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Review

Research Status and Prospect of Ultrasonic Vibration and Minimum Quantity Lubrication Processing of Nickel-based Alloys

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ABSTRACT: Nickel-based alloys has important application value in modern industrial field, but there are a lot of problems that are difficult to solve in traditional processing, and it is a typical difficult-to-process material. In order to improve the machinability of nickel-based alloys, scholars try to use a variety of non-traditional processing methods to explore and study the processing of nickel-based alloys. In these studies, ultrasonic vibration assisted processing technology and minimum quantity lubrication (MQL) processing technology can achieve remarkable results. The intermittent separation cutting characteristics of ultrasonic vibration assisted processing technology can improve the processing quality by changing the tool path, while minimum quantity lubrication processing technology can improve the lubrication effect of cutting, combining ultrasonic vibration assisted MQL processing leverages the benefits of both methods, resulting in improved machinability and expanded application of nickel-based alloys. Summarize the current research status on the machining mechanism of nickel-based alloys assisted by ultrasonic vibration and micro lubrication, and anticipate its developmental trends. This provides a reference for future research on the efficient machining mechanisms and practical applications of nickel-based alloys.

Keywords: Ultrasonic vibration assisted processing; Minimum quantity lubrication processing (MQL); Nickel-based alloys; Combined processing

1. Introduction

The addition of nickel can improve the toughness, ductility, hardness, corrosion resistance and high temperature resistance of the alloy, which is an important way to improve the properties of the alloy. Common nickel-based alloys include GH4738, Inconel718, GH4169, Hastelloy-X alloy, Nimonicalloy75 and ASTM1045, etc. [1–6]. These materials have a non-negligible impact on the development of industry. It is widely used in aerospace, biomedical and chemical industries [7]. However, due to the chemical reaction with a variety of tool materials and low thermal conductivity, nickel-based alloys is generally considered a difficult material in conventional processing [8], which limits its application prospects in a wider field [9]. In order to cope with the difficult machinability of nickel-based alloys, scholars have tried to use other non-traditional auxiliary processing methods to carry out cutting experiments on nickel-based alloys [10,11]. Ultrasonic vibration assistance and minimum quantity lubrication are the more common auxiliary processing methods, which are considered to be able to significantly improve the processing properties of materials.

Ultrasonic vibration assisted processing (UVAM) is a processing method that uses high-frequency vibration to assist cutting. By introducing more than 20kHz vibration into the cutting process, the tool movement trajectory in the processing process is changed [12], so as to achieve the purpose of improving the processing efficiency and processing quality. At present, it is widely used in the processing of various difficult materials such as alloy materials, brittle materials and ceramic materials [13–15] UVAM can be divided into sine UVAM and elliptical UVAM according to the different characteristics of its tool trajectory, and can also be divided into turning UVAM and rotating UVAM according to the processing mode. Compared with traditional processing with non-ultrasonic vibration, the intermittent separation cutting characteristics produced by UVAM due to special tool trajectory is one of the most important

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advantages of UVAM, which can reduce cutting force and cutting temperature, extend tool life and improve the surface quality of the workpiece [16]. However, not all processing conditions can produce intermittent cutting separation characteristics, scholars according to whether the workpiece and the tool can produce separation state defined the specific separation conditions, only when the amplitude, frequency and cutting speed to meet the separation conditions, UVAM has intermittent separation cutting characteristics, its processing advantages can be maximally played out. processing that does not meet the separation conditions may not only lose its own processing advantages, but even cause adverse effects such as tool trajectory distortion, severe tool wear and surface quality decline [17].

Most of the traditional cooling cutting fluids will cause harm to the human body and the natural environment, especially for materials that are easy to produce a lot of cutting heat in processing, and the overused cutting fluids will cause a heavy blow to health and environmental protection [18–20]. In order to solve this problem, scholars have proposed minimum quantity lubrication processing technology. minimum quantity lubrication is composed of nozzles, control systems, pipelines, fuel tanks and air compressors [21], which usually spray a mixture of vaporized compressed gas and a small amount of cutting fluid into the cutting area, and the cutting fluid consumed can be as low as 10ml/h [22], which is an auxiliary processing method that can ensure the cooling effect while using very little cutting fluid. minimum quantity lubrication can usually be divided into four types: vegetable oil type minimum quantity lubrication, low temperature cooling type minimum quantity lubrication, solid lubricant type minimum quantity lubrication and electrostatic atomization type minimum quantity lubrication. Numerous experimental studies have shown that minimum quantity lubrication can reduce cutting temperature, improve surface quality and reduce tool wear, and has the advantages of green, environmental protection, economy and sustainability [23].

Ultrasonic vibration and minimum quantity lubrication processing technology can theoretically improve the processing conditions of nickel-based alloys, and the combination of the two is more likely to solve the processing problems that have been difficult to solve for a long time. In order to better review these contents, this paper searched all the ultrasonic vibration assisted and minimum quantity lubrication technologies related to the processing of nickel-based alloys from Elsevier and Springer databases. Based on this, this paper reviewed the research progress of ultrasonic vibration assisted cutting of nickel-based alloys and minimum quantity lubrication cutting of Nickel-based alloys in recent years, and paid attention to the research status of the combination of the two. To better illustrate the content of this review, Figure 1 illustrates the narrative structure of this article.

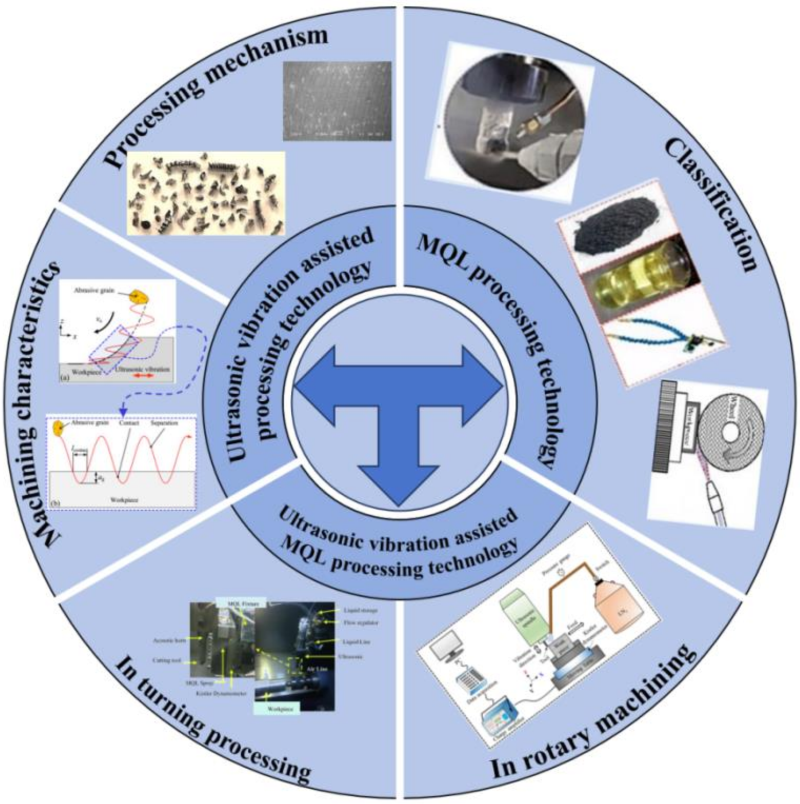

Figure 1. Paper structure chart.

2. Ultrasonic Vibration Assisted Processing Technology

As an important technical means to improve the processing effect, UVAM technology can change the cutting mechanism of nickel-based alloys and effectively improve the processing effect of surface quality, chip shape and tool wear due to its unique processing characteristics and suitable processing parameters.

2.1. Processing Characteristics and Parameters

2.1.1. Intermittent Separation Cutting Characteristics

Intermittent separation cutting is one of the main characteristics of UVAM technology, which is different from the traditional processing. The tool movement in processing is usually coupled by the spindle rotation movement, feed movement and ultrasonic vibration movement. By changing the path of the tool, ultrasonic vibration realizes the special processing process of tool-workpiece contact and separation, so as to achieve a series of improving the processing quality of nickel-based alloys and improving the processing efficiency.

UVAM technology can not achieve intermittent separation cutting characteristics under all conditions, can meet the tool and workpiece separation processing parameters are called separation conditions by scholars, separation conditions just can achieve intermittent separation cutting characteristics of the speed is called critical cutting speed:

$$v_{lim} = 2\pi f A$$

where v_{lim} is the critical cutting speed, f is the ultrasonic vibration frequency, and A is the ultrasonic vibration amplitude. When the cutting speed is lower than the critical cutting speed, ultrasonic vibration assistance can significantly reduce the cutting force and improve the surface roughness, and can generate more compressive stress [24]. It can be seen from the formula that the critical cutting speed is closely related to the ultrasonic vibration amplitude and ultrasonic vibration frequency. Therefore, in order to improve the critical cutting speed in processing, Xu [25] et al. developed a new UVAM system, in which the maximum ultrasonic vibration frequency generated by the transducer can reach 33.52 kHz. The maximum ultrasonic vibration amplitude can reach 24.03 μm. By increasing the ultrasonic vibration frequency and amplitude, the critical speed of cutting Inconel718 can be effectively increased. The preliminary experimental results show that the cutting force and average cutting temperature can be reduced by 23.3 and 19.8%, respectively. Cao et al. [26] used a self-designed ultrasonic vibration system to grind Inconel718 on a high speed grinder, and found that in the process of grinding Inconel718, the intermittent separation cutting characteristic makes the abrasive particles periodically contact and separate from the workpiece surface, and the workpiece is removed by a periodic pulse force, as shown in Figure 2. In this case, the grinding force and grinding temperature can be reduced by about 41% and 40% respectively. They also successfully developed a material removal probability model to determine the key process parameters that affect the intermittent separation cutting characteristics. In the ultrasonic vibration-assisted turning of Nimonic90, due to the influence of intermittent separation cutting characteristics, the tool and the workpiece are repeatedly separated in the processing, which makes the heat generated when the tool is engaged relatively less, resulting in a lower average surface roughness value, which is reduced by 75–80% compared with traditional turning [27]. Although UVAM that meets the intermittent separation cutting characteristics can achieve the optimal processing effect, Wang [28] et al. found that even if the cutting speed in the processing is greater than the critical cutting speed, the processing effect is still conducive to the turning of Inconel718.

