

**STUDY ON MACHINING CHARACTERISTICS AND SURFACE
INTEGRITY OF INCOLOY 925 IN END MILLING USING ECO-
FRIENDLY NOVEL HYBRID NANOFLUID**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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FRIENDLY NOVEL HYBRID NANOFLUID**

by

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DEPARTMENT OF MECHANICAL ENGINEERING

Submitted

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Dedicated to

My Family

Certificate

This is to certify that the thesis entitled, “**Study on machining characteristics and surface integrity of Incoloy 925 in end milling using eco-friendly novel hybrid nanofluid**” submitted by **Mr. Shravan Kumar Yadav** 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 the 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 University or Institute for the award of any degree or diploma.

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Shravan Kumar Yadav

Abstract

This doctoral thesis has attempted to study the machining characteristics and surface integrity of Incoloy 925 under eco-friendly novel hybrid nanofluid, including other suitable sustainable cutting environments. In this regard, first to select a suitable cutting base oil (fluid) to be used for MQL (minimum quantity lubrication), the machining performance of different types of vegetable oils, such as coconut oil, sunflower oil, groundnut oil, and rice bran oil have been tested. Coconut oil is found to be the most suitable base oil among the others. Thermophysical and tribological properties of this oil can be enhanced by dispersing the nanoparticles into it, and the colloid is called a nanofluid which may provide effective lubrication-cooling. It has been reported that hybrid nanofluids-assisted machining performs better than mono nanofluids. However, some solid lubricants (in nanoparticles) transform to another phase (like MoS_2 to MoO_3 and WS_2 to WO_3) at high temperatures, thereby providing a poor lubrication effect during machining, whereas hard nanoparticles like diamond or SiC create scratches on machined surfaces. In this research, a potential novel biodegradable hybrid nanofluid is developed by simultaneously dispersing ceramic nanoparticles (hBN) and soft metallic nanoparticles (Cu) in lubricious coconut oil, ensuring their chemical inertness at high temperatures without compromising the solid lubricant's properties. The physical stability of nanofluids is characterized using ultraviolet-visible near-infrared (UV-Vis-NIR) spectrophotometer and nanoparticles tracking analyzer (NTA); chemical stability is characterized using FTIR (Fourier transform infrared) spectroscopy, whereas the thermal stability of nanofluids is evaluated using thermogravimetric analysis (TGA) and derivative thermogravimetry (DTG) techniques. Thermal conductivity, viscosity, viscosity index, wettability, and tribological performance are also evaluated. The performance of the developed hybrid nanofluid in end milling of Incoloy 925 is investigated in terms of specific cutting energy, carbon

emission, surface roughness, surface topography, chip morphology, tool wear, and microstructure, microhardness, and residual stresses of machined components. Formulated hybrid nanofluid performs better than dry, base oil, and mono nanofluid. The sustainability of machining performance is evaluated with a triple bottom line (TBL) approach, and it is found that product sustainability index (ProdSI) under hybrid nanofluid (HNMQL) assisted machining scores 3 times of oil (MQL) assisted machining and 1.85 times of mono nanofluid (NMQL) assisted machining.

Further, a statistical tool, such as analysis of variance (ANOVA), is used to investigate the combined effects of the radius of inserts and process parameters on the machining performance. Response surface methodology (RSM) and artificial neural network (ANN) are applied to develop the mathematical models between cutting parameters and machining responses, and their prediction results are compared. ANN models are found to be more effective than RSM models. In order to optimize the machining responses, ANN models are coupled with a non-dominated sorting genetic algorithm (NSGA-II). The technique for order performance by similarity to ideal solution (TOPSIS) is used to get the best solution from the optimal set of parameters.

Moreover, in order to investigate the quality of machined components under different cutting environments at optimized cutting parameters, functional performance characteristics such as tribological performance, fatigue behavior, and electrochemical and hot corrosion behavior have been evaluated. It is found that surface characteristics of machined components, such as areal surface roughness/topography and residual stresses, strongly correlate with the product's functional performance.

Keywords: Incoloy 925; Nanofluid; MQL; TBL; ANN-NSGA-II; Surface integrity; Functional performance

