5 CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 Conclusions

The major goal of this research study was to conduct a thorough investigation into improving the grindability of AISI D2 tool steel. Initially, this research investigated the proper selection of suitable environmental conditions for surface grinding of work material. Further, grinding experiments were conducted using indigenously designed and developed cryogenic and Cryo-MQL grinding setups. This research investigated three major sections, i.e., Sections 4.1, 4.2, and 4.3, with some points to conclude each section for better understanding. The major conclusions from the present study are listed in Sections 5.1.1, 5.1.2, and 5.1.3.

5.1.1 Effect of process parameters on the grindability of AISI D2 tool steel under cryogenic cooling

The research was conducted on grinding AISI D2 tool steel using Al_2O_3 wheels in dry, wet, and cryogenic cooling environments at different downfeed-work speed combinations. The experimental results of the grinding forces, specific grinding energy, grinding zone temperature, grinding force ratio, surface roughness, surface modifications, chip morphology, microstructural analysis and microhardness obtained under cryogenic cooling have been compared with those of dry and wet environments. The effect of the delivery pressure of the LN_2 under cryogenic cooling was investigated in terms of the grinding forces, specific grinding energy and surface roughness. This section demonstrated the conclusions of the effect of grinding environments on AISI D2 tool steel. After conducting experimental work on AISI D2 tool steel using a cryogenic grinding setup, the following conclusions may be taken from the findings:

1. Cryogenic cooling is an alternative and effective method for controlling the

grinding zone temperature for difficult-to-cut material, i.e., AISI D2 tool steel.

2. The grinding force increased with an increase in downfeed due to the blunt edges of the alumina grits. Cryogenic coolant led to a reduction in F_t by 64% and 44.97% and F_n by 54.65% and 34.98% at 40 µm, respectively, compared with dry and wet conditions.
3. The influence of cryogenic coolant on grinding force ratio and specific grinding energy was reduced by 20.63% and 64% over the dry and 15.35% and 44.97% over wet conditions at higher downfeed, respectively.
4. A reduction in grinding temperature (T_g) under cryogenic cooling is approximately 65.19% and 50.99% compared to dry and wet cooling. The LN_2 coolant significantly lowered it to improve the surface quality of the ground sample.
5. Roughness parameters (R_a, R_q and R_z) increased with an increase in downfeed. It happened due to the dependency on the softening of the workpiece. A reduction of about 46.63% and 30.76% in R_a, approximately 21.42% and 34.04% in R_q, and about 40.36% and 34.77% in R_z were obtained under cryogenic cooling at 40 µm downfeed, compared to dry and wet environments.
6. After cryogenic cooling, SEM micrographs showed a smooth surface over dry and wet cooling, even at 40 µm downfeed. Therefore, lower height of peaks and valleys in surface topography was noticed. Also, cryogenic cooling lowered S_a and S_q values under all experimental conditions compared with other environments.
7. Severe oxidation was observed, under dry grinding relative to wet and LN_2 grinding, as indicated by the higher value of oxygen (O_2) weight percentage obtained through EDX analysis.
8. C-type or semi-circular chips or small lamellar chips were seen under cryogenic grinding due to sufficient cooling with lubricating effects.

9. No significant change in the microstructure was found under cryo-grinding due to faster heat transfer from the grinding zone by LN_2 coolant.
10. The high delivery pressure (4 bar) of LN_2 resulted in 8% and 6% improvement in F_t and F_n, respectively, compared to the lowest delivery pressure (2 bar). Increasing LN_2 pressure reasonably improved the surface roughness (R_a) in the range of 7-9 %.
11. Because of the increased table feed rate across various conditions, the grindability indices like grinding force, surface roughness, surface functional parameters, grinding temperature and microhardness were significantly impacted, resulting in poor and noticeable readings.
12. Under the grinding experimental study, it was found that an increase in table feed rate results in a rise in the *Sbi*, whereas the *Sci* decreases. Compared to dry and wet conditions, the *Sbi* and *Sci* values in the LN_2 cryogen were more significant, which indicated that the cryogenically cooled ground surface had improved bearing and fluid retention properties, respectively.

5.1.2 Effect of process parameters on the grindability of AISI D2 tool steel under Cryo-MQL environment

A new hybrid Cryo-MQL sustainable lubri-cooling technique has been introduced in this study for enhancing the grindability of work material in surface grinding operations based on lubrication and cooling performance. A comparison of Cryo-MQL grinding with MQL grinding at different lubricants, namely, base fluid (SO), emulsion (SO+DW), and Al_2O_3 NFs (0.5 and 1 wt.%), was made to investigate their grinding performance regarding grinding force, specific grinding energy, surface roughness, ground surface topography, chip morphology and grinding temperature. Also, thermo-physical properties of Al_2O_3 NFs with various weight concentrations were evaluated in terms of thermal conductivity, dynamic viscosity, surface tension, density, pH value, and wettability. Based on the analysis of the results obtained, the following conclusions can be drawn:

1. The addition of Al_2O_3 NPs in SO+DW emulsion has increased the thermal conductivity, dynamic viscosity, density, and pH value of the eco-friendly lubricant. But surface tension rose at a concentration of 0–0.5 wt.% Al_2O_3 NPs, after which surface tension was slightly reduced. The investigation of wettability revealed a decrease in the contact angle of Al_2O_3 NFs with increasing concentration.
2. Under the hybrid Cryo-MQL technique, Al_2O_3 NFs (1 wt.%) provided the lowest apparent friction coefficient (μ: 0.487), grinding force (F_t: 26 N, F_n: 62.5 N), surface roughness (R_a: 0.304 µm, R_q: 0.393 µm, R_z: 2.137 µm, S_a: 0.202 µm, S_q: 0.24 µm, and S_t: 1.468 µm), and grinding temperature (T_g: 178 °C) due to the adequate lubricity and cooling effect through rolling action and faster heat dissipation, respectively.
3. Based on bearing area curve analysis, it was found that the bearing area ratio (86.12%) of Al_2O_3 nanofluid (1 wt.%) in Cryo-MQL is higher than in MQL. Hence, the ground surface is more resistant to wear and friction during service life.
4. The optimal tribological performance was achieved when the concentration of Al_2O_3 NPs was 1 wt.%. It was revealed by SEM and AFM images, indicating better surface texture, less side flow and lower peak and valley heights.
5. The chip morphology investigation demonstrated long and spherical chips during SO and SO+DW under MQL grinding due to their low thermal conductivity. C-type or semi-circular, small and long chips were produced during grinding with a Cryo-MQL environment. Also, the small and semi-circular chips with lower chip-wheel contact areas decreased wheel wear and surface roughness under Cryo-MQL with Al_2O_3 NFs.

6. Al_2O_3 NFs have demonstrated higher tribological performance than base fluids, and their application can significantly improve grinding performance. Using Al_2O_3 NFs Cryo-MQL instead of conventional flood lubrication grinding can provide economic and environmental benefits for developing eco-friendly precision components, which is especially important given the current environmental and health concerns in manufacturing industries.

According to the experimental investigation outcomes, it was concluded that the optimum concentration of the eco-friendly nanofluid for achieving the lowest overall outcomes is 1 wt.%. concentration of Al_2O_3 NPs. This result indicated that adding the NPs in vegetable oil-based deionized water emulsion impacts the grinding performance and that a specific concentration can optimize this effect.

5.1.3 Study on ground sample of AISI D2 tool steel work material through magnetic Barkhausen noise technique

The objective of the current study was to analyze the ground sample through a non-destructive magnetic Barkhausen noise method for evaluating surface integrity during grinding. The work material AISI D2 tool steel was selected because it can cover a wide spectrum of applications for the technique. Section 4.3 assessed the effect of grinding temperature on surface integrity, such as microhardness variation and ground surface topography by BN and HL analysis. The following conclusions may be drawn from the current study:

1. According to MBN analysis, magnetizing frequency and magnetic field intensity significantly affect the penetration of the magnetic field in the ground sample. Lower MF and higher MFI are essential for better magnetic response of AISI D2 tool steel. Better magnetic response of the ground surface in terms of higher BN

RMS and peak was found under Cryo-MQL grinding using Al_2O_3 NFs with 1 wt.% concentration lubricants.

2. Polynomial correlations between BN RMS and microhardness with a correlation coefficient of ~0.9990 could be demonstrated for ground samples under different environments. It was concluded that BN RMS is inversely proportional to the microhardness of the ground samples.
3. As a result of less thermal damage than dry grinding, the MBN envelope during Al_2O_3 NFs-based grinding shifts to the left. Therefore, the long and thin shape of the MBN envelope was obtained.
4. The HL response, i.e., average permeability and coercivity, mainly depends on the MFI and MF parameters. Better results were found in Cryo-MQL with Al_2O_3 NFs (1 wt.%). Due to variations in hardness, the shape of HL becomes changed. Low hardness indicated less energy loss during the single cycle of the hysteresis loop.

5.2 Future work

Many challenges still need to be overcome in the future.

1. Modifications in the indigenously developed cryogenic experimental setup may be attempted to regulate the flow rate of LN_2 and the high pressure of LN_2 delivery in the grinding zone.
2. Machining parameters like grinding wheel speed can be further included as one of the independent variables to be examined in grinding difficult-to-cut materials.
3. The approach of cryogenic and Cryo-MQL grinding of difficult-to-cut materials with a monolayer cBN wheel may be developed to reduce the wheel loading.
4. There is a need for further investigation into the cooling and lubricating effect of Cryo-MQL grinding with various nanofluids of challenging materials, such as superalloys, ceramics, etc.
5. Enhancing the computational fluid dynamics (CFD) numerical model for Cryo-MQL grinding parameters is crucial to examine the heat transfer coefficient, number of droplets, and droplet velocity.
6. Investigation of residual stress for difficult-to-cut materials under cryogenic and Cryo-MQL grinding may be attended, and further analysis of the residual stress correlated with MBN parameters.