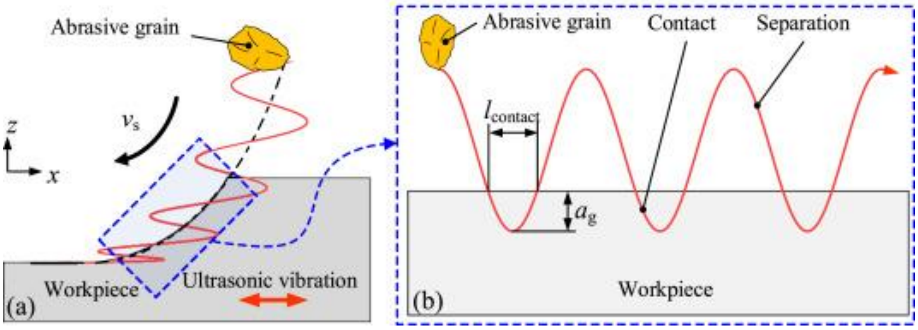

Figure 2. Intermittent cutting separation during ultrasonic vibration assisted grinding of Inconel718: (**a**) abrasive track (**b**) separation diagram [26]. Reproduced with permission from Elsevier.

2.1.2. Influence of Parameters on Processing

The effect of UVAM technology depends on the selection of specific processing parameters. It is generally believed that the parameters in UVAM can be divided into two categories: cutting parameters and vibration parameters. The cutting parameters include feed speed, spindle speed, back cutting tool amount and tool geometry data, etc. The vibration parameters include ultrasonic vibration amplitude, ultrasonic vibration frequency and phase difference. The change of some key parameters directly affects the quality of processing nickel-based alloys. Only with appropriate parameters can UVAM technology give full play to its advantages.

Ultrasonic vibration amplitude is an important parameter affecting the processing effect of nickel-based alloys. The larger the amplitude of ultrasonic vibration, the smaller the processing stress and milling force, and the better the chip breaking effect [29]. The optimal surface roughness can be obtained when the ultrasonic vibration amplitude is maintained at 6 μm [30]. A smaller ultrasonic vibration amplitude can greatly prolong the life of drilling Inconel718 bit [31], and a larger ultrasonic vibration amplitude can reduce the residual stress on the surface, enhance the hardening degree of the machined surface, increase the surface roughness [32], and reduce the thrust of drilling DD6 [33]. However, an amplitude of more than 12 μm will greatly increase the cutting force and aggravate the wear of the drill bit. When the ultrasonic vibration amplitude is 6 μm, the size and number of burrs are the smallest [34].

Feed speed is the most critical factor affecting processing quality and production rate [35]. Lower cutting speed and feed per tooth have the best effect on burr suppression. When the feed rate per tooth was 6 μm, a large number of continuous burrs appeared at the top of the groove [34]. The faster the milling speed, the weaker the intermittent separation cutting characteristics, and the less easily the chips are broken. The greater the radial cutting width, the greater the processing stress and the greater the milling force [29]. However, when the feed speed is low, the processing surface will have obvious defects such as pits, humps and gullies [36]. The amount of back cut and feed speed have an important influence on the roundness of turning, and the choice of tool material is the most important factor affecting the tool wear of cutting Inconel718 [37]. The cutting performance of Inconel718 is optimal when the back cut is 0.1mm, and increases with the decrease of feed speed and cutting speed [38].

2.2. Processing Mechanism

2.2.1. Surface Formation Mechanism

There are obvious differences between UVAM technology and traditional processing in surface formation mechanism. Ultrasonic vibration is conducive to inhibiting the size of burrs and effectively reducing the formation of accumulated edges, and its intermittent cutting separation characteristics, impact characteristics, variable speed characteristics and reciprocating ironing characteristics will greatly reduce the occurrence of surface defects [36]. As shown in Figure 3, ultrasonic vibration can produce regular microtextures on the surface of the workpiece, thereby improving the processing properties of nickel-based alloys [39]. In the process of grinding Inconel718, the intermittent separation cutting feature, in addition to forming a specific texture on the surface, also reduces the number of troughs in the contour curve along the grinding speed, thereby reducing the surface roughness by 20% [26].

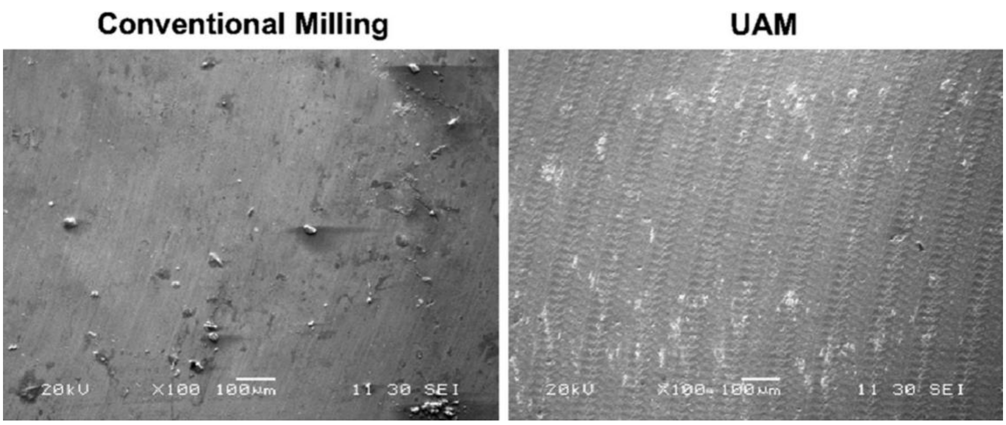

Figure 3. Surface topography under scanning electron microscopy [39]. Reproduced with permission from Springer Nature.

Due to the small loading force, the sub-surface damage of the workpiece obtained by UVAM is less and accompanied by more uniform tissue evolution [40]. As shown in Figure 4, Chang et al. selected a precision processing center to perform ultrasonic vibration assisted milling on nickel-based alloys, and found ultrasonic vibration assisted results in obvious grain refinement of the subsurface microstructure, and the degree of refinement presents a gradient change from the surface to the interior. In addition, the authors observed an orientation deviation of up to 293μm (at the dashed line in the Figure 4), indicating a large plastic deformation of the subsurface [41]. The phenomenon of micro-chip particles on the workpiece surface and the accumulation of tool edges is reduced [42]. In addition, the processing assisted by ultrasonic vibration can obtain thicker surface plastic deformation layer, lower surface roughness, thicker hardened layer [43], higher surface micro-hardness rate and higher surface compressive residual stress [44]. Therefore, compared with traditional processing methods, ultrasonic vibration assisted processing technology can obtain fewer burrs and better surface topography.

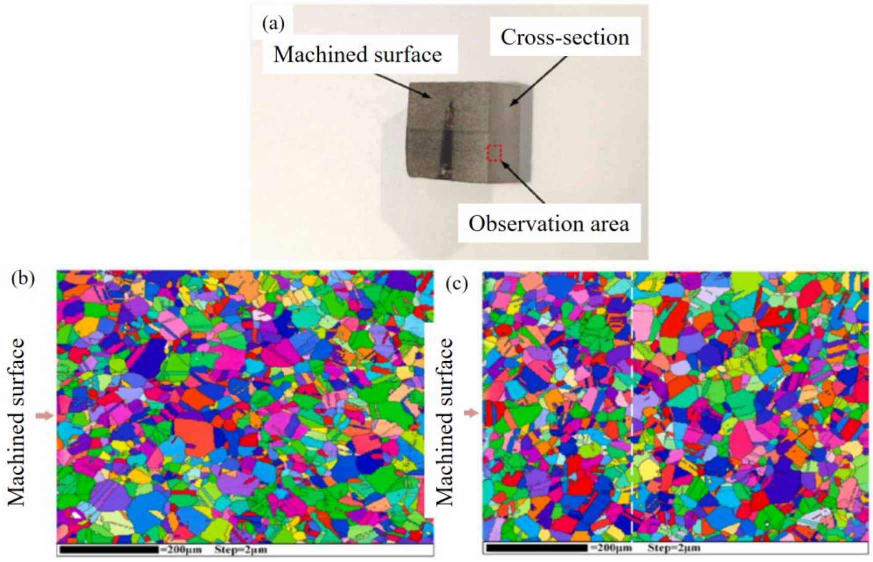

Figure 4. Micro analysis of traditional processing and UVAM. (**b**) Traditional processing, (**c**) UVAM [41]. Reproduced with permission from Elsevier.

