Sustainable Micromilling of Ti6Al4V alloy Using Different Eco-friendly Lubricants with MQL and coated tools

Thesis submitted in partial fulfillment for the

Award of Degree

Doctor of Philosophy

By

Ashutosh Roushan

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI – 221005

Roll No. 15131504

2022

CERTIFICATE

It is certified that the work contained in the thesis titled ***"Sustainable Micromilling of Ti6Al4V alloy Using Different Eco-friendly Lubricants with MQL and Coated Tools"*** by ***"ASHUTOSH ROUSHAN"*** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree. A thesis submitted in partial fulfillment for the Award of Degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy, and SOTA for the award of Ph.D. Degree.

Supervisor
Dr. U. S. Rao
(Associate Professor)
Department of Mechanical Engineering
Indian Institute of Technology
(Banaras Hindu University),
Varanasi-221005, INDIA

Dr. U. SRINIVAS RAO
Associate Professor
Mechanical Engineering Department
Indian Institute of Technology (BHU)
Varanasi-221005

DECLARATION BY THE CANDIDATE

I, ***"ASHUTOSH ROUSHAN"***, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of ***"Dr. U. S. RAO"*** from ***"DECEMBER 2015"*** *to* ***"NOVEMBER 2022"***, at the ***"DEPARTMENT OF MECHANICAL ENGINEERING"***, Indian Institute of Technology (BHU), Varanasi, India. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not wilfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, theses, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

Date: 8/6/2023
Place: Varanasi

Ashutosh Roushan
(ASHUTOSH ROUSHAN)

CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of my knowledge

Supervisor
Dr. U. S. Rao
(Associate Professor)
IIT (BHU), Varanasi, INDIA

Associate Professor
Deptt. of Mechanical Engg.
Indian Institute of Technology (BHU)
Varanasi-221005

Signature of Head of Department

Department of Mechanical Engineering,

विभागाध्यक्ष / HEAD
यान्त्रिक अभियान्त्रिकी विभाग/Deptt. of Mechanical Engg.
भारतीय प्रौद्योगिकी संस्थान/Indian Institute of Technology
(का.हि.वि.o/B.H.U.)
वाराणसी/Varanasi-221005

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: *"Sustainable Micromilling of Ti6Al4V alloy Using Different Eco-friendly Lubricants with MQL and Coated Tools"*

Name of the Student: Ashutosh Roushan

Copyright Transfer

The undersigned hereby assigns to the Indian Institute of Technology (Banaras Hindu University), Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the **Doctor of Philosophy**.

Date: 8/6/2023
Place: Varanasi

Ashutosh Roushan
(Ashutosh Roushan)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for the author's personal use provided that the source and the Institute's copyright notice are indicated.

DEDICATED

To

My Teachers

&

My Family Members

TABLE OF CONTENTS

ABSTRACT

The increased multi-functionality of today's very precise microstructures/components, along with a gradual decline in weight and cost, has made them more attractive in various industries. Several products and features, including micro-slots, microneedles, micro-pins, micro-barbs, microfluidic devices, and microtextured surfaces on biomedical implants, were developed using titanium-based alloys, particularly Ti6Al4V alloy, which found extensive use in the aerospace and biomedical areas. Micromilling used to manufacture complex 3D micro parts and features such as watch making, miniature heat exchanger, micro mould, micro valves, lab-on-chip and micro injection nozzles in a variety of materials. Micro milling is the most flexible process that fabricates three-dimensional microfeatures or components. Moreover, because of the micro tool's minimal diameter (1-999 μm), many factors, including size effect, minimum uncut chip thickness effect, tool run-out, and plowing, impact the chip formation process. The Ti6Al4V alloy's poor thermal conductivity and heat buildup properties promote rapid tool wear, lower the quality of the finished surface, and make it more difficult to machine the material. Two solutions to this problem include introducing hard, wear-resistant coated tools and sustainable cooling and lubrication systems. As an outcome, it is believed that the application of both nanofluid based MQL and coated tools together can enhance the micro-machinability even more, but no related studies have been discovered presently. Also, there is a scope to investigate the impact of hybrid nanofluids (nanofluids where constituent of nanomaterials is more than one) in micro milling of Ti6Al4V. This research uses coated tools and minimum quantity lubrication with eco-friendly vegetable oil and its nanofluids, water-based nanofluids, and vegetable oil-water emulsion to improve micromilling performance. Thus, micromilling tests were performed with uncoated WC and two different coated tools: AlTiN and TiAlN coated

