

**GRINDING OF NIMONIC 90 USING SUSTAINABLE
COOLING TECHNIQUES AND MODELING OF
GRINDING FORCE**

PIRSAB RASULSAB ATTAR



**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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by

PIRSAB RASULSAB ATTAR

DEPARTMENT OF MECHANICAL ENGINEERING

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Dedicated To
My Parents
&
Family

CERTIFICATE

This is to certify that the thesis entitled, “**Grinding of Nimonic 90 Using Sustainable Cooling Techniques and Modeling of Grinding Force**” submitted by **Mr. Pirsab Rasulsab Attar** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** in Mechanical Engineering is a bonafide record of original research work carried out by him under our supervision in conformity with the rules and regulations of the institute.

The results presented in this thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

Dr. Sudarsan Ghosh
Professor
Department of Mechanical Engineering
Indian Institute of Technology Delhi
New Delhi-110016(INDIA)

Dr. P. Venkateswara Rao
Professor
Department of Mechanical Engineering
Indian Institute of Technology Delhi
New Delhi-110016 (INDIA)

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ABSTRACT

Nimonic 90 is a nickel-based alloy that offers many desirable attributes for industrial and commercial use in terms of its high hot hardness, high wear resistance, and good corrosion resistance. Due to these attributes, the Nimonic 90 finds extensive application in aerospace, automobile, nuclear power plants, and petrochemical industries. Despite having many favorable properties, Nimonic 90 is classified as difficult-to-machine material due to its ability to retain high strength at elevated temperature, high strain rate sensitivity which leads to work hardening, low thermal conductivity, and high chemical reactivity. In general, petroleum-based metal working fluids (MWFs) under flood mode are used as a conventional method to reduce the cutting temperature and friction during grinding. However, the MWFs are considered as the most unsustainable component of grinding processes. High costs associated with operational and disposal, environment pollution, operators' health-related issues, and high energy consumption due to the use of MWFs in grinding are the major hurdles for the machining industries. Therefore, the present research aims to eradicate, reduce, or replace the MWFs from the grinding process using sustainable techniques such as minimum quantity lubrication (MQL) and cryogenic cooling using liquid nitrogen (LN₂). The application of these sustainable techniques in grinding can make the grinding process more economical, ecological, and socially viable.

In the present study, MQL has been used as a strategy to reduce the quantity of cutting fluid during the grinding process. The conventional cutting fluid has been replaced with indigenously prepared cutting fluids such as biodegradable emulsion (sunflower oil in water (SOIW), Soybean oil in water (SYOIW), and Palm oil in water (POIW)) and water-based nanofluids. The nanofluids have been prepared by mixing the nano sized alumina (Al₂O₃), graphene nanoplatelets (GnP), and hybrid of them in deionized water and have been employed for the grinding of the Nimonic 90 in a CNC surface grinding machine. The grinding output in

terms of grinding forces, surface roughness, ground surface topography, wheel topography, and grinding chips morphology are obtained when using the prepared fluids and the same has been compared with the dry grinding condition. Upon investigation, the use of alumina-graphene nanoplatelets (Al-GnP) hybrid nanofluids (NFs) with 0.75 Vol.% has been proven to be a better environment than other conditions in terms of reducing grinding forces and surface integrity.

In the last experimental phase of this research work, a comparison between the cryogenic cooling condition, sunflower oil in water (SOIW) with 5 Vol.% biodegradable emulsion and hybrid Al-GnP with 0.75 Vol.% has been conducted by varying the grinding speed, table speed, depth of cut, and grit size. Overall, the cryogenic sustainable cooling technique has been found to be the best sustainable cooling technique followed by MQL with Al-GnP hybrid NFs and MQL with SOIW biodegradable emulsion during grinding of Nimonic 90.

In the last section of this research work, an attempt has been made to develop a pseudo analytical model predicting the grinding force under the sustainable MQL environment. The grinding force is one of the key response variables. It is essential to study the force during grinding because of its direct effect on the ground surface quality, wheel wear, grinding zone temperature, and grinding fixtures' design. Till now, only a few authors have modelled the grinding force and that too under a dry grinding environment. Therefore, the present work deals with developing a mathematical model for predicting the force during the grinding of a Nimonic 90 under a sustainable MQL environment. The model takes into consideration all the three force components such as cutting, rubbing, and ploughing. The total tangential and normal force components equations have been developed during these three processes and stated in terms of experimental constant coefficients and grinding process parameters such as grinding speed, table speed, and depth of cut. All coefficients have been determined by conducting grinding experiments under a sustainable MQL environment. The rubbing force