2.2.2. Chip Morphology

Compared with traditional processing, the chips produced by UVAM are thinner and smoother, and have a smaller bending radius, which is conducive to achieving better processing results [27,45]. Abdelaziz et al. [46] conducted a study on ultrasonic vibration-assisted drilling of Inconel601, and found that segmented chips or short continuous chips could be obtained, as shown in Figure 5, which could effectively solve the serious chip blockage and chip stuck caused by long-term continuous chips. Compared with traditional drilling, the drilling bit has longer life, better hole quality and higher processing efficiency. In the processing of ultrasonic vibration-assisted grinding of Inconel718, due to the ultrasonic lubrication effect and the vibration of the abrasive blade front Angle, ultrasonic vibration has a significant impact on chip size and geometry, which can significantly reduce the cross-sectional area and length of chips. In addition, the formation of shear chips can be avoided under large vibration amplitude, which is conducive to the formation of flow chips [45]. It can be seen that the technology of ultrasonic vibration assisted processing can obtain shorter, thinner and smoother chips than traditional processing.

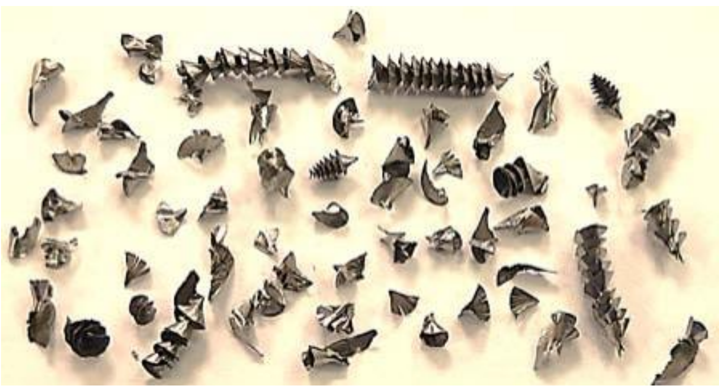

Figure 5. Chip morphology after UVAM [46].

2.2.3. Tool Wear

Due to the poor thermal conductivity of nickel-based alloys, the resulting increased shear stress leads to serious tool wear in traditional processing. Due to the influence of intermittent separation cutting characteristics in UVAM, the separation between the tool and the workpiece has a low contact ratio, thus reducing tool wear [47] and extending the tool life during cutting Inconel718 by 250% [48]. It also reduces the accumulation of tool edges, thereby reducing tool side wear [42]. Chang et al. [3] conducted milling experiments on GH4169 superalloy, and found that ultrasonic vibration-assisted processing technology could significantly reduce the maximum side wear band width and wear rate, as well as the friction coefficient and wear volume, thereby obtaining better tool wear conditions and surface quality.

In the ultrasonic vibration assisted grinding of Inconel718, Cao et al. [49] found that the peak area of the grinding wheel was more prone to wear. As shown in Figure 6. In the stable wear stage, because of the larger interference area between the abrasive particles and the workpiece, the grinding edge in the peak zone removes more workpiece materials than that in the valley zone, resulting in higher grinding wheel wear speed in the peak zone. In the severe wear stage, the binding area of the wear particles is small, so the binding force is smaller than the valley area, which also leads to serious wear. In summary, the wear in the peak area is about 1.14 times that in the valley area. In addition, the increase of grinding wheel speed, feed speed and ultrasonic vibration amplitude will lead to longer abrasive contact length and time, aggravating abrasive wear [50]. Therefore, compared with traditional processing, ultrasonic vibration assisted processing does not always reduce tool wear.

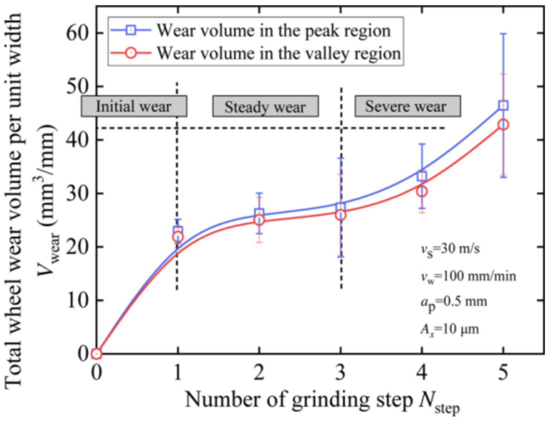

Figure 6. Grinding wheel wear in peak and valley regions [49]. Reproduced with permission from Elsevier.

3. Minimum Quantity Lubrication Processing Technology

Wet processing is a widely adopted lubrication method during the processing process. Its primary functions include cooling, lubrication, and chip removal in the cutting zone, effectively reducing the heat generated between the tool and the chips. Simultaneously, it prolongs the tool's lifespan, protects workpieces and tools from corrosion, and enhances the surface condition and dimensional accuracy of products. In contrast, lubricants typically account for 20% of the processing cost in traditional manufacturing processes [51–53]. However, in some cases, adopting minimal amounts of lubricant or dry processing (without lubricant) is crucial for reducing manufacturing costs. Dry processing can significantly reduce manufacturing costs, shorten production time, achieve comparable surface finish, and also reduce or eliminate harmful cooling media to the environment [54]. Although completely eliminating lubricants may seem attractive, it can become challenging considering tool wear and part quality [55]. Therefore, to maintain reasonable tool life and part quality, it is usually necessary to use minimal amounts of lubricant. This has also led to a focus on Minimum Quantity Lubrication (MQL) as a lubrication method. Minimum Quantity Lubrication (MQL) technology can reduce cutting temperature and improve lubrication conditions while protecting nature and human health. Many studies have shown that it is feasible to apply MQL technology to nickel-based alloy processing, which can improve processing quality and efficiency [56]. Therefore, it is necessary to deeply discuss the application of MQL technology in nickel-based alloy processing.

3.1. Vegetable Oil-based MQL Processing of Nickel-based Alloys

As mechanical processing advances towards sustainable development, it is recommended to replace traditional mineral oil with plant-based biodegradable oil in MQL processes [57]. This trend comes with multiple benefits. Firstly, the triglyceride structure in vegetable oil (Figure 7) not only enhances lubrication quality but also possesses long polar fatty acid chains that play a crucial role in reducing wear and friction between the tool and workpiece [58]. Numerous experiments have confirmed the significant effects of adopting MQL techniques based on vegetable oil in the processing of nickel-based alloys [59–62]. Rahim et al. [60] employed a combination of castor oil and synthetic esters in the MQL process for drilling Inconel 718. Their research results demonstrated superior performance of vegetable oil in terms of lubrication and cooling. Additionally, better outcomes were achieved in microhardness, surface roughness, surface defects, and subsurface deformation. This advantage is mainly attributed to the high viscosity of castor oil, providing effective support for lubrication and cooling. Similar studies were conducted by Sarikaya et al. [63], where mineral oil, synthetic esters, and vegetable oil were considered as different lubricating environments. In their MQL turning of the challenging material Haynes 25, they found that the performance of vegetable oil surpassed that of mineral oil and synthetic esters. Specifically, vegetable oil not only effectively reduced surface roughness but also played a significant role in reducing tool wear, resulting in less flank wear and notch wear.

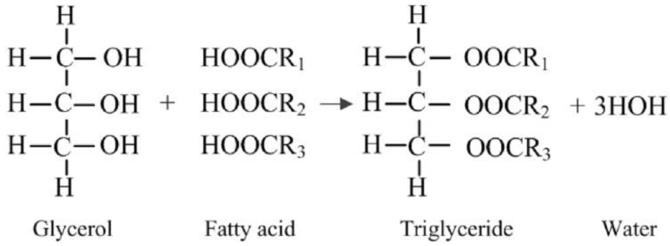

Figure 7. Reaction of triglyceride formation [64]. Reproduced with permission from Elsevier.

Saleem et al. [65] conducted turning of Inconel 718 in an MQL environment using castor oil and sunflower oil, with a focus on tool wear and surface integrity. The study revealed that feed rate and cutting speed are critical factors influencing surface roughness and tool wear. Under the same conditions, sunflower oil exhibited the best performance, attributed to its viscosity and wetting surface characteristics. This approach achieved a minimum tool wear of 116 μm and a surface roughness of 0.43 μm (Figure 8a,b). Tool wear under high speed cutting is shown in Figure 6c. Under high parameter combination, wear characterized by groove marks and chips is the main tool wear mode. This can be explained, on the other hand, the absence of BUEs at higher conditions/the smaller adhesion may be due to the formation of flow zones at higher speeds. BUE, even when formed, is worn due to high temperature, shear, and compression stresses acting on the flow zone of the tool-workpiece interface, ultimately leading to the wear and grooving observed in this work. Here, the observed groove marks may be attributed to the presence of hard particles in Inconel 718 workpieces, which wear down the tool material, especially under relatively harsh processing conditions. Li et al. [62] investigated the grinding of GH4169 using seven plant-based oils (castor oil, soybean oil, rapeseed oil, corn oil, sunflower oil, peanut oil, and palm oil) in an MQL environment. The results showed that MQL based on castor oil had the lowest grinding force but the highest grinding temperature and energy ratio. In contrast, MQL based on palm oil exhibited the lowest grinding force, temperature, and energy ratio (Figure 9a–c). From a lubrication perspective, the oil film formed by castor oil demonstrated good friction resistance and load-carrying capacity (Figure 9d). Subsequently, Li et al. [61] used these seven plant-based oils as the base oil for MQL and evaluated their frictional performance. The results indicated that MQL grinding of GH4169 based on castor oil achieved the optimal surface morphology and minimal roughness, with a friction coefficient of 0.3. The polar molecules in plant oil formed an adsorption film on the workpiece surface, proving to be crucial for this effect (Figure 9e–h). The research suggests that a single plant-based oil may have performance limitations.

