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Effect of different cutting environments on surface integrity and wear resistance properties of Incoloy 925

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Abstract

Ideally, machining is the final manufacturing process for the product; however, surface integrity (SI) produced by it, especially for Ni-based alloys, is a primary concern for the manufacturer. Induced surface integrity can influence the mechanical properties of the material. In order to improve the surface properties of the machined component, in this study, nano-metallic copper (Cu) based nanofluid (dispersed Cu in coconut oil) is used as a cutting environment and compared with dry machining and pure oil-based MQL (minimum quantity lubrication) condition. Further, its consequences on the wear resistance of machined components are studied with the help of ball-on-disc in reciprocating mode. Results show that dry machining produces poor surface integrity (in terms of surface roughness, surface topography, and microhardness) due to lack of lubrication and cooling, consequently, leads to higher wear of material for the machined component as compared to components machined in MQL and n-MQL (nanofluid-based minimum quantity lubrication) conditions.

Keywords: Incoloy 925, n-MQL, Surface integrity, Surface wear resistance

1. Introduction

Incoloy 925, one of the advanced versions of Ni-based alloys, is extensively used in the oil and gas industry owing to a combination of high strength and superior resistance to sulfide stress cracking and stress corrosion cracking [1]. However, Ni-based alloys are often difficult to machine and show poor machinability and machining-induced surface integrity, which results in a decline in the functional performance of the material when it is in use [2]. The relationship between mechanical cutting and functional performance is significant, which is why several studies have been done to improve the machining-induced surface integrity and wear resistance of the machined surface. Furthermore, wear (a progressive loss of materials) causes significant financial losses and possible failures [3]. Wear accounts for one-third of primary energy use and almost 60 % of mechanical component failure [4]. Grain refinement, hardness increase, and surface roughness reduction are common ways to improve the machining-induced surface integrity and wear resistance of machined surfaces [5,6]. Within the domain of mechanical cutting, the approaches utilized to enhance the wear resistance and surface integrity of machined surfaces are primarily classified as (i) Unconventional machining techniques (such as thermally aided machining, ultrasonic vibration assisted machining, and abrasive water jet machining), (ii) Advancement and optimization of cutting tools (such as coatings, micro-textures, and geometric parameters), and (iii) Cutting-edge lubrication and cooling methods include minimum quantity lubrication (MQL), nanofluids, cryogenic cooling, high pressure cooling (HPC), and hybrid cooling. Unconventional techniques utilize high specific energy. Hence, conventional machining (like turning and milling) is still attractive for machining superalloys.

However, because nickel alloys have low thermal conductivity, heat builds up, and temperatures rise at tool surfaces, compromising the integrity of the surface in terms of microstructural changes, thermo-mechanical stresses, and mechanical property changes. Hence, cooling and lubrication are needed to dissipate heat from the cutting zone. Several researchers [7,8] have reported that the surface integrity of rigid materials is significantly impacted by cooling and lubrication during the machining process. On the other hand, conventional lubrication raises the cost of machining and frequently leads to excessive lubricant wastage. Furthermore, traditional cutting fluids harm the environment and people [9]. Considering the present climate change condition and the exhaustion of natural resources, it is recommended to avoid using the traditional lubricating approach. Thanks to nanotechnology helped to develop cutting-edge fluid (called nanofluid), showing excellent properties to conventional cutting fluid, which has been proven to be an efficient cutting fluid when it is used under the minimum quantity lubrication (MQL) technique [10,11]. From the previous research investigations, it is observed that most of the research is focused on improving the surface integrity of superalloys, and very limited work is available on relating the surface integrity to functional performance (such as tribological performance) of machined components. Hence, this work investigates the influence of different sustainable cutting environments on microstructure evolution and wear resistance properties of one of the advanced superalloys (Incoloy 925).

