

PREFACE

AISI D2 tool steel is a widely used tool steel that belongs to the D-series group of high-carbon, high-chromium steels. It is known for its exceptional wear resistance, high hardness, and good toughness, making it suitable for a variety of applications in the tool and die industry. Furthermore, AISI D2 tool steel is also a “difficult-to-machine” or “difficult-to-cut” material by increasing the cutting temperature and friction at the cutting zone due to its high hardness and poor thermal conductivity. Nowadays, close dimensional tolerances, precise geometries and high surface quality requirements are more demanding for difficult-to-machine material. As a result, grinding processes have a good surface finish and closer tolerances than other traditional machining operations like milling, etc. During the grinding operation, the material removal process occurs due to the shearing action of a rapidly revolving abrasive wheel over the workpiece, which results in barely visible microchips to the stripped eye. A higher material removal rate generates a large amount of heat in the grinding zone. Because of high heat generation between the abrasive wheel and workpiece, many defects occurred over the surface and into the subsurface, such as microcracks, surface burns, phase transformation, adhered material to the abrasive wheel, and extreme wheel wear. Therefore, cooling and lubrication in grinding have emerged as one of the most important study topics in recent years. Cutting fluid in large quantities has been used for decades to improve grindability by reducing the produced heat at the grinding zone. Cutting fluid raises the overall quality of the product and increases its production. In general, grinding of “difficult-to-machine” materials may result in a 20-30% growth in the price of cutting fluid relative to the total production cost to remove the heat from the grinding zone. However, this high usage can lead to significant issues such as worker illnesses, environmental contamination, and increased machining costs. Concerning economic, eco-friendly and operator’s health, there is a strong need to develop innovative

technologies that would eliminate or minimize the usage of cutting fluids in manufacturing sectors. Therefore, the present research aims to establish an economical and sustainable grinding environment using sustainable techniques such as cryogenic and cryogenic minimum quantity lubrication (Cryo-MQL) grinding of AISI D2 tool steel. From ecological and economic considerations, cryogenic coolant, i.e., liquid nitrogen (LN_2), has a unique position in manufacturing industries. It is the most abundant, odorless, and non-hazardous. Moreover, the direct ejection of LN_2 into the atmosphere during grinding processes is environmentally harmless. Cryo-MQL is a new eco-friendly method that produces superior outcomes with minimum quantity of cutting fluids or lubricants.

In the present research work, the work first focuses on selecting low-cost and better-performing conventional grinding wheels for grinding AISI D2 tool steel. The appropriate conventional alumina wheel has been selected for grinding AISI D2 tool steel after conducting detailed experiments in dry condition. Furthermore, an in-laboratory fabricated economic cryogenic cooling and Cryo-MQL setup were used in the present study to enhance the cooling and lubrication effects during the grinding operation. Before each grinding experiment, the surface topography of the abrasive wheel was uniformed using a single-point diamond dresser with a $10\ \mu\text{m}$ dressing depth. Grinding process parameters with significant level such as downfeed ($10, 20, 30, 40\ \mu\text{m}$), table feed rate ($6, 9, 12\ \text{m/min}$), wheel speed ($39.42\ \text{m/s}$), LN_2 delivery pressure ($2, 3, 4\ \text{bar}$), flow rate (LN_2 : $0.2\ \text{l/min}$, MQL: $200\ \text{ml/h}$), air pressure ($4\ \text{bar}$), nozzle angle (12°), and stand-off distance (LN_2 : $50\ \text{mm}$, MQL: $40\ \text{mm}$) were selected under dry, wet, cryogenic, Cryo-MQL, MQL with vegetable oil (soybean oil), vegetable oil-based deionized water emulsion and prepared eco-friendly nanofluid (Al_2O_3 nanoparticle with concentration of 0.5 and $1\ \text{wt.}\%$) based on preliminary tests.

During the use of a cryogenic grinding setup for supplying LN_2 coolant, grinding

experiments were carried out to analyze the performance of a cryogenic LN₂ environment. Grinding operations carried on AISI D2 tool steel with alumina wheel under dry, wet and LN₂. The grinding response parameters, i.e., grinding forces, specific grinding energy, grinding temperature, force ratio, surface roughness, surface modifications, bearing area curve analysis, chip morphology, microstructure, and microhardness, have been studied. Based on these studies, the result obtained with LN₂ coolant is compared with those of dry and wet environments. Furthermore, the comparative analysis indicated that LN₂ coolants delivered enhanced grinding performance compared to dry and wet grinding.

Nowadays, hybrid Cryo-MQL is an emerging sustainable technique. In the present study, an indigenous developed Cryo-MQL setup was also used to study the combined effect of LN₂ and MQL lubricants such as soybean oil (SO), soybean oil-based deionized water emulsion (SO+DW), Al₂O₃ nanofluids with (concentration of 0.5 and 1 wt.%) for grinding of AISI D2 tool steel. The thermo-physical properties of vegetable oil-based deionized water emulsion and Al₂O₃ nanofluids with different concentrations (0.5 and 1 wt.%) were measured in terms of thermal conductivity, dynamic viscosity, surface tension, density, pH value, and wettability analysis. Based on the results obtained from experimental work, compared to MQL, it can be concluded that grinding with the simultaneous supply of LN₂ and MQL lubricants had substantial benefits with respect to grinding forces, specific grinding energy, surface roughness, bearing area curve analysis, surface topography, grinding chip morphology and grinding zone temperature. These results also suggest that highly concentrated Al₂O₃ nanofluids (1 wt.%) under Cryo-MQL perform better grindability of AISI D2 tool steel.

The application of magnetic Barkhausen noise is another evolving field, especially in evaluating the surface integrity of ferromagnetic materials. It is one of the objectives of this study. This technique is best for online monitoring of ground surface due to its fast, less

time-consuming characteristics. The grinding experiments were conducted on AISI D2 tool material under different environments, i.e., dry, wet, MQL, and Cryo-MQL at higher downfeed. The magnetic Barkhausen noise (MBN) technique was used to assess the thermal damage surface during the grinding operation. The magnetic Barkhausen noise technique has BN and hysteresis loop (HL) outcomes like root mean square (RMS), peak, average permeability, coercivity, MBN and HL envelopes correlated with surface property, i.e., microhardness under different environments. Overall, the Al₂O₃ nanofluid with the concentration of 1 wt.% under the Cryo-MQL environment was found to be the best mode, followed by the other environments.