Identifying optimization methods using MQL and Cryo-treatments for turning inconel alloy with nanofluids

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Abstract. Nickel-based superalloy, which is also known as Inconel alloy considerably used in various sectors due to its exclusive properties like excellent corrosion resistance, thermomechanical properties, and having high melting temperatures of 1390°C to 1425°C. This paper intends to look over the effect of both nanofluid MQL technique and the combined impact of cryo-minimum quantity lubrication technique on turning of Inconel material using coated carbide inserts or cryogenic treated inserts. It also reveals optimization techniques such as Taguchi methods for studying machining performance and machine learning techniques.

1. Introduction

Inconel belongs to the family of austenitic nickel-chromium based superalloy. It is difficult to cut due to high toughness, high hot hardness, work hardening tendency, etc. Due to its remarkable properties, they have been much used in aerospace industries, automobile industries, marine industries, atomic reactors, oil and gas industries, biomedical industries, and also in chemical and food processing industries [1]. Inconel material is well suited for harsh environments at high pressure and high temperature. They are resistant to oxidation and corrosion. Earlier, flood cooling was the cooling strategy to remove the heat generated in the machining interface. Due to the enormous use of metalworking fluid, it causes harm to the environment and operator’s health [2], and it also steps up the cost of the dumping. To reduce fluid consumption, environmental conscious cooling, known as minimum quantity lubrication has conformed to improve the machinability. MQL machining is also known as eco-friendly machining. In MQL machining, a limited quantity of biodegradable oil was mixed with compressed air to bring impressive cooling and lubrication at the tool–chip interface. Minimum quantity lubrication came out to be the best and effective method compared to dry and flood machining [3]. To enhance the machining performance, industries have started some sustainable cooling and lubrication techniques such as nanofluid-assisted MQL machining and cryogenic machining. Nanofluid is a smart fluid which carries nanoparticles that helps in providing excellent lubrication and cooling properties and also helps in enhancing thermal conductivity and anti-wear property when added to base oil [4]. Nanofluids such as Molybdenum disulfide, Aluminium oxide, Carbon nanotubes and Graphite powder are used broadly.

Cryogenic treatment is the cooling process of materials at cryogenic temperature (below -190°C) to improve the hardness of materials, wear resistance, electrical conductivity, etc. Compared to other refrigerants, liquid nitrogen is more advantageous as it can be utilized at a wide temperature range. Application of cryogenic cooling not only provides excellent lubrication but also helps in reducing the friction and heat generation at the tool-chip interface. There are different types of cutting tools for machining nickel-based alloys. Both
uncoated and coated tools are primarily used in machining Inconel material. To improve the tribological characteristics of cutting inserts coating, is necessary. The coating helps to protect the tool from tool wear, and it gives better surface quality. These coating helps to increase the tool life and reduces the friction force. The main objective of coating a tool is to improve the quality of the product. Chemical vapor deposition (CVD) and physical vapor deposition (PVD) methods are used vastly for the coating of cutting inserts. Both the layers give fascinating features and benefits. When compared, it was noticed that CVD coated inserts perform less than PVD coated inserts in terms of machining performance [5]. Cryogenic treatment of cutting inserts has also been used broadly by intensifying the microstructure of tools to enhance the hardness of tool, thermal conductivity, and wear resistance.

Many researchers have been using machine learning techniques to solve a wide range of complex problems. Machine learning techniques such as artificial neural networks (ANNs), genetic algorithm, and teacher learning-based optimization (TLBO) are beneficial in solving complex problems. These are the techniques that are controlled to optimize the cutting parameters and predict the optimal values of responses accurately. Yogesh V Deshpande et al. reported that the TLBO approach is much faster and delivers correct results than a genetic algorithm. Yogesh V Deshpande et al. also said that when the Artificial neural network compared with the modified regression model, it was realized that ANN shows more than 98% accuracy in predicting surface roughness. However, the regression model shows more than 90% accuracy. Gupta investigated the comparison between two advanced optimization algorithms (e.g., particle swarm optimization (PSO) and teacher learning-based optimization (TLBO) approach). On comparing the two algorithms, PSO turned out to be the most elegant algorithm for predicting the exact responses. To understand the complicated relationships between input and output parameters in turning, a design of experiment (DOE) is adopted. The design of experiment is considered one of the widely used approaches to optimize the manufacturing processes. This method is practiced to investigate the effects of process parameters on the output parameters [9]. The Taguchi method is a standardized version of DOE. Taguchi approach is a user-friendly and economical method used to solve the problem with minimum experiments and minimum time required for experimental investigations.