2. Materials and methods

Alloy 925, also known as Incoloy 925, was chosen as the workpiece and vertical milling center as a machine (model, VMC 600 II, Hardinge), whereas TiAlN/TiN PVD coated carbide, grade of KCSM40 inserts (ISO EDPT10T312PDERHD) with a 0.8 mm nose radius made by Kennametal with indexable shoulder end mill as a tool holder (ISO 16A02R025A16ED10) were used. Machining parameters were chosen according to the manufacturer's suggestion for the cutting tool. These parameters included a cutting speed of 60 meters per minute, a feed rate of 0.075 millimeters per tooth, an axial depth of cut 0.4 millimeters, and a radial depth of cut 16 millimeters. Optimized MQL parameters in a previous study [12] such as nozzle pressure of 6 kg/cm^2, a nozzle distance of 30 mm, a nozzle angle of 30° from vertical, and a flow rate of 150 ml/hr were used to supply the nanofluid that was prepared using two steps technique [13] in which 0.1 Vol.% Copper (Cu) nanoparticles with an average size of 80 nm were dispersed in coconut oil (having superior lubricity and excellent thermal oxidation resistance owing to almost 90 % saturated fatty acids (more details of pure coconut oil can be found in previous report [1])) using 30 minutes magnetic stirrer (1000 rpm) and 1-hour ultra-probe sonication (20 kHz).

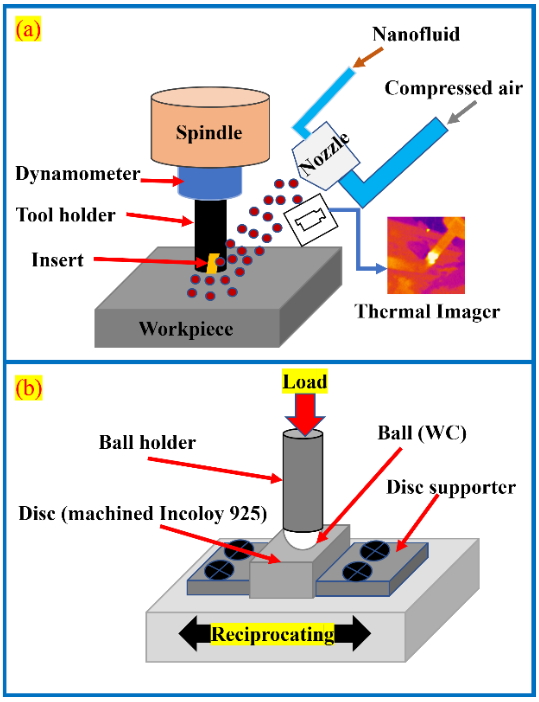

Figure 1. Schematic sketch of :(a) Machining setup and (b) Tribological testing

A dynamometer (model: RCD 9170A, Kistler) was used to record the cutting force signals (F_x, F_y, and F_z), and the resulting cutting force (F) was computed using Equation (1), whereas cutting temperature was measured using thermal camera (model: TIM 8, Epsilon, Germany).

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

With an optical profiler (Lambda-2), the surface topography of machined samples was captured. A metallurgical optical microscope (model: Leica ICC50 HD) was used to take micrographs of machined samples (cross-section) after they had been polished to a mirror finish using various grades of SiC paper and alumina slurry followed by etching using HCl + H_2O_2. Using a micro-Vickers hardness tester (model: HMV-G, Shimadzu), microhardness was measured on a polished cross-section of a machined surface at different positions with a 50 g load and a 12-second holding period.

A 6 mm tungsten carbide ball against 30 mm x 8 mm x 15 mm machined samples was used for the tribological test in the reciprocating mode of a multi-functional tribometer (model MFT 5000, R-tec instruments with an integrated Lambda-2 optical profiler) with a 5 N load, 2 mm stroke, 2 Hz frequency, and a sliding duration of 15 minutes. The details of the machining setup are displayed in the sketch (Figure 1 (a)), while the schematic drawing for tribological testing is displayed in Figure 1(b).