सार

इस डॉक्टरेट थीसिस में अन्य उपयुक्त संधारणीय कटिंग वातावरणों सहित पर्यावरण के अनुकूल नवीन हाइब्रिड नैनोफ्लुइड के तहत इनकोलॉय 925 की मशीनिंग विशेषताओं और सतह अखंडता का अध्ययन करने का प्रयास किया गया है। इस संबंध में, सबसे पहले एमक्यएल (न्यूनतम मात्रा स्नेहन) के लिए उपयोग किए जाने वाले उपयुक्त कटिंग बेस तेल (द्रव) का चयन करने के लिए, विभिन्न प्रकार के वनस्पति तेलों, जैसे कि नारियल तेल, सूरजमुखी तेल, मूंगफली तेल और चावल की भूसी के तेल के मशीनिंग प्रदर्शन का परीक्षण किया गया है। नारियल तेल अन्य तेलों में सबसे उपयुक्त बेस ऑयल पाया गया है। इस तेल के थर्मोफिजिकल और ट्रिबोलॉजिकल गुणों को इसमें नैनोकणों को फैलाकर बढ़ाया जा सकता है, और कोलाइड को नैनोफ्लुइड कहा जाता है जो प्रभावी स्नेहन-शीतलन प्रदान कर सकता है। यह बताया गया है कि हाइब्रिड नैनोफ्लुइड्स-सहायता प्राप्त मशीनिंग मोनो नैनोफ्लुइड्स से बेहतर प्रदर्शन करती है। हालांकि, कुछ ठोस स्नेहक (नैनोकणों में) उच्च तापमान पर दूसरे चरण (जैसे मोलिब्डेनम डाइसल्फाइड से मोलिब्डेनम ट्राइऑक्साइड और टंगस्टन डाइसल्फाइड से टंगस्टन ट्राइऑक्साइड) में बदल जाते हैं, जिससे मशीनिंग के दौरान खराब स्नेहन प्रभाव होता है, जबकि हीरा या सिलिकन कार्बाइड जैसे कठोर नैनोकण मशीनी सतहों पर खरोच पैदा करते हैं। इस शोध में, एक संभावित नया बायोडिग्रेडेबल हाइब्रिड नैनोफ्लुइड को चिकनाई वाले नारियल के तेल में सिरेमिक नैनोकणों (एचबीएन) और नरम धातु नैनोकणों (ताँबा) को एक साथ फैलाकर विकसित किया गया नैनोफ्लुइड्स की भौतिक स्थिरता को पराबैंगनी-दृश्यमान निकट-अवरक्त स्पेक्ट्रोफोटोमीटर और नैनोपार्टिकल्स ट्रेकिंग एनालाइजर का उपयोग करके चिह्नित किया जाता है; रासायनिक स्थिरता को फूरियर ट्रांसफॉर्म इंफ्रारेड स्पेक्ट्रोस्कोपी का उपयोग करके चिह्नित किया जाता है, जबकि नैनोफ्लुइड्स की थर्मल स्थिरता का मूल्यांकन थर्मोग्रेविमेट्रिक विश्लेषण और व्युत्पन्न थर्मोग्रेविमेट्री तकनीकों का उपयोग करके किया जाता है। थर्मल चालकता, श्यानता, श्यानता सूचकांक, गीलापन और ट्रिबोलॉजिकल प्रदर्शन का भी मूल्यांकन किया जाता है। इनकोलॉय 925 की एंड मिलिंग में विकसित हाइब्रिड नैनोफ्लुइड के प्रदर्शन की जांच विशिष्ट कटिंग ऊर्जा, कार्बन उत्सर्जन, सतह खुरदरापन, सतह स्थलाकृति, चिप आकारिकी, उपकरण घिसाव, और मशीनी घटकों के सूक्ष्म संरचना, सूक्ष्म कठोरता और अवशिष्ट तनाव के संदर्भ में की जाती है। तैयार हाइब्रिड नैनोफ्लुइड सूखे, बेस तेल और मोनो नैनोफ्लुइड से बेहतर प्रदर्शन करता है। मशीनिंग प्रदर्शन की स्थिरता का मूल्यांकन ट्रिपल बॉटम लाइन दृष्टिकोण के साथ किया जाता है, और यह पाया जाता है कि हाइब्रिड नैनोफ्लुइड सहायता प्राप्त मशीनिंग के तहत उत्पाद स्थिरता सूचकांक तेल सहायता प्राप्त मशीनिंग से 3 गुना और मोनो नैनोफ्लुइड सहायता प्राप्त मशीनिंग से 1.85 गुना अधिक है।

आगे, एक सांख्यिकीय उपकरण, जैसे कि विचरण का विश्लेषण (एनोवा), का उपयोग मशीनिंग प्रदर्शन पर आवेष्टन की त्रिज्या और प्रक्रिया मापदंडों के संयुक्त प्रभावों की जांच करने के लिए किया जाता है। कटिंग मापदंडों और मशीनिंग प्रतिक्रियाओं के बीच गणितीय मॉडल विकसित करने के लिए प्रतिक्रिया सतह पद्धति और कृत्रिम तंत्रिका नेटवर्क (एएनएन) को लागू किया जाता है, और उनके पूर्वानुमान परिणामों की तुलना की जाती है। कृत्रिम तंत्रिका नेटवर्क मॉडल प्रतिक्रिया सतह पद्धति मॉडल की तुलना में अधिक प्रभावी पाए गए हैं। मशीनिंग प्रतिक्रियाओं को अनुकूलित करने के लिए, कृत्रिम तंत्रिका नेटवर्क मॉडल को एक गैर-प्रभुत्व वाली सॉर्टिंग जेनेटिक एल्गोरिदम (एनएसजीए-II) के साथ जोड़ा जाता है। आदर्श समाधान की समानता द्वारा ऑर्डर प्रदर्शन के लिए तकनीक का उपयोग मापदंडों के इष्टतम सेट से सर्वश्रेष्ठ समाधान प्राप्त करने के लिए किया जाता है।