2. Literature reviews

Several efforts have been given out to replace or minimize the quantities of conventional cutting fluids used in machining as they have harmful effects on the environment and operator health. Singh [2] investigated the suitability of NMQL (carbon nanotubes; CNT in vegetable oil) in the machining of Inconel 625. Inconel 625 of the diameter of 55 mm and length 127 mm was run as workpiece material for machining. The insert used was PVD coated carbide: (AlTi-N). Three process parameters were appointed that are cutting speed, feed rate, and depth of cut. In this study, the comparison of machining performance under different cutting environments has also been researched. Compared to dry and conventional flood machining, it was detected that tool wear is reduced by 18.17% and 4.54%, and surface finish was improved by 55.58% and 5.48% under nanofluid MQL (NMQL) respectively. Hence this revealed superiority of NMQL in terms of better tool life and improved surface finish.

A novel cooling approach of combined minimum quantity lubrication with cryogenic coolant was examined by Allu [3] to improve the machinability of Inconel 718 and compared with dry, wet, minimum quantity lubrication, and cryogenic cooling conditions. The inserts comprised of multilayer CVD coating (TiCN/Al2O3/TiN). Tool wear, cutting forces, and chip morphology was inspected under three cutting parameters cutting speed, feed rate, and depth of cut. The results revealed that abrasive wear was monitored while machining under dry and wet conditions. The tool wear and cutting force
under cryo-machining were significantly high. The tool wear and cutting forces under MQL machining were significantly low. Combined, C-MQL came out to be the best cutting condition producing the least tool wear and cutting effects due to adequate cooling and lubrication. And CMQL machining produced continuous and long chips with uniform chip morphology.

Gupta [4] demonstrated the performance evaluation of vegetable oil-based nano-cutting fluids on machining Inconel-800 Alloy. The cutting tool used is Cubic boron nitride (CBN). The machining parameters chosen were cutting speed, feed rate, and depth of cut. Composite desirability approach (CDA) were utilized for optimizing the machining parameters to bring out an accurate prediction in less possible time. In this study, the researcher has explored the characteristics of different nano cutting fluid such as aluminum oxide (Al₂O₃), molybdenum disulfide (MoS₂), and graphite. On comparing, graphite-based nanofluid found to be superior in improving the machining characteristics amongst the other two nanofluids. It provides excellent tribological and cooling properties and has a more covalent chemical structure due to which it enhances the overall performance.

The study objective made by K. Venkatesan [5] was to investigate the turning performance of h-BN nanoparticle in coconut oil on comparing with the dry mode on Hast-X with two coatings (PVD and CVD). The two advanced cemented carbide turning inserts of PVD (TiAlN), and CVD (TiCN/Al₂O₃/TiN) to be used in the study. Hexagonal Boron Nitride (h-BN) nanoparticles with 0.25 wt. % and 0.50 wt. % in coconut oil was taken as nanofluids. The levels of turning speed (V), feed (f), and weight concentration( wt. %) were selected based on the previous literature. The results revealed that the 0.25 wt.% with MQL PVD showed improvement in turning force, surface roughness, wear at tool-tip, shear angle, coefficient of friction, and chip thickness ratio that of MQL CVD and dry PVD.

Deshpande [6] discussed the estimation of optimum parameters using teacher learning-based optimization (TLBO) and compared them to those obtained by the Genetic Algorithm (GA) in turning of Inconel 718. In this study, the diameter and length of the Inconel 718 workpiece were 22 mm and 120 mm. PVD coated tungsten carbide inserts are used for experiments. The parameters cutting speed, feed rate, and depth of cut were selected as independent variables. Surface roughness, tool flank wear, and the cutting temperature were selected as response parameters. The lower values of tool flank wear and cutting temperature were obtained by TLBO whereas the same value of surface roughness was found in both TLBO and genetic algorithm. Hence it was confirmed that TLBO analysis produced marginally better results than GA optimization.

In this paper, Deshpande [7] explained the artificial neural network (ANN) approach to predict surface roughness using cutting parameters, force, sound, and vibration in turning of Inconel 718. Experiments were conducted by using cryogenically treated and untreated inserts. The paper has presented multiple regression and ANN-based models. In this study, the results of the regression modeling technique were compared and analyzed using ANN application. It was noticed that the models developed by the artificial neural network predict surface roughness with more than 98% accuracy. Further, the predictions obtained by the artificial neural network was compared with the results of regression-based prediction models earlier proposed by the authors. The modified regression models were estimating surface roughness with more than 90% accuracy. Finally, it was ended that artificial neural network models are a better prediction tool for estimating surface roughness than the regression models.

