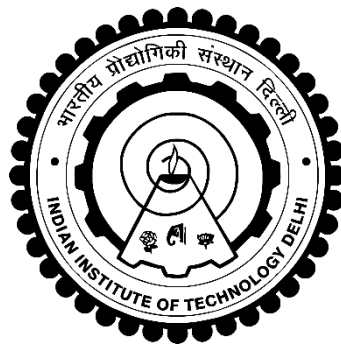


EXPERIMENTAL INVESTIGATION OF SEQUENTIAL LASER AND CONVENTIONAL MICROMACHINING PROCESSES

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**DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
MARCH 2022**

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by

ASHISH KUMAR SAHU

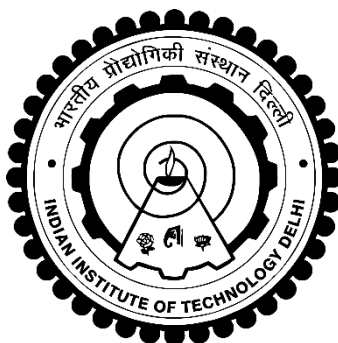
Department of Mechanical Engineering

Submitted

In fulfillment of the requirements of the degree of

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Philosophy to the



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Dedication

*The thesis is dedicated to my beloved father, Late Shri Narayan Prasad Sahu,
who believed in me and always shown the right path in life.*



CERTIFICATE

This is to certify that the thesis entitled “Experimental Investigation of Sequential Laser and Conventional Micromachining Processes” submitted by Mr. Ashish Kumar Sahu to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy, in the Department of Mechanical Engineering is a record of bonafide original research work carried out by him under my guidance and supervision.

The results contained in it have not been submitted in part or full to any other institute or university for the award of any degree/diploma.

Prof. Sunil Jha

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(Ashish Kumar Sahu)

ABSTRACT

Microchannels have applications in micro-heat exchangers, -coolers, -heat tubes, gas turbine blade cooling, automotive cooling, chemical reactors, microelectronics, flow boiling heat transfers, liquid flow in biomedical on titanium and its alloys. Common manufacturing techniques for microchannels are tool based mechanical cutting, wet and dry etching, lithography embossing, imprinting, injection molding and laser micromachining. Microchannel manufacturing faces many challenges in tool-based micromachining techniques related to the cutting forces, burrs, surface finish, tool failure, integrity of channels geometry, and other post-processing requirements. To tackle such problems, laser micromachining has been evolved and enabled to solve the problems to a wide extent. However, high temperature inherited with the process severely changes the surface roughness, surface integrity, and micro-structure, affecting the channel's quality. A laser-based sequential process can provide an alternative technique to overcome the limitations of both methods. In the present study, laser-based hybrid methods have been developed for the fabrication of microchannels on titanium by considering challenges with conventional tool and laser-based manufacturing techniques. An advanced micromachining system is developed for hybrid processes equipped with in-situ measurement system.

In the present dissertation, the thermal ablation mechanism of the laser micro milling process has been studied by a finite element-based heat transfer model to predict the geometrical parameters of microchannel by simulating the temperature and compared with experimental results. Two-stage phase transformations of material state have been considered in simulation at varied heat flux levels considering the thermophysical properties of a phase.

Further parametric study of the laser micro milling process has been carried out to analyze the effect of pulse repetition rate, scanning velocity, scanning times, assist gas pressure on microchannels quality, i.e., top kerf width, taper, surface roughness, and metal removal rate. Thermal stress was also studied by analyzing the surface cracks of microchannels through scanning electron microscopy. In addition, redeposition was observed on the titanium surface at a slower scanning velocity and pulse repetition rate. Oxidation degrades the surface integrity and affects aspect ratio of micro-channels.

Extensive experimental work has been done in the present study by using laser pre channel micro milling (LPCMM) and laser assisted sequential micro milling (LASMM) in overcoming the problems of laser micro milling for microchannel fabrication. In both processes, the lower cutting forces and top burr width were observed on microchannels edges than conventional micro milling (CMM). The resultant cutting force decreased by 24% and 60% in LASMM and LPCMM methods compared to CMM. A comparison of both processes was carried out at varied cutting speed and tool feed.