component has been estimated using experimental grinding contact length and dynamic grit density. The single grit experiments have been performed to model the ploughing force component. The single alumina abrasives with different sizes, i.e., 24, 20, and 16 mesh numbers, have been used to investigate the actual material deformation behavior during single grit grinding. These grinding experiments have been performed using in-house developed alumina brazed tools fitted into a dummy aluminium grinding wheel. The geometrical parameters of the scratches have been measured and analyzed using a coherence correlation interferometer optics microscope to investigate the ploughing phenomenon. The present study indicates that the ploughing becomes more influential due to the size effect during grinding of harder material like Nimonic 90 alloy at low depth of cut. The total normal and tangential force values obtained from the analytical model have been validated based on experimental data of total normal and tangential forces in surface grinding under a sustainable MQL environment. A good agreement between the predicted and experimental force values have been noticed.

Keywords: Cryogenic grinding, MQL, Hybrid nanofluids, grinding force model

सार

निमोनिक 90 एक निकल-आधारित मिश्र धातु है जो अपनी उच्च गर्म कठोरता, उच्च पहनने के प्रतिरोध और अच्छे संक्षारण प्रतिरोध के संदर्भ में औद्योगिक और व्यावसायिक उपयोग के लिए कई वांछनीय गुण प्रदान करता है। इन विशेषताओं के कारण, निमोनिक 90 एयरोस्पेस, ऑटोमोबाइल, परमाणु ऊर्जा संयंत्रों और पेट्रोकेमिकल उद्योगों में व्यापक अनुप्रयोग पाता है। कई अनुकूल गुण होने के बावजूद, निमोनिक 90 को कठिन-से-मशीन सामग्री के रूप में वर्गीकृत किया गया है, क्योंकि ऊंचे तापमान पर उच्च शक्ति बनाए रखने की क्षमता, उच्च तनाव दर संवेदनशीलता जो काम को सख्त, कम तापीय चालकता और उच्च रासायनिक प्रतिक्रिया की ओर ले जाती है। आम तौर पर, फ्लड मोड के तहत पेट्रोलियम आधारित धातु काम करने वाले तरल पदार्थ (एमडब्ल्यूएफ) का उपयोग पारंपरिक तरीके के रूप में किया जाता है ताकि पीसने के दौरान काटने के तापमान और घर्षण को कम किया जा सके। हालांकि, MWF को ग्राइंडिंग प्रक्रियाओं का सबसे अधिक अरक्षणीय घटक माना जाता है। परिचालन और निपटान से जुड़ी उच्च लागत, पर्यावरण प्रदूषण, ऑपरेटरों के स्वास्थ्य संबंधी मुद्दे, और पीसने में MWF के उपयोग के कारण उच्च ऊर्जा खपत मशीनिंग उद्योगों के लिए प्रमुख बाधाएं हैं। इसलिए, वर्तमान शोध का उद्देश्य न्यूनतम मात्रा स्नेहन (एमक्यूएल) का और तरल नाइट्रोजन (एलएन 2) क्रायोजेनिक कूलिंग जैसी टिकाऊ तकनीकों का उपयोग करके एमडब्ल्यूएफ को पीसने की प्रक्रिया से मिटाना, कम करना या बदलना है। पीसने में इन टिकाऊ तकनीकों का उपयोग पीसने की प्रक्रिया को अधिक किफायती, पारिस्थितिक और सामाजिक रूप से व्यवहार्य बना सकता है।

वर्तमान अध्ययन में, एमक्यूएल का उपयोग पीसने की प्रक्रिया के दौरान तरल पदार्थ काटने की मात्रा को कम करने की रणनीति के रूप में किया गया है। पारंपरिक काटने वाले तरल पदार्थ को स्वदेशी रूप से तैयार करने वाले तरल पदार्थ जैसे बायोडिग्रेडेबल इमल्शन (पानी में सूरजमुखी तेल, पानी में सोयाबीन तेल, और पानी में पाम तेल) और पानी आधारित नैनो फ्लुइड्स के साथ बदल दिया गया है। नैनो आकार के अल₂ओ₃, जीएनपी, और उनके हाइब्रिड को विआयनीकृत पानी में मिलाकर नैनोफ्लुइड्स तैयार