3. Results and discussion

3.1. Surface roughness and topography

Surface roughness and topography of components play an important role in the tribological performance. Hence, its characterization is essential. The 3D topography (Figure 2) of machined components shows that the highest variation in roughness (peaks and valleys) is found in dry cutting. In contrast, the lowest variation is observed in nanofluid-based minimum quantity lubrication (n-MQL) assisted machining due to adequate lubrication compared to dry cutting. Further, from Figure 3, it is observed that areal surface roughness parameters, Sa (average roughness) and Sq (root mean square roughness), are found lowest in n-MQL assisted machining, followed by MQL (pure oil-based minimum quantity lubrication) and dry cutting.

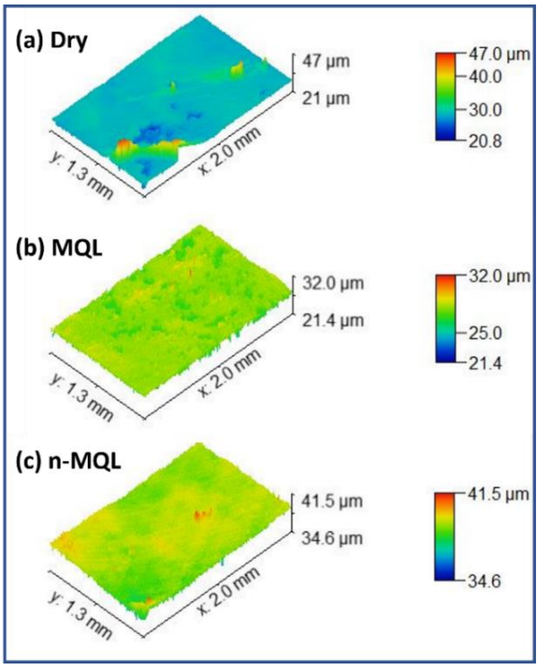

Figure 2. Surface topography of machined components under different cutting environments

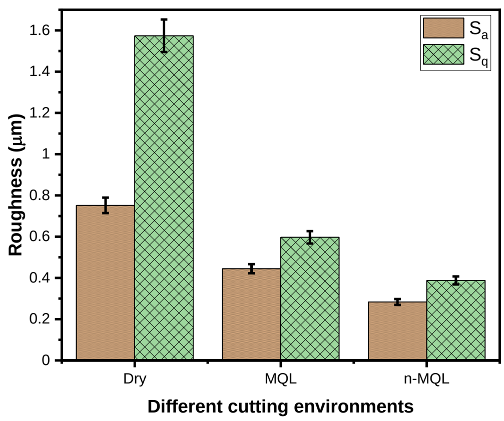

Figure 3. Areal surface roughness of machined components under different cutting environments

3.2. Microstructure and microhardness

All the mechanical properties of components depend on the microstructure of the material. Figure 4 shows the optical micrograph of cross-section of the machined surface under different cutting environments. It is observed that within a certain limit of depth from the machined surface, deformation of grain has occurred for all the cutting environments, possibly due to thermo-mechanical effect [9]. Figure 5 shows that heat generation and cutting force are higher in dry cutting. In the case of MQL assisted machining, heat generation and cutting force are lower due to reduced coefficient of friction caused by lubrication effect which reduces tool wear and result in lower deformation, whereas, in the case of n-MQL assisted machining, it is further reduced due to combination of nanoparticles and oil which enhances lubrication and heat transfer as compared to MQL and dry conditions.