Further, a laser assisted micro grinding (LAMG) approach using a micro pencil grinding tool has been used sequentially and compared with conventional micro grinding (CMG). The impact of laser structuring on CMG forces and surface finish demonstrated the superior performance of the LAMG process. The microchannel obtained with LAMG has better dimensional accuracy and surface finish at lower tangential and normal force. Increasing laser input energy density reduced the forces at cost of surface finish.

Keywords: laser micromachining, laser assisted machining, microchannels, sequential machining, laser machining, micro milling, micro grinding

सार

टाइटेनियम और उसकी मिश्र धातुओं पर बनाए गए माइक्रो चैनलों का उपयोग माइक्रो -ऊष्मा विनिमायक, शीतक, माइक्रो-हीट एक्सचेंजर्स, -कूलर, -हीट ट्यूब, गैस टर्बाइन ब्लेड कूलिंग, ऑटोमोटिव कूलिंग, केमिकल रिएक्टर, माइक्रोइलेक्ट्रॉनिक्स, फ्लो बॉयलिंग हीट ट्रांसफर, बायोमेडिकल में तरल प्रवाह के अनुप्रयोग हैं। माइक्रो चैनल के लिए सामान्य निर्माण तकनीकों उपकरण आधारित यांत्रिक कटाई, गीली और सूखी नक्काशी, लिथोग्राफी एम्बॉसिंग, इम्प्रिंटिंग, इंजेक्शन मोल्डिंग और लेजर माइक्रो मशीनिंग हैं। माइक्रो चैनल निर्माण को टूल-आधारित माइक्रोमशीनिंग तकनीकों में कटिंग बल, बर्, सतह परिष्करण, टूल फेल्योर, चैनल ज्यामेट्री की अखंडता और अन्य पोस्ट-प्रोसेसिंग आवश्यकताओं से संबंधित कई चुनौतियों का सामना करना पड़ता है। ऐसी समस्याओं से निपटने के लिए, लेजर माइक्रोमशीनिंग विकसित की गई है, जो समस्याओं को व्यापक रूप से हल करने में सक्षम है। हालांकि, प्रक्रिया के साथ मिला उच्च तापमान सतह की खुरदरापन, सतह की अखंडता और माइक्रो संरचना को गंभीर रूप से बदल देता है, जिससे चैनल की गुणवत्ता प्रभावित होती है।

एक लेजर-आधारित अनुक्रमिक प्रक्रिया दोनों विधियों की कमियों को दूर करने करने के लिए एक वैकल्पिक तकनीक प्रदान कर सकती है। वर्तमान अध्ययन में, पारंपरिक उपकरण और लेजर-आधारित निर्माण तकनीकों के साथ चुनौतियों पर विचार करके टाइटेनियम पर माइक्रोचैनल के निर्माण के लिए लेजर-आधारित हाइब्रिड विधियों का विकास किया गया है। इन-सितु मापन प्रणाली से लैस हाइब्रिड प्रक्रियाओं के लिए एक उन्नत माइक्रोमशीनिंग प्रणाली विकसित की गई है।

वर्तमान शोध प्रबंध में, तापमान का अनुकरण करके और प्रयोगात्मक परिणामों की तुलना में माइक्रोचैनल के ज्यामितीय मापदंडों की भविष्यवाणी करने के लिए एक परिमित तत्व-आधारित गर्मी हस्तांतरण मॉडल द्वारा लेजर माइक्रो मिलिंग प्रक्रिया के थर्मल एल्लेशन तंत्र का अध्ययन किया गया है। भौतिक अवस्था के दो-चरण परिवर्तनों को प्रत्येक चरण के थर्मोफिजिकल गुणों पर विचार करते हुए विभिन्न ताप प्रवाह स्तरों पर अनुकरण में माना गया है।

पल्स पुनरावृत्ति दर, स्कैनिंग वेग, स्कैनिंग समय और सहायक गैस के दबाव के प्रभाव का विश्लेषण करने के लिए लेजर माइक्रो मिलिंग प्रक्रिया का आगे पैरामीट्रिक अध्ययन माइक्रोचैनल गुणवत्ता अर्थात् शीर्ष केर्फ चौड़ाई, टेपर, सतह खुरदरापन और धातु हटाने की दर पर किया गया है। स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी के माध्यम से माइक्रो चैनलों की सतह दरारों का विश्लेषण करके थर्मल तनाव का भी अध्ययन किया गया था। इसके अलावा, टाइटेनियम सतह पर धीमी स्कैनिंग वेग और पल्स पुनरावृत्ति दर पर पुनर्वितरण देखा गया था। ऑक्सीकरण सतह की अखंडता को कम करता है और माइक्रो चैनलों के पहलू अनुपात को प्रभावित करता है।

