeds under dry, MQL, and cryogenic cooling conditions using LN_2 and LCO_2, respectively, in an open slot milling operation.

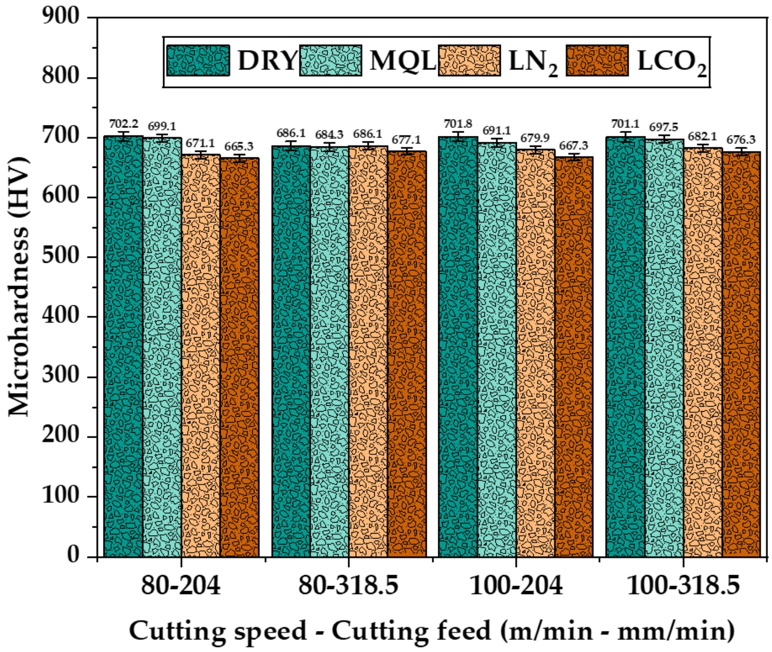

Figure 17. Microhardness variations at various cutting speeds and cutting feeds under dry, MQL, and cryogenic cooling conditions with LN_2 and LCO_2, respectively.

As shown in Figure 17, when increasing cutting speeds from 80 m/min to 100 m/min with a constant cutting feed of 204 mm/min and a constant machining time of 70 min to obtain a total depth of cut of 0.3 mm in an open slot milling operation, the microhardness values of the machined surface slightly decreased in both the dry and MQL machining environments. This decrease ranged from HV 702.2 to 701.8 and from HV 699.1 to 691.1, respectively. However, the microhardness values of the machined surface slightly increased under cryogenic cooling with LN_2 and LCO_2; the increase ranged from HV 671.1 to 679.9 and HV 665.3 to 667.3, respectively. In a comparable manner, when the cutting speed was increased from 80 m/min to 100 m/min while maintaining a steady cutting feed of 318.5 mm/min and a machining duration of 46 min, there was a minor increase in the microhardness values of the surface after machining in both the dry and MQL conditions. This increase was observed within the range of HV 686.1 to HV 701.1 for dry machining and

HV 684.3 to HV 697.5 for MQL machining. Conversely, a slight decrease in microhardness was noted when cryogenic cooling using LN_2 and LCO_2 was applied, with the values dropping from HV 686.1 to HV 682.1 and from HV 677.1 to HV 676.3, respectively.

As shown in Figure 17, microhardness ranged HV 686.1–702.2, HV 684.3–699.1, HV 671.1–686.1, and HV 665.3–677.1 under dry, MQL, and cryogenic cooling with LN_2 and LCO_2, respectively. The high temperature during the cutting process causes a lot of heat stress on the surface being cut. This stress makes the surface harder, resulting in a surface layer that is harder than the layers below it. The impact of the heat and pressure from cutting becomes weaker the further you go into the material, away from the surface that was cut. This means that it stays closer deeper inside the material and, therefore, closer to its original hardness prior to any cutting. This depth-wise variation in microhardness indicates the extent of the layer impacted by thermal and mechanical stress. Dry machining showed higher microhardness due to greater tool wear and full chip combustion. In comparison to other lubrication methods, dry machining resulted in higher microhardness. Cryogenic cooling with LN_2 and LCO_2 yielded similar microhardness, with LN_2 showing a slightly higher level. The low temperatures under cryogenic machining contribute to increased hardness on both the surface and subsurface due to strain hardening and reduced thermal softening [25]. Microhardness was lower just below the surface of the hardened AISI H13 steel that was end-milled; however, deeper below the surface, the hardness did not change much. A cross-section analysis showed no signs of a heat-affected zone [1]. In this study, the microhardness values across all four machining environments showed minimal or negligible variation. Clearly, the findings of this study are in agreement with the literature reviews mentioned earlier. Figure 18 depicts the process of measuring the microhardness of the machined surfaces under four distinct machining environments.