Therefore, to address the performance limitations of a single plant-based oil, many researchers have adopted the approach of blending two or more types of plant oils and found that such mixtures can achieve better processing results. Guo et al. [66] used castor oil as the base oil and mixed it in a 1:1 ratio with six other plant oils (soybean oil, corn oil, peanut oil, sunflower oil, palm oil, and rapeseed oil). These mixtures were used as the base oil for MQL in the grinding of GH4169 to assess the lubrication at the wheel/workpiece interface. Experimental results showed that the mixed oil significantly reduced the specific tangential grinding force, specific normal grinding force, and specific grinding energy compared to the base oil. Among them, the values for soybean/castor oil were the lowest (0.664 N/mm, 1.886 N/mm, 60.71 J/mm^3), representing reductions of 27.03%, 23.15%, and 27.07%, respectively, compared to castor oil.

Furthermore, to address the limitations of plant oils, scholars have found that it is possible to improve them by adding solid lubricants and ionic liquids [67]. However, unfortunately, the addition of solid lubricants has led to the issue of aggregation, primarily dependent on the concentration of solid lubricants. As the concentration increases, the problem of aggregation becomes more likely to occur [68].

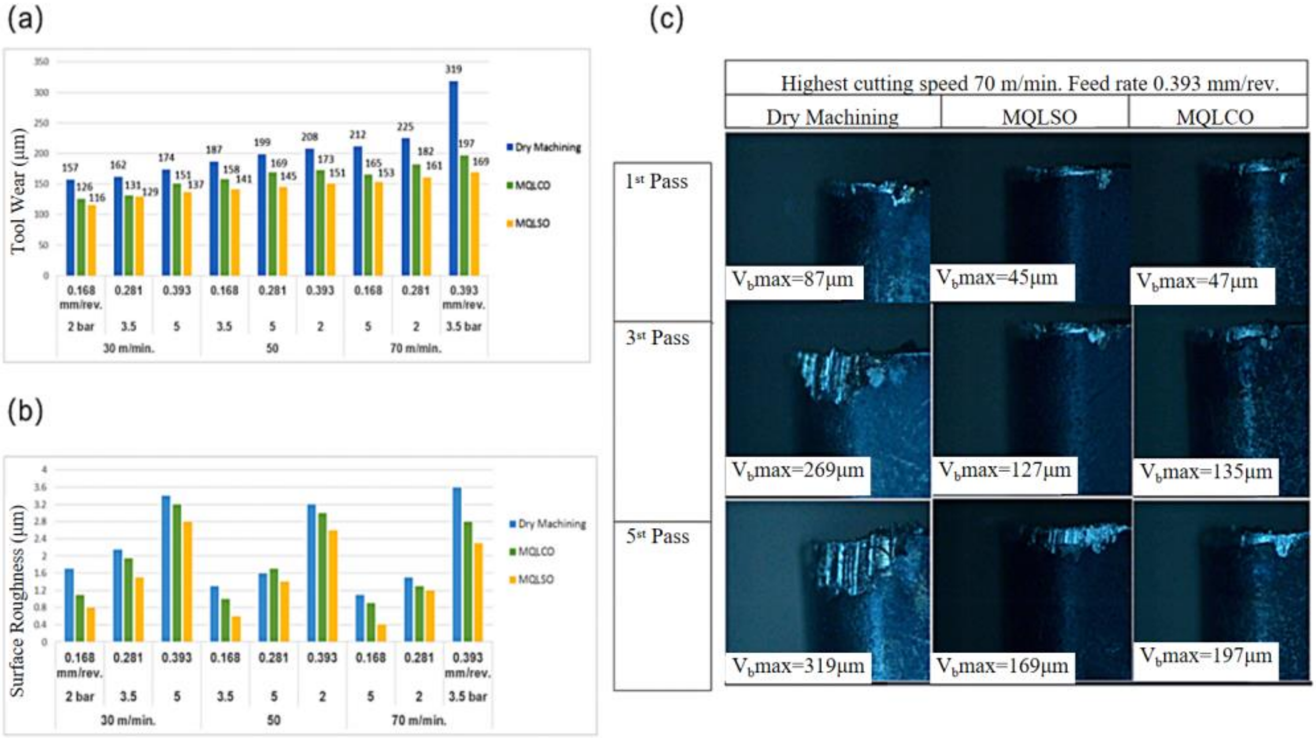

Figure 8. (**a**) Comparison of tool wear for all processing conditions (Dry, MQLCO = MQL + castor oil, MQLCO = MQL + sunflower oil). (**b**) Comparative analysis of surface roughness for all processing conditions (Dry, MQLCO = MQL + castor oil, MQLCO = MQL + sunflower oil). (**c**) Tool wear progression at highest cutting speed/feed rate combination [65]. Reproduced with permission from Elsevier.

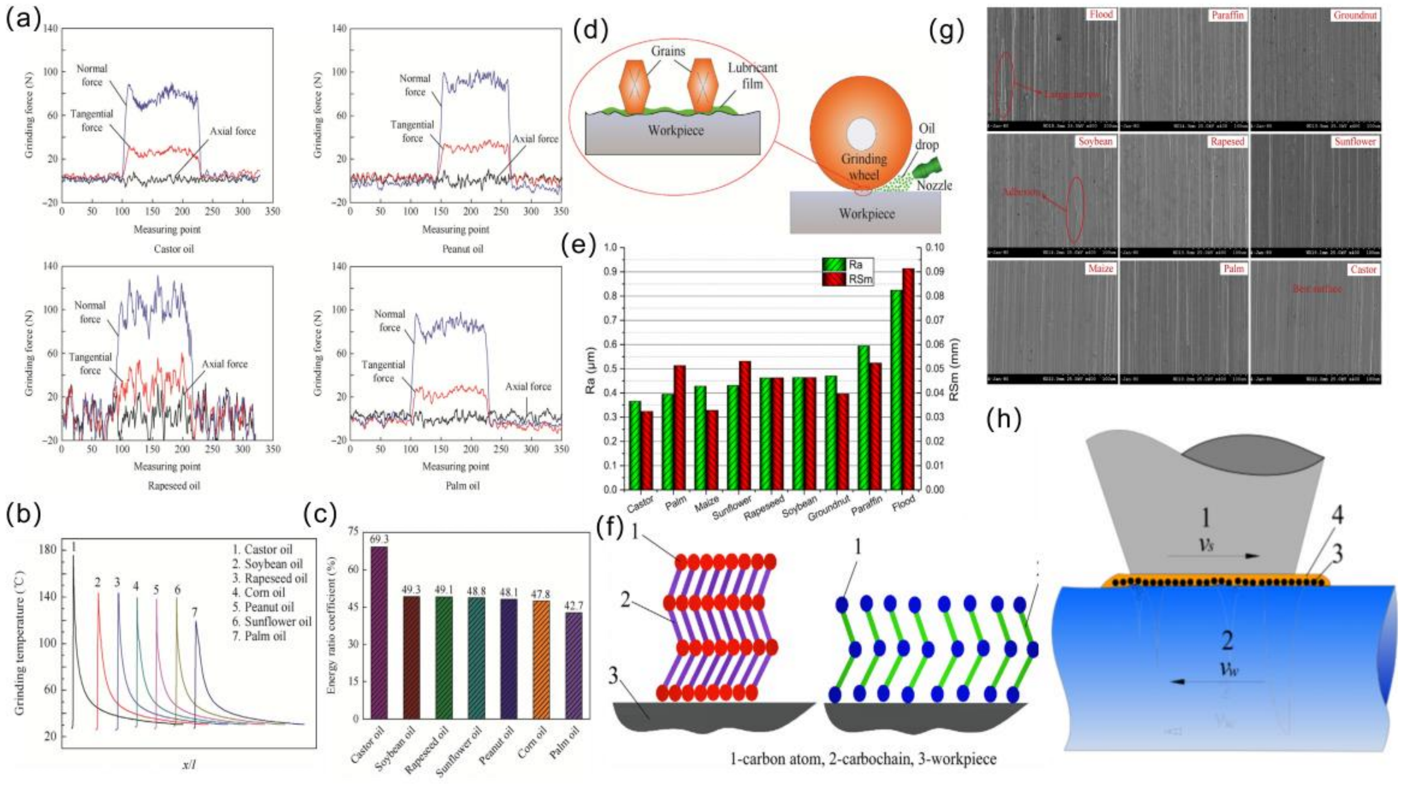

Figure 9. (**a**) Signal graph of the measured grinding force of the four kinds of vegetable oils in MQL grinding. (**b**) Grinding temperature graph for seven kinds of vegetable oil. (**c**) Ratio coefficients of energy transferred into workpieces for the seven kinds of vegetable oil used in MQL grinding. (**d**) Schematic of the antiwear and load-carrying capacity of lubricant film [62]. (**e**)Surface roughness under different working conditions. (**f**) Schematic of the London dispersion forces between molecules. (**g**) Surface morphology of GH4169 under flood, paraffin oil, and vegetable oils using MQL techniques. (**h**) Schematic of lubrication in the grinding interface [61]. Reproduced with permission from Elsevier.

3.2. Nanofluid MQL Processing of Nickel-based Alloys

Due to the poor thermal conductivity of nickel-based alloys, there are certain limitations to MQL when processing such materials. To address the deficiencies related to friction control and heat generation, Nano-fluid MQL has been proposed to overcome these challenges [69–71]. Nano-particles not only enhance thermal conductivity but also exhibit the effects of ball bearings and polishing, forming a protective lubricating film at the processing interface (Figure 10). This improvement enhances the friction and lubrication conditions at the processing interface, offering potential advancements in MQL processing performance for nickel-based alloys.