Gupta [8] enlisted the parametric optimization and process capability analysis for machining of nickel-based Inconel 800. The length and diameter of the workpiece were 150 mm and 50 mm, respectively. The insert used was Cubic boron nitride having model no CCGW09T304-2. The experiment performed under three cutting speeds (i.e., 200, 250, and 300 m/min), three feed rates (0.10, 0.15, and
0.20 mm/rev and cutting tool angle (60, 75, and 90). In this experimental work, two advanced optimization algorithms (i.e., particle swarm optimization (PSO) and teacher learning-based optimization (TLBO) approach) have been used for predicting the measured responses. On comparing the two algorithms, PSO turned out to be the finest algorithm for predicting the exact answers.

Deshpande [10] has attempted to examine the effect of cryogenic treatment of tool and minimum quantity lubrication in terms of indicators such as surface quality of the workpiece, tool wear, and material removal rate. The workpiece material was Inconel 718 (46 HRC) with a diameter of 22 mm and a length of 150 mm. The tools which were used in operation were uncoated, and cryo-treated tungsten carbide inserts under Dry, Dry-CT, MQL, and MQL-CT condition. The control parameter used were cutting speed, feed rate, and depth of cut. ANOVA and RSM both used for optimizing the response parameters in turning of Inconel 718. In conclusion, the MQL-CT results in achieving the lowest value of cutting force, vibration, and cutting temperature than machining with Dry, Dry-CT, and MQL conditions. Also, the use of MQL-CT resulted in better surface finish, improvement in tool life, and material removal rate. Thus, MQL-CT was identified as the best method for improving the overall productivity of the process.

Gutnichenko [11] demonstrated the effect of reliable lubricant assisted minimum quantity lubrication (MQL) on the machining performance when turning alloy 718 with cemented carbide tools. PVD coated TiAlN insert has used in the study. The material which was used in the experiment is Alloy 718 (46 HRC) with a diameter of 70 mm and length of 250 mm. The objective of the study was to investigate the influence of GnP additive to vegetable oil on machining performance when MQL-assisted turning alloy 718. The process parameters which was used in the study were cutting speed, feed rate, and depth of cut. It was concluded that the use of GnP additives of 0.2% (vol.) in vegetable-based oil could significantly improve the performance in terms of tool life, surface finish, and process stability.

A study was conducted by Hegab [12] to explain the effects of nano-cutting fluids on tool performance and chip morphology during machining Inconel 718. The material used was Inconel 718 (ASTM SB 637), and the cutting insert used in the experiment was tungsten carbide CNMG432MMH13A (ANSI). In this investigation, three design variables were employed with three levels each (i.e., cutting speed, feed rate, and weight percentage of added nano-additives). Nano additives that were adopted are Multi-walled carbon nanotubes (MWCNTs) and aluminum oxide (Al₂O₃) gamma nanoparticles. In this investigation, both nanofluids showed the better results, but it has found that MWCNT nanofluid has shown better performance than Al₂O₃ nanofluid.

Joshi [13] enlisted the concept of effects of minimum quantity lubrication (MQL) with Al₂O₃ nanofluid on surface roughness and its prediction using a hybrid fuzzy controller in turning operation of Inconel 600. Uncoated carbide inserts were used at different feed, speed, and depth of cut under Dry, MQL, and MQL with nanofluids condition. It was detected that by using nanofluid with MQL technique can remarkably intensify the performance at low or moderate cutting speed, feed rates, and depth of cut. MQL with the nanofluid condition showed better surface roughness as compared to dry and MQL with vegetable oil. Results obtained from the experimental investigation were closely matching with the results obtained from the hybrid fuzzy controller approach.

Singh [14] demonstrated the tribological effects of H-Bn nano cutting fluid with Minimum Quantity Lubrication (NF-MQL) on the machining performance of Inconel 625 was compared with other lubricating conditions (dry, wet, MQL conventional). The cutting tool used for machining was PVD coated carbide insert. This paper concluded that the addition of h-BN nanoparticles in a conventional
cutting fluid provides better tribological performances like reduction in tool wear, cutting force, and surface roughness along with improved chip morphology. Finally, it found that the tribological effects of h-BN NF-MQL show a viable and sustainable option for improving the machining performance of hard-to-cut material like Inconel 625.