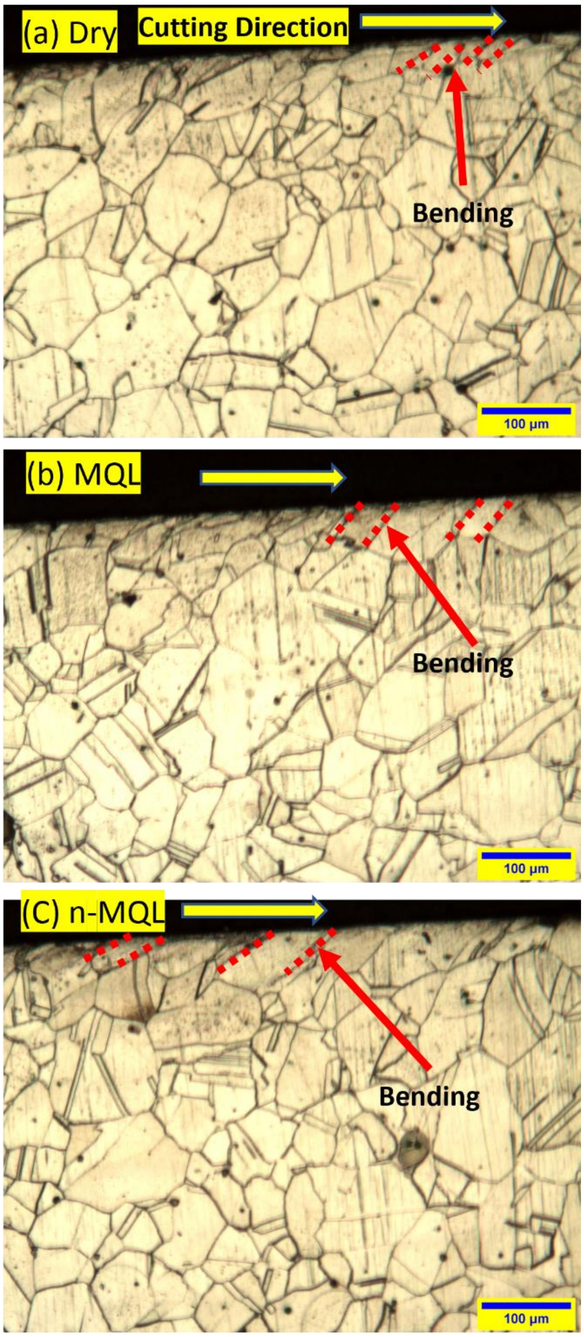

Figure 4. Microstructure of machined components (cross-section) under different cutting environments

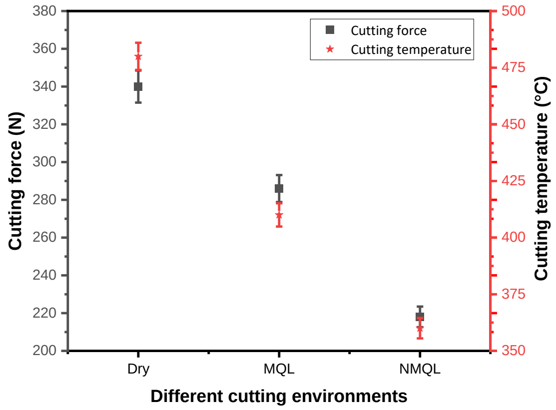

Figure 5. Cutting force and Cutting temperature for different cutting environments

Further, Figure 6 shows that microhardness is the highest in the case of dry cutting, followed by MQL and n-MQL assisted machining, possibly due to plastic deformation caused by the thermo-mechanical effect, as discussed previously. However, the increment in micro-hardness is limited to a certain depth from the machined surface for all the components machined under different cutting environments, possibly due to the reduction of the thermo-mechanical effect as the depth increases from the machined surface.

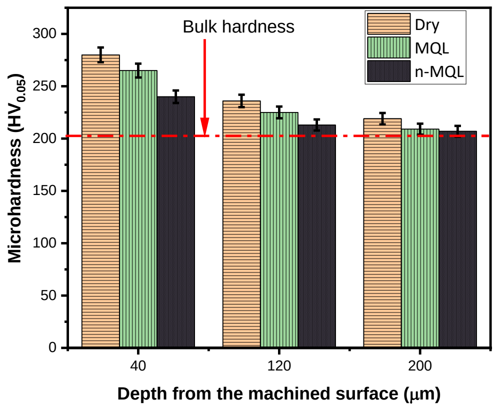

Figure 6. Microhardness of machined components(cross-section) under different cutting environments