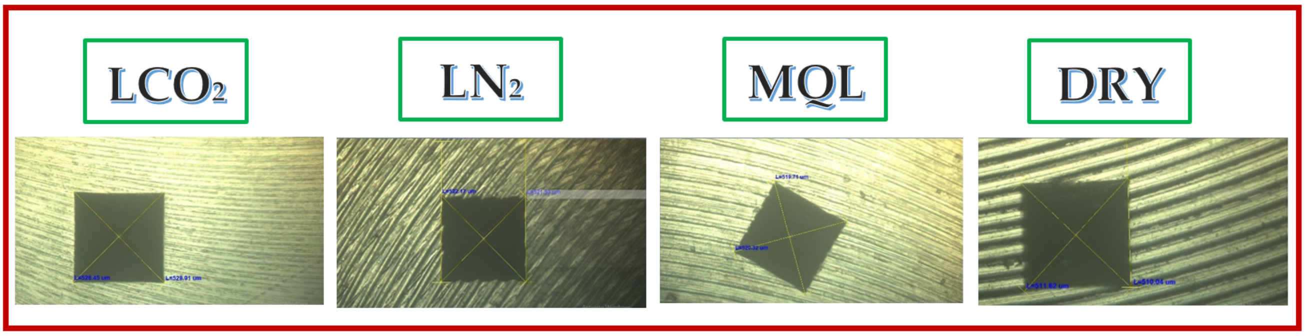

Figure 18. Microhardness measurement of samples obtained from different machining settings conducted at a cutting speed of 100 m/min and with a cutting feed of 204 mm/min.

4. Conclusions

We analyzed the machinability of tempered JIS SKD11 during open slot milling under four distinct machining settings. These settings included various cutting speeds and cutting feeds, and we studied the resulting tool wear, surface roughness, cutting temperature, and microhardness. The study has identified the following pivotal points:

∗∗∗ By investigating temperature variations in the cutting region under different machining environments and varying cutting parameters, we found the following temperature ranges: dry machining (182–206 °C), minimum quantity lubrication (MQL) (117–150 °C), cryogenic cooling with LN_2 (11.5–17.6 °C), and cooling with LCO_2 (28.5–33 °C). Cryogenic cooling with LN_2 effectively dissipates heat in the cutting zone but also increases material brittleness, leading to higher surface roughness and tool wear.

∗∗∗ We measured the maximum and minimum flank wear values under four machining settings of dry, MQL, and cryogenic cooling with LN_2 and LCO_2. As cutting speed was increased from 80/min to 100 m/min and cutting feed was increased from 204 mm/min to 318.5 mm/min, the wear ranged from 0.75 mm to 1.08 mm, 0.62 mm to 0.79 mm, 0.33 mm to 0.79 mm, and 0.22 mm to 0.32 mm, respectively. The wear mechanism primarily involved adhesion and abrasion. Notably, abrasion was pronounced in the MQL machining medium, and no built-up edge was observed in this medium across the different cutting parameters. Our analysis reveals that cryogenic cooling with liquid carbon dioxide (LCO_2) results in the lowest flank wear values compared to a dry, MQL, and LN_2 machining environment.

∗∗∗ Surface roughness was influenced by different machining settings, i.e., dry cutting, minimum quantity lubrication (MQL), and cryogenic cooling using LN_2 and LCO_2. The resulting roughness values varied from 0.561 μm to 0.895 μm, 0.339 μm to 0.542 μm, 0.316 μm to 0.435 μm, and 0.197 μm to 0.28 μm, respectively. Notably, compared to cooling with LCO_2, cryogenic cooling with LN_2 led to significantly higher roughness when cutting speed and cutting feed are increased. Overall, cryogenic cooling with liquid carbon dioxide (LCO_2) effectively improves machined surface quality across varying cutting parameters.

∗∗∗ In an open slot milling operation for tempered JIS SKD11 steel, microhardness measurements were taken under four different machining environments, i.e., dry, minimum quantity lubrication (MQL), and cryogenic cooling with LN_2 and liquid CO_2 (LCO_2). The microhardness values ranged from HV 686.1 to 702.2, HV 684.3 to 699.1, HV 671.1 to 686.1, and HV 665.3 to 677.1, respectively. Notably, the microhardness values with cryogenic cooling with LN_2 and LCO_2 were lower than those under the other conditions. This discrepancy is attributed to the wide and long open slot; as the cutter moved toward the center of the slot, the cutting zone temperature decreased, resulting in only marginal material softening. Consequently, the microhardness (HV) of the machined surface showed minimal enhancement.

Using cryogenic cooling with liquid carbon dioxide (LCO_2) and optimal cutting conditions (speed and cutting feed) significantly affect tool wear and surface roughness during milling. Therefore, careful evaluation of these factors is crucial for enhancing overall performance.

5. Future Research

Sustainable manufacturing methods, such as eco-conscious practices, are vital for both operator health and environmental preservation in machining operations. These practices, which have been discussed in earlier conversations, are expected to play a significant role in future projects; they aim to enhance the surface finish of machined components, reduce tool wear, and extend the lifespan of parts made from additive-manufactured stainless steel and high-performance superalloys. Additionally, the integration of MQL (Minimum Quantity Lubrication) and cryogenic cooling techniques is planned for future studies to further benefit the materials mentioned above.

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