An experimental investigation in turning of Incoloy 800 in Dry, MQL, and flood cooling conditions was carried out by Joshi [15]. Uncoated tungsten carbide tool of ISO designation CNMG 120408 was utilized to accomplish the turning experiments. In this experiment, two types of MQL, namely MQL1 (150 ml/h) and MQL2 (230 ml/h), has implemented. The flooded cooling rate has fixed as 600 ml/h. The experiments were conducted at cutting speed of 40, 50, and 60 m/min; the feed rate of 0.066 and 0.132 mm/rev; and depth of cut as 0.5, 0.75, and 1.0 mm. Grey regression analysis and ANOVA was carried out in this research work. The researcher focused on surface roughness and tool wear. The outcomes obtained showed that surface roughness and tool wear both were minimum under MQL conditions, whereas performance under MQL2 was more favorable than MQL1.

Research work for investigating machining performance of Inconel 825 using physical vapor deposition-titanium nitrate inserts, with a focus on sustainable machining, was explained by Tamang [16]. The effect of cutting parameters, viz. cutting speed (v), feed (f), and depth of cut (d) has been explored in two different machining environments, viz. dry and minimum quantity lubrication (MQL). In this work, the GA algorithm was used for simultaneously optimizing three aspects of sustainability, i.e., tool wear, power consumption, and surface roughness in the dry and MQL machining environment. The experimental results showed a significant improvement in MQL machining in terms of reduction in tool wear, power consumption, and surface roughness. Compared to dry machining, the tool wear and cutting power were reduced by 16.57, and 8.47% and surface roughness were improved by 10.41% under MQL machining, respectively.

Gaddam [17] evaluated the effect of minimum quantity lubrication (MQL), cryogenic cooling with liquid nitrogen (LN2), and hybrid Cryo-MQL methods on tool wear behavior, cutting temperature, surface roughness and chip morphology in turning of Ni-based alloy 625. A type of PVD TiAlN/TiN coated carbide tool (ISO designation: CNGG 120404 (S05-S25)) was employed. The experiments were performed at three cutting speeds (50, 75, and 100 m/min), fixed cutting depth (0.5 mm), and feed rate (0.12 mm/rev). Results showed that Cryo-MQL improved surface roughness by 24.82% as compared to cryogenic cooling. For lower roughness value, the medium level of cutting speed (75 m/min) can be preferred. Compared to cryogenic machining, tool wear was decreased by 50.67% and 79.60% by using MQL and Cryo-MQL.

Gaddam [18] evaluated the effect of the addition of h-BN nanofluid along with the MQL technique on turning of Ni-based Inconel 625. The machining experiments were carried out under four different cutting conditions dry cutting, pure-MQL, and nano-MQL at 0.5vol% h-BN and 1vol% h-BN additive ratios. In this study, tool life, surface roughness, tool wear, and tool-chip interface temperature was analyzed. SEM photographs and EDX analysis was used to evaluate the wear mechanisms. The research revealed that the highest tool life was obtained in nano-MQL with 0.5vol% h-BN, while the lowest tool life was obtained from dry machining. The best surface quality (Ra=0.497μm) has occurred in nano-MQL containing 0.5vol% h-BN, while the worst surface quality was seen in dry machining. The cutting fluid that contains 1vol% h-BN produced the lowest tool chip interface temperature regarding cooling conditions. It has observed that the responses such as tool life, surface roughness, and temperature were mostly affected by the cutting speed, feed rate, and cooling condition, respectively.
Darshan [19] investigated the performance of textured tools to explore its potential benefits in achieving favorability in the machining of Inconel-718. The uncoated carbide tool with ISO designation of TNMA 160408-THMF were utilized for the machining tests. In this study, the performance comparison of the non-textured and textured tools has conducted at cutting speed of 80, 120, and 180 m min⁻¹ and at a successive increment of machining times up to 10 min. Based upon the experiment, as the cutting speed and time increase improvement in the surface finish is noticed. The increase in cutting speed and machining time demonstrated the larger values of tool flank wear. Also, the texturing on cutting tool provides the right lubricating action at the tool–chip interface and reduces the tool flank wear values as compared with non-textured tools. For cutting force estimation, it has noted that the textured tools produced a much lesser cutting force than the non-textured tools. And two types of chips had been presented with untextured and textured tools i.e., serrated type long and spring type short chips. Lastly, it was concluded that the use of dimple textured tools during machining of Inconel-718 alloys showed very positive results.