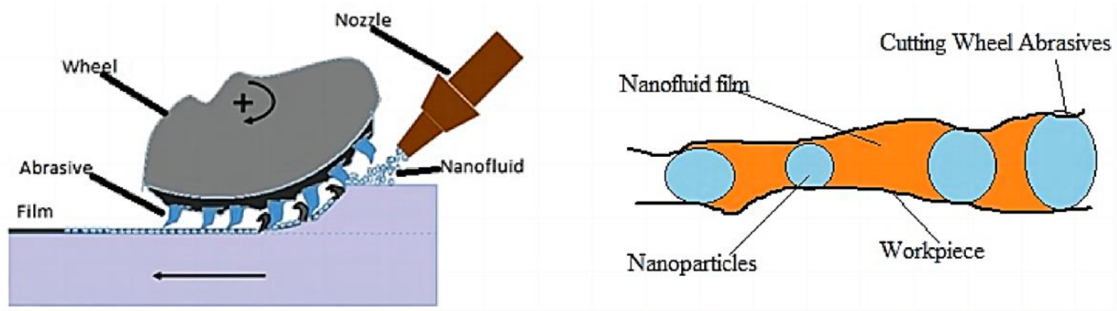

Figure 10. Schematic of Nanofluid film formation under MQL Grinding Process [72]. Reproduced with permission from Elsevier.

Different materials exhibit different properties, and lubrication efficiency largely depends on the form of trace lubricating additives [73]. Li et al. [74] mixed six types of nanofluids (MoS_2, ZrO_2, CNT, PCD, Al_2O_3, SiO_2) with palm oil, each at a concentration of 3%, to investigate the heat transfer performance of different nanofluids in the grinding of a nickel-based alloys. These six nanofluids were used as MQL fluids for grinding GH4169. The results showed that SiO_2 nanofluid had the lowest grinding force, followed by MoS_2 nanofluid, indicating that SiO_2 and MoS_2 had the best lubricating performance, while CNT and Al_2O_3 exhibited moderate lubricating performance among the six types of nanoparticles.

The concentration of nanoparticles also has a significant impact on the lubricating effect. Makhesana et al. [75] analyzed three concentrations (0.5%, 1%, and 1.5%) of nanofluid (MoS_2 + palm oil) as MQL medium for turning Inconel 718. They found that a 1% concentration of nanofluid significantly reduced surface roughness, tool wear, and microhardness. However, at 0.5% concentration, tool wear was minimized. At 1.5% concentration, agglomeration started, and surface quality, tool wear, and microhardness began to deteriorate. Makhesana and Patel [76], by studying the friction coefficient, thermal conductivity, viscosity, and wetting properties of nanofluids, determined the optimum concentration. They added different concentrations (0.5%, 1%, and 1.5%) of MoS_2 nanoparticles to rapeseed oil and found that a 1% concentration had lower surface tension, a smaller contact angle, and the highest thermal conductivity. Danish et al. [77] analyzed the dispersion stability, thermal conductivity, viscosity, and wetting angle of nanofluids with concentrations ranging from 0 to 1.1wt%. They observed that at a graphene concentration of 0.7%, the nanofluid exhibited maximum absorption, highest thermal conductivity, high dynamic viscosity, and a small contact angle.

Furthermore, it has been reported that blending nanofluids with multiple types of nanoparticles significantly alters the processing performance of MQL [78]. Sirin et al. [79] conducted milling experiments on Inconel X-750 at three different cutting speeds and three different feed rates, finding that hBN/Grpt reduced cutting temperature, increased surface roughness, and extended tool life.

Numerous experiments have demonstrated that MQL based on nanofluids can enhance processing quality, tool life, processing temperature, and efficiency [80]. However, micron-sized solid lubricants are also an economical and effective choice to meet lubrication requirements.

3.3. Cryogenic MQL Processing of Nickel-based Alloys

To reduce heat during the processing of nickel-based alloys, low-temperature MQL is a direction worth considering for improving MQL cooling and lubrication [81]. Cryogenic Minimum Quantity Lubrication (CMOL) is a novel lubrication system that combines low-temperature cooling technology with MQL technology. Its cooling media include liquid nitrogen, liquid carbon dioxide, cold air, and supercritical carbon dioxide [82]. LN2, as a cooling medium, can reach −196 °C at atmospheric pressure, and its effectiveness is notable [83]. However, due to the relatively high storage and transportation costs of liquid nitrogen, there are limitations to the coupling effects of liquid nitrogen and MQL. Additionally, its application scope in the cutting of difficult-to-machine materials is relatively small and requires further exploration [84,85].

When liquid CO_2 is sprayed into the processing area, a portion will evaporate, while another part will form a stream of dry ice particles to achieve the purpose of cooling. However, the application of liquid CO_2 is also limited due to the complexity of the hybrid system [86]. Cold air involves transforming compressed air into air or nitrogen with temperatures ranging from −10 °C to −30 °C, which is environmentally friendly. However, the cooling of cold air cannot meet the high-speed cutting requirements of difficult-to-machine materials. $scCO_2$ is a fluid form of CO_2 with temperatures and pressures above the critical point, and it can be prepared at room temperature [87,88]. In the supercritical state, $scCO_2$ exhibits properties of both gas and liquid, and it is currently the most widely used supercritical fluid solvent [89,90]. Zhang et al. [91] employed $scCO_2$, $scCO_2$-based MQL ($scCO_2$+MQL with oil droplet cutting fluid), and supercritical CO_2-based Minimum Lubrication ($scCO_2$+OoW) as cooling lubrication methods for milling Inconel 718. Experimental data indicated that compared to dry cutting and $scCO_2$ alone, $scCO_2$+MQL performed better in terms of cutting force, cutting temperature, surface roughness, and tool wear. In this case, the particles are smaller. Interestingly, the performance of $scCO_2$+OoW surpassed $scCO_2$+MQL, as oil molecules could adsorb on the water droplet surface to form an oil film, which could be transported by $scCO_2$ to the surfaces of the workpiece and tool. Stiphensona et al. [88] analyzed tool wear and metal removal rate (MRR) when cutting Inconel 750 under $scCO_2$ MQL. They found that compared to flood cooling, using supercritical CO_2 MQL resulted in lower tool wear and higher MRR. This is because in processing nickel-based alloys, supercritical CO_2 MQL changes the predominant wear mechanism from rapid notch wear to gradual pit wear and chip hammering (Figure 11). From existing literature, it appears that as a lubrication/cooling solution for the processing of nickel-based alloys, CMQL can effectively reduce substantial heat during the processing process.

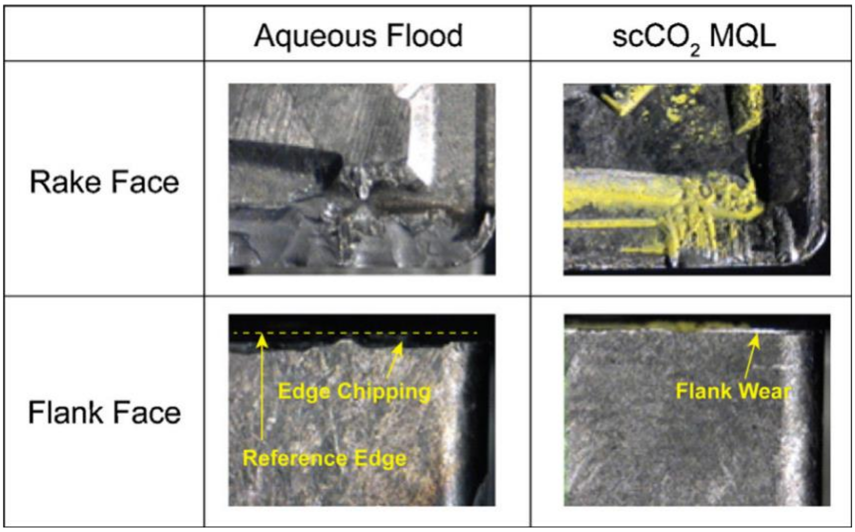

Figure 11. SEM images of tool inserts under flood and CMQL environment [88]. Reproduced with permission from Elsevier.

3.4. Electrostatic MQL Processing of Nickel-based Alloys

Additionally, many researchers have found that the use of MQL in high-speed cutting tends to generate high temperatures, which is highly detrimental to the processing of nickel-based alloys [92]. Furthermore, traditional MQL that employs pneumatic atomization is prone to producing PM10 and PM2.5, posing threats to the environment and human health. The atomization performance of high-viscosity bio-lubricants is also suboptimal [93]. Some scholars have proposed Electrostatic MQL (EMQL), which combines electrostatic atomization and MQL [94–96]. EMQL involves charging the lubricant and breaking it down into tiny droplets, enhancing the adhesion, wetting, and atomization of charged droplets, resulting in smaller droplets. This improves the lubrication and cooling performance of EMQL compared to traditional MQL [97,98].

However, there is limited research on the application of EMQL in nickel-based alloys processing. Bartolomeis et al. [99] primarily investigated a dual-electrode nozzle combined with MQL to form an EMQL system (Figure 12a), using rapeseed oil as the lubricant for Inconel 718 in EMQL. They found that under EMQL, the tool life of Inconel 718 was worse than that under MQL, with the main wear mechanisms being abrasion and BUE (Figure 12c). This was mainly attributed to their designed EMQL system not improving the wetting, penetration, and atomization of charged droplets, and the high oxygen content negatively affecting friction behavior on the tool and cutting surface [90]. In terms of surface roughness and specific cutting energy (SCE), EMQL performed better (Figure 12d). Especially in surface integrity, EMQL achieved the lowest roughness of 0.42μm for the machined profile at 120 m/min. This was due to the phenomenon of “mirror charge” formed by the adhesion of charged oil droplets on the tool surface (Figure 12b) [100]. Therefore, they continued to conduct in-depth studies on the surface integrity of Inconel 718 under EMQL conditions [93]. According to SEM images, the micro-surface under EMQL (EL) conditions was smoother compared to flood cooling and MQL (Figure 12e,f). However, the microhardness was similar.