micro end mills. First, the various volume concentrations of CuO nanofluids are made, and their stability, wettability, and viscosity are assessed in reducing the gap. Experimental research was done to evaluate the impacts of the various systems on cutting force, tool wear, surface roughness, and burr formation. Tool wear is analyzed in terms of percentage diameter reduction and various tool wear mechanism such as adhesion, abrasion, grains pull-out, edge chipping, built-up edge, and coating delamination. Uncoated tool in dry conditions is subjected to severe tool wear due to combined influence of residual stress, cyclic loading and abrasion. AlTiN coated tool shows better machining performance in dry conditions due to a lower coefficient of friction and higher hardness. The surface morphology of uncoated and coated tools after machining under 1 vol% CuO nanofluids MQL conditions shows the absence of built-up edge and material adhesion. This happens due to the enhanced lubrication and cooling rate of nanofluids with an increased volume percentage of CuO nanoparticles. The outcomes demonstrated that the AlTiN-coated WC micro end-mill with 0.25 vol% CuO water-based nanofluids significantly reduced surface roughness and cutting forces. Minimum average top burr widths of 9.93 μm and 10.58 μm were found in up milling and down milling, with AlTiN and TiAlN coated WC tools under 0.25 vol% CuO nanofluid based MQL. Using uncoated and coated tools, MQL generated a consistent surface topography with fewer defects.

Another experiment was done to determine how effectively minimum quantity lubrication (MQL) would work by adding CuO and MoS_2 nanoparticles separately and mixing them together with vegetable oil. Further, these nanofluids are utilized in the micromilling of Ti6Al4V under plowing (0.3 μm/tooth feed) and shearing (4 μm/tooth feed) conditions. Results showed that hybrid CuO-MoS_2 nanofluids significantly improved surface finish due to the combined effect of rolling and shearing by CuO

nanoparticles and MoS_2 nanoplatelets. Viscosity, wettability, and coefficient of friction of pure soybean oil and mono and hybrid nanofluids are characterized. The results demonstrated that the addition of CuO and MoS_2 nanoparticles improved the wettability, viscosity, and tribological properties of the cutting fluid and provided a considerable improvement over dry conditions in tool wear, specific cutting force, burr formation, and surface roughness. CuO nanofluid-based-MQL exhibited the best result in the shearing-dominant region by reducing tool wear, burrs, and specific cutting force due to the best wetting nature and rolling action. The surface roughness at 0.3 μm/tooth feed was lessened by about 34.8%, 50.1%, 37.6% and 59.9% using soybean oil MQL, CuO, MoS_2 and CuO-MoS_2 nanofluids MQL compared to dry conditions. Similarly, at 4 μm/tooth feed surface roughness is reduced by about 34.8%, 50.1%, 37.6% and 59.9% using soybean oil MQL, CuO, MoS_2 and CuO-MoS_2 nanofluids MQL compared to dry conditions. For the shearing regime at 4 μm/tooth feed, CuO and MoS_2 NF-MQL were found more effective for adhesion wear than vegetable oil MQL and dry conditions. However, for plowing regime at 0.3 μm/tooth feed, pure soybean oil MQL reduces tool adhesion through proper lubrication. Surface topography has also shown smoother with fewer feed marks and surface defects for hybrid nanofluids due to synergistic effect produced by the spherical CuO and the lamellar MoS_2, as well as by the improvement in the effectiveness of the interfacial slipping action mechanism.