K Venkatesan [20] listed the effect of different concentrations of nanofluids along with the application of Taguchi-response surface analysis to optimize the cutting parameters on turning of Inconel X-750. PVD (AlTiN) coated inserts were used for experiments. The experiment were conducted at cutting speed of (40, 60, 100 m/min), feed rate of (0.14, 0.17, 0.20 mm/rev) and % concentration of nanofluid is (0.25, 0.50, 1.00). It found that the increment in feed rate leads to an increase in the force, surface roughness, tool wear. Increment in cutting velocity results in decrementing the cutting force, surface roughness and increasing the tool wear. In the case of % concentration, when the % concentration from 0.25% to 0.5% increases, then there is an increase in cutting force and tool wear and then reduce. The decrement in surface roughness were observed at 0.5% than the 0.25% and 1.00%. From this research, it found that 1.00% of nAl₂O₃ nanofluids in coconut oil along with cutting speed of 87 m/min and feed rate of 0.14 mm/rev has proved the better machining performance.

Experimental study and optimization of turning Inconel 718 using coated and uncoated inserts under dry machining was carried out by Reddy [21] in his research. PVD coated TiN tool was used as a cutting insert. The control parameter used were cutting speed, feed rate, and depth of cut and the performance characteristics were cutting force, and surface roughness. By comparing the results, it has observed that the cutting force and surface roughness were found to be low in using coated inserts compared with the uncoated tool. The coated tool is efficient with low cutting speed and a maximum depth of cut with the moderate feed. The uncoated tool is reliable with average speed, small depth of cut, and average feed rate.

P. Sivaiah [22] carried out the effect of novel hybrid texture tool on turning process performance in MQL machining of Inconel 718 superalloy. PVD AlTiN coated carbide inserts were used for machining. In this work, there is the comparison of the performance of three tools namely, untextured tool (T1), texture tool having circular pit holes (T2), and hybrid texture tool combination of circular pit holes and linear grooves (T3) under MQL cooling technique. The machining considerations taken were cutting speed, feed rate, and depth of cut. It has observed that hybrid texture tool (T3) significantly reduced the cutting zone temperature, tool flank wear and surface roughness to a maximum of 36%, 59%, and 46%, respectively, when compared to the T1 tool, in contrast, it was 22%, 48%, and 30% when compared to the T2 tool, respectively. Enhanced improvement was observed when machining with texture tools over un-texture tools.
Bevara [23] presented the project that focused on performance evaluation of Minimum Quantity Lubrication (MQL) application of graphene nano cutting fluid while turning Inconel 718 alloy at constant cutting conditions. Graphene-based nanofluids were prepared in different concentrations: 0.1wt%, 0.3wt%, and 0.5wt% by dispersing graphene in conventional soluble oil (1:20). Cutting experiments were conducted using coated carbide tool CNMG120408MS KC5010 at constant cutting conditions: cutting velocity 74 m/min, depth of cut 0.5 mm, and feed of 0.14 mm/rev. Machining was performed at different machining conditions such as dry machining, MQL machining without graphene (0wt%), MQL machining using 0.1wt%, 0.3wt%, and 0.5wt% graphene dispersed cutting fluid. Results showed that the cutting forces decreased when the concentration of graphene increased. MQL machining with 0.5wt% of graphene showed a 74% reduction in the least force compared to dry machining. Least surface roughness was observed in using 0.5wt% graphene nanofluid. And by machining with 0.3wt% graphene nanofluid, it showed minimum tool wear.

Investigation on Influence of hybrid nanofluid-MQL on surface roughness in turning Inconel-718 was listed by Mechiri [24]. The inserts used were TiAlN coated insert from Kennametal with ISO designation CNGG 120408. The objective of this work was to evacuate the consequence of cutting parameters when machined under dry, MQL, and MQL using nano-fluid conditions. The results of nano- MQL was compared with dry and Veg/MQL lubricating conditions. And it was found that the surface roughness was reduced by 39% when compared to dry machining. In conclusion, it has found that the major contributor for surface roughness is the feed rate followed by speed and depth of cut.

3. Conclusions

From the following literature reviews, it is concluded that the use of biodegradable oil using the MQL technique is advantageous as compared to dry and flood cooling. Many researchers observed that nano fluid using the MQL technique and Cryo-MQL technique improves the machining performance. Graphite-based nanofluid provides better results due to their excellent lubrication and cooling properties compared to Molybdenum disulfide and Aluminium oxide nanofluid. The researcher has also found that tool coating is consequential if one has to achieve a better surface finish, tool life, and intensify the machining characteristics. PVD and CVD coatings, show that PVD coating provides a better coat to cutting insert. Hence, PVD coating is endorsed in machining hard to machine materials like Inconel. The paper reveals that the use of Cryogenically treated inserts also helps achieve better results; hence MQL with cryogenically treated inserts are suggested for turning of Inconel. Various machine learning techniques have been implemented by optimizing the machining parameters to obtain minimal response values. Some methods, like PSO, TLBO, and ANN, produce marginally accurate results than other optimization techniques.

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