किया गया और एक सीएनसी सतह पीसने वाली मशीन में निमोनिक 90 को पीसने के लिए नियोजित किया गया है। पीसने वाले बल, सतह खुरदरापन, जमीन की सतह स्थलाकृति, पहिया स्थलाकृति, और पीसने वाले चिप्स आकारिकी के संदर्भ में पीसने वाले आउटपुट को तैयार तरल पदार्थ का उपयोग करते समय प्राप्त किया जाता है और इसकी तुलना सूखी पीसने की स्थिति से की जाती है। जांच करने पर, 0.75 Vol% के साथ अल-जीएनपी हाइब्रिड नैनोफ्लुइड का उपयोग पीसने वाले बलों और सतह अखंडता को कम करने के मामले में अन्य स्थितियों की तुलना में बेहतर वातावरण साबित हुआ है।

इस शोध कार्य के अंतिम प्रायोगिक चरण में, क्रायोजेनिक कूलिंग कंडीशन, 5 Vol% बायोडिग्रेडेबल इमल्शन के साथ पानी में सूरजमुखी के तेल और 0.75 Vol% के साथ हाइब्रिड अल-जीएनपी की तुलना पीसने की गति, टेबल स्पीड, कटौती की गहराई और ग्रिट आकार को अलग करके की गई है। कुल मिलाकर, क्रायोजेनिक सस्टेनेबल कूलिंग तकनीक को सबसे अच्छी टिकाऊ कूलिंग तकनीक के रूप में पाया गया है, जिसके बाद निमोनिक 90 की ग्राइंडिंग के दौरान अल-जीएनपी हाइब्रिड एनएफ के साथ एमक्यूएल और एसओआईडब्ल्यू बायोडिग्रेडेबल इमल्शन के साथ एमक्यूएल है।

इस शोध कार्य के अंतिम भाग में, एक प्रयास किया गया है। एक छद्म विश्लेषणात्मक मॉडल विकसित करने के लिए बनाया गया है जो स्थायी MQL वातावरण के तहत पीस बल की भविष्यवाणी करता है। पीस बल प्रमुख प्रतिक्रिया चर में से एक है। पीसने के दौरान बल का अध्ययन करना आवश्यक है क्योंकि इसका ग्राउण्ड की सतह की गुणवत्ता, पहिया घिसने, पीसने वाले क्षेत्र के तापमान और पीसने वाले जुड़नार के डिजाइन पर सीधा प्रभाव पड़ता है। अब तक, केवल कुछ लेखकों ने ग्राइंडिंग फोर्स का मॉडल तैयार किया है और वह भी शुष्क ग्राइंडिंग वातावरण में। इसलिए, वर्तमान कार्य एक स्थायी एमक्यूएल वातावरण के तहत निमोनिक 90 के पीसने के दौरान बल की भविष्यवाणी के लिए गणितीय मॉडल विकसित करने से संबंधित है। मॉडल काटने, रगड़ने और जुताई जैसे तीनों बल घटकों को ध्यान में रखता है। इन तीन प्रक्रियाओं के दौरान कुल स्पशरिखा और सामान्य बल घटक समीकरण विकसित किए गए हैं और प्रयोगात्मक स्थिर गुणांक और पीसने की गति, टेबल गति और कटौती की गहराई जैसे पीसने की

प्रक्रिया पैरामीटर के संदर्भ में कहा गया है। सभी गुणांक एक स्थायी MQL वातावरण के तहत पीस प्रयोगों का संचालन करके निर्धारित किए गए हैं। प्रायोगिक पीस संपर्क लंबाई और गतिशील धैर्य घनत्व का उपयोग करके रगड़ बल घटक का अनुमान लगाया गया है। प्लोइंग (Ploughing) बल घटक को मॉडल करने के लिए एकल धैर्य प्रयोग किए गए हैं। सिंगल ग्रिट ग्राइंडिंग के दौरान वास्तविक सामग्री विरूपण व्यवहार की जांच के लिए विभिन्न आकारों, यानी 24, 20, और 16 मेष आकारों के साथ एकल एल्यूमिना अपघर्षक का उपयोग किया गया है। इन ग्राइंडिंग प्रयोगों को एक डमी एल्युमिनियम ग्राइंडिंग व्हील में फिट किए गए इन-हाउस विकसित एल्यूमिना ब्रेज़्ड टूल्स का उपयोग करके किया गया है। प्लोइंग (Ploughing) की घटना की जांच के लिए एक सुसंगत सहसंबंध इंटरफेरोमीटर ऑप्टिक्स माइक्रोस्कोप का उपयोग करके खरोंच के ज्यामितीय मापदंडों को मापा और विश्लेषण किया गया है। वर्तमान अध्ययन इंगित करता है कि निमोनिक 90 मिश्र धातु जैसी कठोर सामग्री को कट की कम गहराई पर पीसने के दौरान आकार के प्रभाव के कारण जुताई अधिक प्रभावशाली हो जाती है। विश्लेषणात्मक मॉडल से प्राप्त कुल सामान्य और स्पर्शरिखा बल मूल्यों को एक स्थायी MQL वातावरण के तहत सतह पीसने में कुल सामान्य और स्पर्शरिखा बलों के प्रयोगात्मक डेटा के आधार पर मान्य किया गया है। अनुमानित और प्रायोगिक बल मूल्यों के बीच एक अच्छा समझौता देखा गया है।