The objective of the final section of this study was to select the appropriate emulsion for Ti6Al4V alloy micromilling at a specific flow rate and a range of spindle speeds, as well as to evaluate micromilling performance in terms of cutting force, burr formation, surface roughness, and surface topography. It has been observed that significant cutting force, surface roughness, and burr reduction occur using emulsions (paraffin oil-water emulsion and soybean oil-water emulsion) at different flow rates.

ACKNOWLEDGEMENT

The author is pleased to express his sincere thanks and gratitude beyond words to his supervisor Dr. U. S. Rao for his consistent help, encouragement and valuable discussions during the entire period of his research work. The author would not have been able to complete the thesis without his utmost involvement and invaluable efforts. He motivated the author to pursue research problems and the need for persistent effort to accomplish the goal. The author is truly indebted to him.

Besides supervisors, the author would like to thank his RPEC members, Dr. Meghanshu Vashista and Dr. C. K. Behera for their insightful comments and encouragement. The author is very much thankful to Prof. Karali Patra, Mechanical Engineering Department, IIT Patna, for providing Experimental facility. The author acknowledges his deep sense of gratitude to the current and former Heads of the Department of Mechanical Engineering for providing all the research facilities to accomplish his research in the Department successfully. The author has an immense sense of gratitude to all the faculty members of the Department of Mechanical Engineering, IIT (BHU), Varanasi for their cooperation and inspiration.

The author is grateful to all his friends Mr. Priyabrata Sahoo, Mr. Homender Kumar, Mr. Sooraj Singh Rawat, Mr. Akash Awale, Mr. Ashwani Ranjan, Mr. Miraz, Mr. Asgar Shakil Khan, Mr. Jitendra Kumar Singh, Mr. B. Rajak, Mr. Ajit Jha, Mr. Anupam Tiwari, Mr. Adarsh and Mr. Partha Sarathi Mallick, Mr. Nitesh Dubey and seniors especially Mr. Siddharth Yadav and Mr. Manish Deo for their constant encouragement, making joyful and memorable life being with him in moments of happiness and difficulties at IIT (BHU), Varanasi. The author is also thankful to all the lab and office staff of the department, especially Mr. Rajendra Prasad (Production lab).

The author would also like to express his immense gratitude to his parents Smt. Lilawati Devi and Shri Ram Gopal Prasad, wife Chanda Kumari, lovely Son Chinu, and other family members for their unconditional support and encouragement, to pursue his interest. The author also wishes to thank all those who have helped in any manner during the course of his research work.

(ASHUTOSH ROUSHAN)

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREAVIATIONS/SYMBOLS

FIB	Focused ion beam
WEDM	Wire electric discharge machine
LIGA	Lithography-electroplating-molding
PLA	Pulsed laser ablation
MQL	Minimum quantity lubrication
PVD	Physical vapor deposition
MUCT	Minimum uncut chip thickness
RMS	Root mean square
P-V	Peak-to-valley
CVD	Chemical vapor deposition
DAQ	Data Acquisition System
WC	Tungsten carbide
SEM	Scanning electron microscope
EDS	Energy dispersive spectroscopy
XRD	X-Ray diffraction
TEM	Transmission electron microscope
DLS	Dynamic light scattering
SDS	Sodium dodecyl sulfate
NF-MQL	Nanofluids minimum quantity lubrication
COF	Coefficient of friction
CuO	Copper oxide
MoS_2	Molybdenum disulfide
SO+DIW	Soybean oil-water emulsion
PO+DIW	Paraffin oil-water emulsion
AlTiN	Aluminum Titanium Nitride
TiAlN	Titanium Aluminum Nitride

Symbols used

mm	Millimeter
HV	Viker's Hardness
μm	Micrometer
θ	Theta
Sec	Second
Min	Minute
T	Temperature
F_x, F_y	Forces (N) in feed and perpendicular to feed directions
f_z	Feed per flute (μm/tooth)
n	Spindle speed (RPM)
d	Diameter of tool (mm)
Z_c	Number of flutes
γ_{sv}, γ_{sl}, γ_{lv},	Surface tension among solid-vapor, solid-liquid, liquid-vapor states
R_a	Roughness average
S_a	Arithmetical mean of the surface