While a few experiments with EMQL-assisted processing of nickel-based alloys have shown significant improvements in processing outcomes, due to limited experiments in this field, we have not fully grasped the factors influencing the quality of nickel-based alloys processing with EMQL, and further exploration is needed.

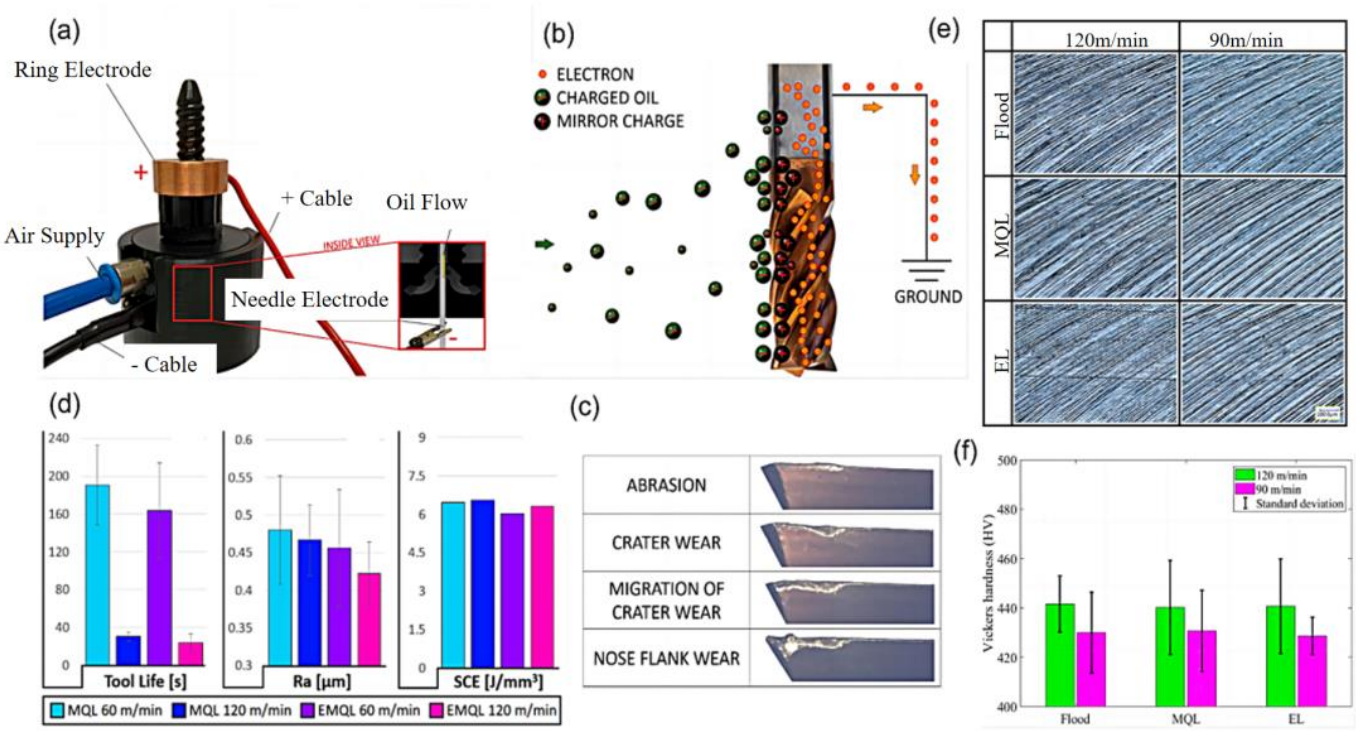

Figure 12. (**a**) Nozzle design. (**b**) Mirror effect on a cutting tool. (**c**) Wear behavior stages when processing under EMQL. (**d**) Tool life, Surface roughness, and SCE at 60 and 120 m/min with EMQL and MQL scenarios [99]. (**e**) Topological comparison of the surfaces machined under Flood, MQL and EL conditions at 120 and 90 m/min cutting speed. (**f**) Average Vickers hardness in Flood, MQL and EL conditions [101].

4. Ultrasonic Vibration Assisted MQL Processing Technology

Inconel 718 is the most widely used nickel-based superalloy in aerospace, automobile and nuclear energy industries for its superior chemical, mechanical and thermal properties. However, the aforesaid properties by themselves offer poor processing characteristics. To overcome processing difficulties, hybrid processing processes have been introduced. A hybrid of an ultrasonic vibration-assisted turning and lubri-cooling technique is considered as one of the similar strategies. Duman et al. [102] conducted an experimental study of ultrasonic vibration-assisted MQL at different cutting speeds and uncut cutting thicknesses. In addition, they estimate economic feasibility or total process cost analysis by evaluating machine tool investment, lubricant/coolant delivery system and ultrasonic vibration system costs, waste disposal and management costs, cutting tool and labor costs, cutting fluid costs and energy consumption. On the other hand, environmental feasibility is assessed by estimating carbon emissions (CE) due to power consumption, material utilization, and waste treatment and management. The results show that the cost is reduced by about 20–30% when using the MQL + UVAM cooling type compared to the dry and dry + UVAM cooling types. Compared to the MQL cooling type, the cost value of MQL + UVAM is reduced by about 8–20%. When processing in Dry and Dry + UVAM cutting environments, CE values decrease by about 105–120% due to lack of cutting fluid and reduced machine utilization compared to MQL and MQL + UVAM cutting environments. Therefore, considering the cost and environmental factors, ultrasonic vibration assisted MQL technology is undoubtedly a processing technology with great development potential.

4.1. Application in Turning Processing

Airao et al. [103] applyed ultrasonic vibration together with MQL and LCO_2 to improve the work-ability of Inconel718. They compared the machinability of Inconel718 in dry, wet, MQL and LCO_2 with conventional and ultrasonic assisted turning (UAT). The results show that conventional turning under LCO_2 can reduce back tool face wear by 32–60% and power consumption by 4–41% compared to dry, wet and MQL strategies. The combination of LCO_2 and ultrasonic vibration significantly reduces cutting energy and tool wear without compromising surface quality. In addition, this combination helps to improve chip break ability and reduce strain localization. Alemayehu et al. [104] independently developed ultrasonic vibration-assisted turning (UVAT) and MQL mixing device to study the cutting force and surface roughness of Inconel718, as shown in Figure 13. The experimental results show that, compared with CT+MQL at the feed speed of 0.07mm/rev, the main cutting force (Fy) decreases by 11.3%, 10% and 12%, and the feed force (Fz) decreases by 25%, 9% and 14%, respectively, at the cutting speed of 15, 20 and 25 m/min, respectively. Average surface roughness (Ra) was reduced by 27% and 10%, respectively. However, a significant change in radial force (Fx) between the UVAT+MQL and CT+MQL processes has not been observed. Airao et al. [105] attempted to study the machinability of conventional and ultrasonic assisted turning of Nimonic-90. Ultrasonic assisted turning and conventional turning of materials are carried out under a dry and sustainable cutting fluid (i.e., plant-based cutting fluid), keeping all process parameters unchanged. Canola oil is used as vegetable oil. The machinability in terms of power consumption and tool life is analyzed. Ultrasonic assisted turning with sustainable cutting fluids significantly reduces power consumption and extends tool life. Duman et al. [102] studied the processing of Inconel718 under dry, MQL, dry +UVAM and MQL+UVAM cutting conditions. The results show that the combination of MQL and UVAM methods (MQL+UVAM) can improve the chip break ability and generate short comma chips. Compared with dry cutting, Fc and Ft are reduced by 27% and 34% respectively under the MQL+UVAM hybrid method, the cutting temperature is significantly reduced by 30%, and the roughness is reduced by up to 36%. Airao et al. [106] attempted to combine ultrasonic vibration with vegetable oil-based cutting fluid (VCF) to extend tool life and machinability. It is found that UAT under VCF can reduce the contact length between tool and chip by 12–45%, the cutting force by 10–25%, and the feed force by 20–40%. In addition, ultrasonic assisted turning using vegetable oil-based cutting fluids also reduces the adhesion and wear of the rake face. Lin et al. [107] combined MQL and ultrasonic elliptical vibration (UEV) cutting to compare the effect of different nozzle angles on processing performance under UEV turning conditions. Compared with CT, UEV temperature decreases by 10.2% and UEV+MQL decreases by 16.9%. The main cutting force and thrust decreased by about 61.7% and 72.9% respectively, while UEV and UEV+MQL decreased by 67.8% and 79.7%, respectively. When the nozzle angle is parallel to the front cutting surface, the temperature of the work-piece and the tool is lower, and the tool stress is smaller. But the nozzle angle has little effect on cutting force. In order to improve the quality of the work-piece and tool life, it is necessary to choose an appropriate nozzle angle. Khanna et al. [108] analyzed the turning performance of Nimonic90 using self-developed cryogenic ultrasonic assisted turning (CUAT) and cryogenic assisted turning (CAT) processes, as shown in Figure 14, Liquid nitrogen with a capacity of 200 L stored in a Dewar bottle is supplied to the cutting area through a vacuum jacketed hose at a flow rate of 0.6 L/min from a nozzle jet with a diameter of 1 mm. The flow rate of liquid nitrogen is measured by a capacitance-based liquid refrigerant level sensor mounted with a dewar bottle. To ensure that nitrogen is transported in liquid form, vacuum jacketed hoses and phase separators are used in the liquid nitrogen delivery system. The CUAT process combines the advantages of CAT and UAT processes. It was found that compared to the CAT process, using the CUAT process has better effects in reducing energy consumption (up to 20%), carbon emissions, and overall processing costs. In addition, it was observed that compared to the CAT process, the surface smoothness of the CUAT process was also improved (up to 29%). The positive effect of liquid nitrogen in reducing the temperature of the cutting area leads to a decrease in the adhesion of the machined surface and an improvement in surface smoothness. This may be due to the assistance of ultrasonic vibration, which enhances the permeability of low-temperature fluids at the cutting interface. Theoretical analysis by Ni et al. [109] indicates that the intermittent cutting mechanism and acoustic cavitation of UVAM can promote the lubrication/cooling performance of MQL systems. Under the influence of surface acoustic energy and acoustic cavitation, the relatively uniform and fine droplets sprayed by the MQL nozzle will further atomize into super uniform and ultrafine droplets. Separate cutting provides great convenience for the tool workpiece interface where ultrafine atomized droplets and compressed air are immersed in UVAM.