कीवर्ड: क्रायोजेनिक ग्राइंडिंग, एमक्यूएल, हाइब्रिड नैनो फ्लुइड्स, ग्राइंडिंग फोर्स मॉडल

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NOTATION

A	Fraction of wheel's wear surface
A_0	Contact area, mm ²
A_a	Rubbing area during grinding, mm ²
A_b	Bearing area of scratch, mm ²
a_p	Depth of cut or infeed, mm
ANOVA	Analysis of Variance
b	Grinding width, mm
C	Number of active grits per unit area, mm ⁻²
CCI	Coherence Correlation Interferometer
d_e	Equivalent diameter of grinding wheel, mm
d_g	Grit diameter, mm
FESEM	Field Emission Scanning Electron Microscope
e	Grit penetration or scratch depth, mm
g	Constant
GnP	Graphene Nanoplatelets
h	Pile up height, mm
h_l	Left side pile up height, mm
h_r	Right side pile up height, mm
H	Pile up ratio
H_c	Workpiece hardness, N/mm ²
H_s	Scratch hardness, N/mm ²
K	Chip thickness coefficient
K_1	Chip thickness coefficient
K_2	Experimental Constant
K_3	Experimental Constant
K_4	Experimental Constant
K_5	Experimental Constant
L_c	Geometrical contact length, mm
L_{exp}	Experimental contact length during grinding, mm

MQL	Minimum Quantity Lubrication
MRR_{grit}	Metal removal rate for a grit, mm^3
p_0	Experimental Constant
\bar{p}	Average contact pressure between workpiece and abrasive grain, N/mm^2
P_{gn}	Single grit normal force, N
P_{gnc}	Single grit normal chip formation force, N
P_{gnp}	Single grit normal ploughing force, N
P_{gnr}	Single grit normal rubbing force, N
P_{gt}	Single grit tangential force, N
P_{gtc}	Single grit tangential chip formation force, N
P_{gtp}	Single grit tangential ploughing force, N
P_{gtr}	Single grit tangential rubbing force, N
POIW	Palm Oil In Water
P_n	Normal grinding force, N
P'_n	Specific normal grinding force, N/mm
P_{nc}	Normal chip formation force, N
P'_{nc}	Normal component of specific chip formation force, N/mm
P_{np}	Normal ploughing force, N
P'_{np}	Normal component of specific ploughing force, N/mm
P_{nr}	Normal rubbing force, N
P'_{nr}	Normal component of specific rubbing force, N/mm
P_t	Tangential grinding force, N
P'_t	Specific tangential grinding force, N/mm
P_{tc}	Tangential chip formation force, N
P'_{tc}	Tangential component of specific chip formation force, N/mm
P_{tp}	Tangential ploughing force, N
P'_{tp}	Tangential component of specific ploughing force, N/mm
P_{tr}	Tangential rubbing force, N
P'_{tr}	Tangential component of specific rubbing force, N/mm

Q_i	Chip cross sectional area, mm ²
RSM	Response Surface Methodology
SEM	Scanning Electron Microscope
SOIW	Sunflower Oil In Water
SYOIW	Soybean Oil In Water
SZM	Stereo Zoom Microscope
TEM	Transmission Electron Microscope
u_{pl}	Specific ploughing energy, J/mm ³
V_c	Grinding wheel speed, m/min
V_w	Table speed, m/min
W	Normal load, N
x	Constant
y	Constant
z	Constant
φ	Ratio of tangential chip formation force to normal chip formation force
Δ	Deviation of radius of curvature of cutting path and grinding wheel radius, mm
μ_{sl}	Sliding coefficient of friction
α	Semi apex angle of grit, deg
α_0	Constant
β	Constant
φ	Ratio of tangential chip formation force to normal chip formation force
Δ	Deviation in radius of curvature of cutting path & grinding wheel radius, mm
μ_{sl}	Sliding coefficient of friction