3.3 Tribological performance

A ball-on-disc-based tribological test in reciprocating mode under dry conditions has been performed to correlate the tribological performance of machined components with surface topography, microstructure, and microhardness. From Figure 7, it is observed that the sample machined under dry cutting gives the highest coefficient of friction although having the highest hardness (see Figure 6) as compared to other samples machined under MQL and n-MQL conditions, which is possibly due to the domination effect of surface roughness parameters (see Figure 3). Further, Figure 8 shows that the wear (degradation of material) of the sample machined under dry cutting is higher than those machined under MQL and n-MQL conditions, confirming that surface roughness dominates over microhardness for tribological performance. A similar phenomenon was reported by Yuan et al. [14].

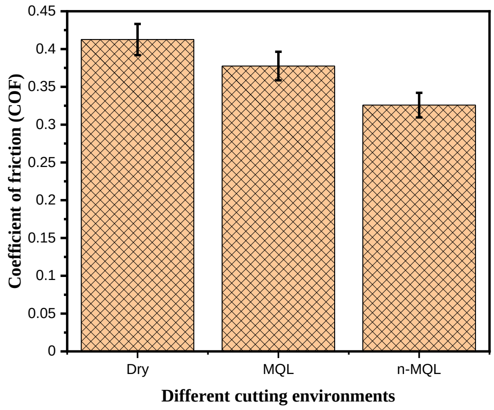

Figure 7. Coefficient of friction of machined components under different cutting environments

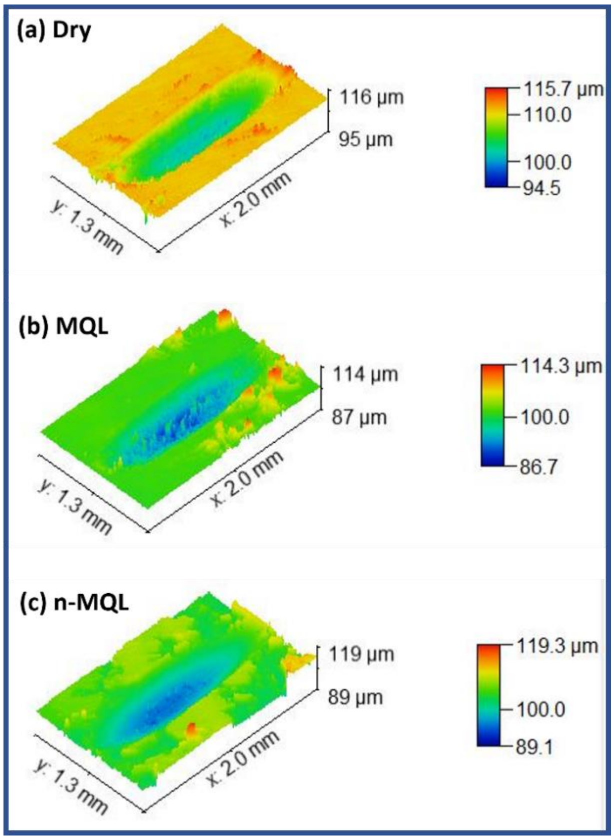

Figure 8. Wear topography of components machined under different cutting environments

5. Conclusion

The effects of surface characteristics processed by machining under different cutting environments on the tribological performance of Incoloy 925 have been investigated. The following key conclusion can be drawn out:

- Nanofluid-assisted machining gives the best topography with a reduction in areal surface roughness, Sa (average roughness), and Sq (root mean square roughness) by 62 % and 75 %, respectively, compared to dry cutting due to enhanced lubrication and heat transfer properties.
- The coefficient of friction for the sample processed with n-MQL-assisted machining is lower by 21 % and 13.7 % compared to dry cutting and MQL-assisted machining, respectively, due to lower areal surface roughness.
- Although microhardness for the sample processed with n-MQL assisted machining is lower than that of samples processed with MQL and dry conditions, it gives lower wear of the material, possibly due to the domination effect of surface roughness over microhardness.

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