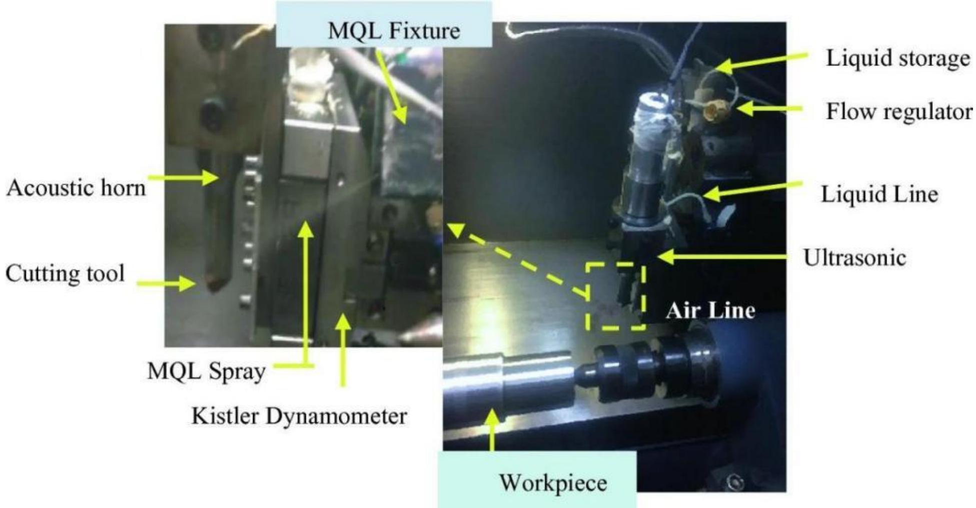

Figure 13. Ultrasonic vibration assisted Turning (UVAT) and Minimum lubrication (MQL) devices [104]. Reproduced with permission from Springer Nature.

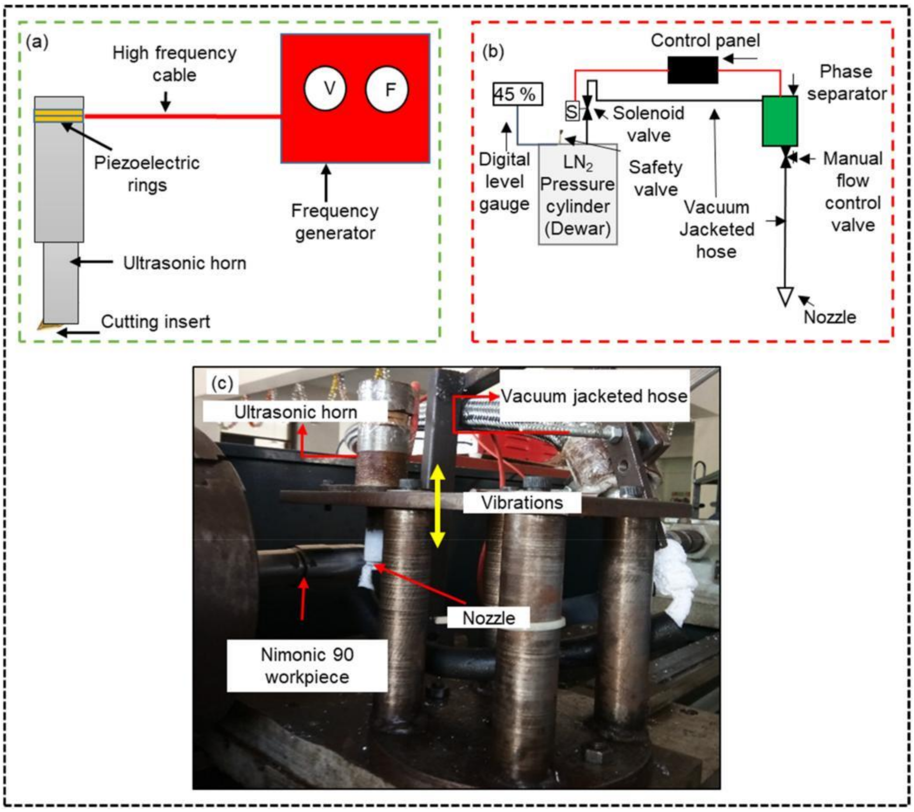

Figure 14. Experimental setup components: (**a**) UAT process schematic, (**b**) CAT process schematic, and (**c**) hybrid turning setup [108]. Reproduced with permission from Elsevier.

4.2. Applications in Rotary Processing

Gao et al. [110] studied the coupling effect between two-dimensional ultrasonic vibration assisted grinding (UVAG) and nanofluid MQL, and found that the nanoparticles in the mixed nanofluid MQL enhanced the heat transfer ability of the fluid in the grinding zone, playing a good cooling effect. At the same time, nanoparticles exhibit good wear resistance, wear resistance, and load-bearing capacity, thereby enhancing the lubrication effect of the grinding area. Secondly, due to the application of ultrasonic vibration, trace amounts of nanofluids in the work-piece and cutting area can be transformed from Cassie state to Wenzel state. It can also better penetrate into the work-piece and cutting area, exerting better cooling and lubrication effects. Therefore, compared to a single nanofluid MQL and ultrasonic vibration technology, the combination of the two technologies enhances the mutual processing effect of the two. Das et al. [111] found that the combination of UVAG and MQL has a positive effect, achieving minimal grinding force. Compared with CG, combining UVAG with MQL reduces tangential force by 42% and normal force by 31%. The reason is that the application of MQL leads to the formation of surface facial mask, which reduces friction and makes abrasive particles slip. The atomization jet can take away the heat generated in the grinding area and effectively remove loose particles in the grinding area. The separation processing characteristics of UVAG can reduce grinding force and better dissipate heat in the contact area. Molaie et al. [112] investigated the simultaneous application of UVAG method and MQL technology. The results indicate that ultrasonic vibration can effectively reduce normal grinding force, and MQL can effectively reduce tangential grinding force. Molaie and Akbari concluded that using UVAG and MQL simultaneously can reduce grinding force by about 60%. Due to the significant environmental and economic advantages of nanofluid MQL technology. Jia et al. [113] recently studied the effect of simultaneous use of UVAG and nanofluid MQL techniques on grinding performance. The experimental results indicate that the simultaneous application of UVAG and nanofluid MQL methods can effectively improve adhesion and material peeling phenomena. In addition, Madarkar et al. [114] initially proposed the concept of ultrasonic vibration assisted micro lubrication (UMQL), which uses ultrasonic vibration horns to completely atomize cutting fluid into ultrafine droplets. Compared to dry cutting and general MQL technology, Madarkar believes that UMQL technology can greatly improve the grindability of alloys, such as smaller grinding forces and better surface quality.

In order to alleviate the difficulties of traditional grinding, Singh et al. [115] studied the effects of ultrasonic assisted grinding and atomized lubricants on the surface integrity of Nimonic80A grinding. The research results indicate that the dual advantages of ultrasonic vibration and atomized cutting fluid significantly enhance the surface integrity of the ground surface. In addition, during the atomized fluid ultrasonic assisted grinding (FUAGA) process, the compressive properties of residual stress are higher than those of similar products. Microscopic analysis shows that the proposed process has the least impact on the microstructure compared to other grinding schemes. The hardness value of FUAGA grinding scheme is relatively low. The dual advantages of ultrasonic vibration and atomization (mist like) cutting fluid can be explained by this. The combination of ultrasonic vibration makes periodic grinding possible, promoting more grains to participate in the cutting zone and acoustic softening of the material, thereby reducing the necessary static stress for plastic deformation of the workpiece material. In addition, periodic grinding allows micrometer sized droplets to enter the grinding area, providing better lubrication and cooling. This prevents work hardening and reduces the depth of the hardened layer, which is smaller compared to other grinding schemes. Naskar et al. [116] used a hybrid grinding method (UVAG+CMQL) to study the effect of fluid lubricity on the interaction between sand particles and work-piece during the grinding process. Research has found that the stronger the lubricity, the smaller the resistance to vibration transmitted to the grinding area. Therefore, the effective vibration amplitude increases with the increase of lubricity. It significantly controls the mechanism of the formation of ground scallops. In addition, the stronger the lubricity of vegetable oil, the lower the grinding force generated and the higher the residual compressive stress. In addition, under UVAG, the compression residual stress was improved by 20–100%. Singh et al. [117] utilized the dual advantages of ultrasonic assisted grinding (UVAG) and ultrasonic atomization as a new green cutting fluid to improve the mechanism of the grinding process, achieving better performance and enhanced sustainability. They compared the grinding performance and sustainability prospects of different grinding strategies of Nimonic80A. Compared with CG process, ultrasonic assisted grinding with ultrasonically atomized fluid UAFUAG reduces normal cutting force by 66.22% and tangential cutting force by 52.66%, surface roughness by 46.48%, and minimum coefficient of friction (CoF) by 30.42%. The presence of ultrasonic vibration increases the contact between grains in the grinding area and the acoustic softening of the material, thereby reducing the apparent static stress required for plastic deformation of the material. In addition, the tiny droplets of atomized cutting fluid reach the grinding area, providing better lubrication during this process. Madarkar et al. [118] studied the grinding performance of UVAG combined with MQL using soluble oil on alloys through surface grinding experiments. The results showed that compared with traditional dry and ultrasonic vibration assisted dry grinding, UAG using MQL grinding technology achieved a significant improvement in surface smoothness and a reduction in grinding force. Sinha et al. [119] investigated the grinding force and surface smoothness (Ra parameters) of Inconel718 under different cooling lubrication conditions (dry, wet, MQL, and liquid nitrogen LN). It was found that lower tangential forces were observed during MQL grinding. Through SEM micrographs and EDS analysis, MQL grinding resulted in slight surface oxidation. A higher average surface roughness was found in the MQL grinding surface, which may be due to better retention of the sharp cutting edge of the grinding sand. De Oliveira et al. [120] conducted an experimental study on the grinding of Inconel718 using traditional green silicon carbide grinding wheels (code 39C60KVK) under various cooling and lubrication conditions: dry, immersion, MQL, and MQL dispersed in environmentally friendly cutting fluids. Although the research results show that Ra roughness is relatively low (<0.42 μ m) However, regardless of the grinding conditions, the author observed microcracks on all grinding surfaces.