इसके अलावा, अनुकूलित कटिंग मापदंडों पर विभिन्न कटिंग वातावरणों के तहत मशीनी घटकों की गुणवत्ता की जांच करने के लिए, कार्यात्मक प्रदर्शन विशेषताओं जैसे कि ट्रिबोलॉजिकल प्रदर्शन, थकान व्यवहार और इलेक्ट्रोकेमिकल और गर्म संक्षारण व्यवहार का मूल्यांकन किया गया है। यह पाया गया है कि मशीनी घटकों की सतह विशेषताएं, जैसे कि क्षेत्रीय सतह खुरदरापन/स्थलाकृति और अवशिष्ट तनाव, उत्पाद के कार्यात्मक प्रदर्शन के साथ दृढ़ता से सह-संबंधित हैं।

कीवर्ड: इनकोलॉय 925; नैनोफ्लुइड; एमक्यूएल; टीबीएल; एएनएन-एनएसजीए-II; सतह अखंडता; कार्यात्मक प्रदर्शन

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List of Abbreviations

AMGA	Archive-based micro genetic algorithm
ANFIS	Adaptive neuro-fuzzy interface system
ANN	Artificial neural network
ANOVA	Analysis of variance
ASTM	American society for testing and materials
ATR	Attenuated total reflectance
BAC	Bearing area curve
BO	Bayesian optimization
BUE	Built-up edge
CFs	Cutting Fluids
CNC	Computer numerical control
CNO	Coconut oil
CNTs	Carbon nanotubes
COF	Coefficient of friction
CRITIC	Criteria importance through intercriteria correlation
CTAB	Cetyltrimethylammonium bromide
CVD	Chemical vapor deposition
DOE	Design of experiment
DSA	Drop shape analyzer
DTC	Discovery thermal conductivity
DTG	Derivative thermogravimetry
EBSD	Electron backscatter diffraction

EDM	Electric discharge machining
EDS	Energy dispersive X-ray spectroscopy
EMS	Environmental management system
EP	Extreme pressure
FCO	Forced convection oven
FESEM	Field emission scanning electron microscope
FTIR	Fourier transform infrared
GB	Grain boundary
GDP	Gross domestic product
GNB	Gram-negative bacteria
GNO	Groundnut oil
GP	Genetic programming
GRA	Gray relational analysis
HAGB	High-angle grain boundary
hBN	Hexagonal boron nitride
HLB	Hydrophilic-lipophilic balance
HPC	High pressure cooling
HNMQL	Hybrid nanofluid minimum quantity lubrication
HTHC	High-temperature hot corrosion
HUVC	High speed ultrasonic vibration cutting
IARC	International agency for research on cancer
IPF	Inverse pole figure
ISO	International organization for standard

KAM	Kernel average misorientation
LAGB	Low-angle grain boundary
LCF	Low cycle fatigue
LTHC	Low-temperature hot corrosion
MAPE	Mean absolute percentage error
MCDM	Multi-criteria decision making
MFT	Multifunctional tribometer
MID	Mean ideal distance
MOEAs	Multi-objective evolutionary algorithms
MOPSO	Multi-objective particle swarm optimization
MQL	Minimum Quantity Lubrication
MS	Maximum spread
MWF	Metal working Fluid
NCFs	Nano cutting Fluids
NDM	Near-dry machining
NF	Neural-fuzzy
NMQL	Nanofluid minimum quantity lubrication
NPs	Nanoparticles
NSGA-II	Non-dominated sorting genetic algorithm
NTA	Nanoparticle tracking analyzer
OA	Orthogonal array
OCP	Open-circuit potential
OES	Optical emission spectroscopy

OHSMS	Occupational health and safety management systems
OIM	Orientation imaging microscopy
PEG	Polyethylene glycol
ProdSI	Product sustainability index
PSO	Particle swarm optimization
PVC	Poly vinyl chloride
PVD	Physical vapor deposition
PVP	Polyvinylpyrrolidone
RBF	Radial basis function
RBO	Rice bran oil
RCD	Rotating cutting force dynamometer
RMSPE	Root mean square percentage error
RS	Residual stresses
RSM	Response surface methodology
SA	Simulated annealing
SDBS	Sodium dodecyl benzene sulphonate
SDS	Sodium dodecyl sulphate
SEM	Scanning electron microscope
SFO	Sunflower oil
SQL	Small-quantity lubrication
TBL	Triple bottom line
TEM	Transmission electron microscopy
TGA	Thermogravimetric analysis

TLBO	Teaching-learning-based optimization
TOPSIS	Technique for order preference by similarity to the ideal solution
UNS	Unified Numbering System
UV-vis-NIR	Ultraviolet visible near infrared
VI	Viscosity index
VMC	Vertical machining center
XRD	X-ray diffraction