Erturune et al. [121] studied the ultrasonic vibration assisted drilling (UAD) of Inconel718 under different cooling and/or lubrication conditions. The applicability of UAD to Inconel718 drilling was evaluated in terms of thrust, surface roughness, roundness error, burr formation, subsurface microstructure and microhardness, tool wear, and chip morphology. The results showed that compared with dry conditions, the thrust of CCF and MQL conditions decreased by 0.28–3.18% and 5.64–8.47%, respectively. The CD and UAD strategies achieved the lowest thrust values under MQL conditions. It can be said that the decrease in thrust value is achieved by reducing the friction between the tool and the work-piece, as well as the decrease in the adhesion performance of the work-piece material under the applied cooling/lubrication conditions. In addition, the MQL condition provides a lubricating film formed by oil mist particles at the tool workpiece interface, and the permeation efficiency of oil particles and pressurized air is higher than that of CCF. This can better dissipate heat, reduce friction and thermal interaction between tools and work-pieces. Yan et al. [122] also reported similar observations. According to the author, in ultrasonic assisted cutting, due to the capillary effect, the modulated contact between the tool and the workpiece allows the coolant and/or lubricant to easily and effectively penetrate the cutting interface. In addition, the maximum thrust reduction (up to 8.47%) was achieved by simultaneously applying UAD and MQL conditions.

In order to improve the machinability of Inconel718, Xu et al. [123] proposed a new processing method, as shown in Figure 15, which is cryogenic ultrasonic vibration assisted milling (CUVAM). Experimental data shows that low-temperature assistance can effectively improve the processing environment and CoF, and enhance surface integrity. On the other hand, due to the low-temperature brittleness of Inconel718, ultrasonic vibration assistance in CUVAM can suppress the increase of cutting force. CUVAM combines the advantages of low-temperature assistance and ultrasonic assistance very well. Compared with CM, the CUVAM method can reduce cutting force by 36.5% and have a beneficial impact on tool life. The chip effect is more pronounced. Compared with CM, the surface roughness after CUVAM decreased by 39.1%.

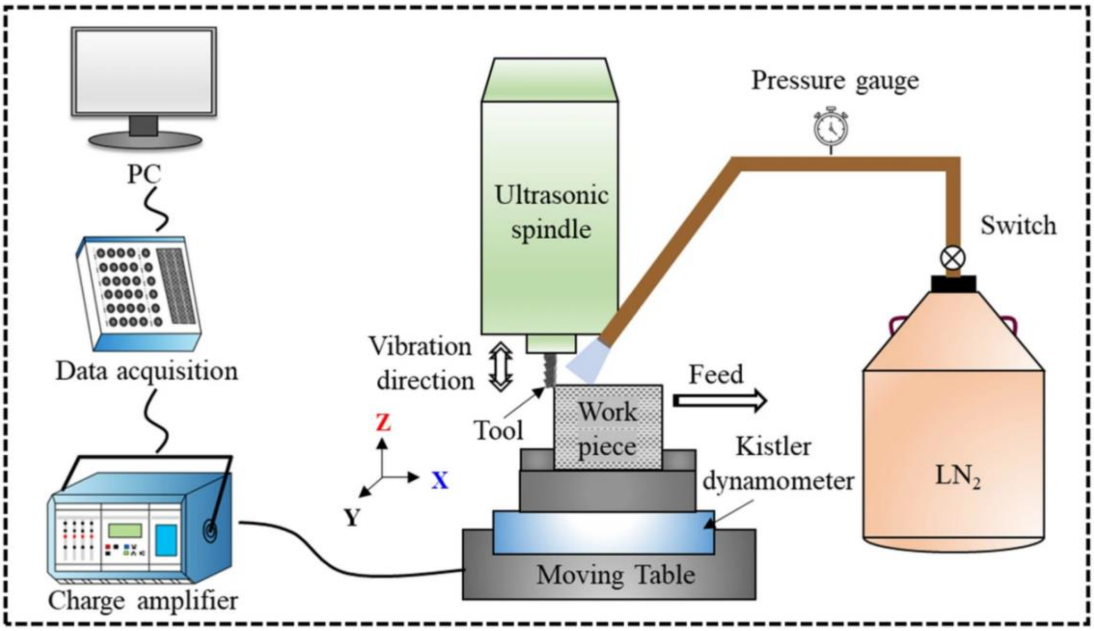

Figure 15. Schematic diagram layout in the CUVAM system [123]. Reproduced with permission from Springer Nature.

Tool wear is an important factor affecting surface quality and integrity, cutting force and power consumption, cost, etc. Tool wear occurs due to chemical, physical and mechanical reactions in the deformation zone. It also depends on the tool and workpiece material, input parameters, and cooling conditions [124]. In the processing process of nickel-based superalloys, the high temperature caused by the high temperature in the secondary and tertiary deformation zones makes the process unstable due to the thermomechanical load, which rapidly aggravates the tool wear.

Airao & Khanna [125,126] adopted a sustainable cooling strategy, which includes MQL, electrostatic minimum lubrication (EMQL), and LCO_2, combined with ultrasonic assisted turning to reduce tool wear during processing of Inconel718. The experiment compared six different combinations of cooling strategies. These cooling strategies are LCO_2+MQL (in this case, LCO_2 is used on the front side of the mold and MQL is used on the side of the mold), MQL+LCO_2, EMQL+LCO_2, LCO_2+EMQL, EMQL+MQL, and MQL+EMQL. Detected tool wear, cutting specific energy, energy consumption, surface roughness, and chip morphology. The results indicate that, without affecting surface quality, providing the minimum amount of electrostatic lubrication on the cutting surface and liquid carbon dioxide oxide on the front surface of the tool can significantly reduce tool wear, power consumption, and cutting specific energy. This novel combination of LCO_2 and EMQL improves sustainability without affecting the surface quality of the processed Inconel718.

5. Conclusions

As an important technical means to improve the processing effect, ultrasonic vibration assisted processing technology and MQL technology can change the cutting mechanism of nickel-based alloy, effectively improve the processing quality and efficiency. The ultrasonic vibration assisted MQL processing technology combined with the two has played its respective advantages, can effectively improve the machinability of nickel-based alloys, and further expand the application field of nickel-based alloys. This paper summarizes the development status of the above three processing methods and draws many conclusions.

(1) Quite a number of studies have proved that compared with traditional processing, ultrasonic vibration assisted processing technology and MQL technology have corresponding advantages when they are used alone, such as ultrasonic vibration assisted processing technology, by implementing intermittent interrupted cutting and adjusting key processing parameters, has obvious processing effects in optimizing chip shape and improving tool life. MQL technology, especially variants based on plant oil, nanofluids, low-temperature, and electrostatic MQL can improve the surface quality of nickel-based alloy, reduce tool wear and reduce cutting heat, and has the characteristics of green processing.

(2) When these two technologies are used in combination, the intermittent cutting mechanism and sound cavitation effects of UVAM can improve the lubrication/cooling performance of MQL systems. Under the action of surface sound energy and sound cavitation, relatively uniform and fine droplets sprayed by MQL nozzle will be further atomized into very fine droplets. Due to the capillary effect, the modulated contact between the tool and the workpiece allows the coolant or lubricant to penetrate easily and efficiently into the cutting interface. This can reduce cutting force, improve surface quality, reduce tool wear, thereby improving cutting efficiency and processing quality.

(3) The combination of the ultrasonic vibration assisted processing technology and MQL technology usually requires additional equipment and systems, which can increase equipment investment and operating costs. In addition, additional energy supplies are also required, which can lead to an increase in overall energy consumption. The overall system has become more complex, increasing the difficulty of equipment maintenance, and putting higher technical requirements on operators, requiring additional training costs.

Future development may focus on the introduction of intelligent control systems, through sensors and adaptive control algorithms to achieve real-time monitoring and adjustment, analysis of processing parameters, tool wear, material characteristics and other information, automatic adjustment of ultrasonic vibration and MQL parameters. Such a system can respond more flexibly to different processing conditions and material characteristics, improving processing efficiency and accuracy. Second, future trends are likely to emphasize a focus on environmental friendliness and energy efficiency. Researchers may work to develop more environmentally friendly lubrication materials, reduce waste generation, and optimize energy consumption.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by DW, SW, BZ, and ZS. The first draft of the manuscript was written by GG and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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