वर्तमान अध्ययन में माइक्रोचैनल निर्माण के लिए लेज़र प्री चैनल माइक्रो मिलिंग (एलपीसीएमएम) और लेजर असिस्टेड सीकेंशियल माइक्रो मिलिंग (एलएसएमएम) का उपयोग करके, लेजर माइक्रो मिलिंग की समस्याओं को कम करने व्यापक प्रयोगात्मक कार्य किया गया है। दोनों प्रक्रियाओं में, पारंपरिक माइक्रो मिलिंग (सीएमएम) की तुलना में कम मशीनन बल और शीर्ष बर् माइक्रो चैनल किनारों पर देखा गया है। परिणामी काटने के बल में 24% और 60% की कमी में एलपीसीएमएम LASMM और एलएसएमएम विधियों सीएमएम की तुलना में आई। दोनों प्रक्रियाओं की तुलना विभिन्न काटने की गति और उपकरण फ़ीड पर किया गया था।

इसके अलावा, लेजर सहायता प्राप्त माइक्रो ग्राइंडिंग (एलएमजी) प्रक्रिया में, एक माइक्रो पेंसिल ग्राइंडिंग उपकरण का उपयोग का अनुक्रमिक रूप से किया गया है और पारंपरिक माइक्रो ग्राइंडिंग (सीएमजी) के साथ तुलना की गई है। लेजर संरचना का प्रभाव कम मशीनन बलों और बेहतर सतह परिष्करण, एलएमजी प्रक्रिया का बेहतर प्रदर्शन है। एलएमजी माइक्रोचैनल बेहतर आयामी सटीकता और सतह, कम स्पशरिखा और सामान्य बल के साथ प्राप्त होता है। बढ़ती हुई लेजर इनपुट ऊर्जा घनत्व, सतह परिष्करण की लागत पर **मशीनन** बलों को कम कम करती है।

कीवर्ड: लेजर माइक्रो मशीनन, लेजर सहायता प्राप्त मशीनन, माइक्रोचैनल, अनुक्रमिक मशीनन , लेजरमशीनन , माइक्रो मिलिंग, माइक्रो ग्राइंडिंग

Table of Contents

Certificate	i
Acknowledgement	ii
Abstract	iv
List of figures	xvi
List of tables	xvix
Abbreviation	xxii
CHAPTER 1	1
INTRODUCTION AND LITERATURE REVIEW	1
1.1 Introduction	1
1.2 Microchannel fabrication methods	3
1.2.1 Mechanical micromachining	3
1.2.2 Lithography	3
1.2.3 Wet and dry etching	4
1.2.4 Embossing and imprinting	4
1.2.5 Injection molding	5
1.2.6 Laser micromachining	6
1.3 Laser micromachining process	6
1.3.1 Mechanism	7
1.3.2 Challenges in LBM	8
1.3.3 Need for hybrid machining processes	10

1.4 Laser-based hybrid micromachining processes	12
1.4.1 Laser assisted hot machining	15
1.4.1.1 Laser assisted turning	15
1.4.1.2 Laser assisted milling	16
1.4.1.3 Laser assisted grinding	17
1.4.1.4 Laser assisted electrochemical machining	18
1.4.2 Laser structuring prior to conventional machining	19
1.4.2.1 Laser structuring in milling	19
1.4.2.2 Laser structuring in grinding	20
1.4.3 Sequential laser machining method	20
1.4.3.1 Sequential LBM and conventional micro-drilling	20
1.4.3.2 Sequential LBM and EDM machining processes	21
1.5 Literature review	22
1.5.1 Modeling of laser beam machining process	23
1.5.2 Parametric analysis of laser micro milling process	25
1.5.3 Laser-based hybrid milling method	28
1.5.4 Laser-based hybrid grinding method	32
1.6 Research gap	34
1.7 Objective of the present work	36
1.8 Thesis organization	37
 CHAPTER 2	 40

DESIGN AND DEVELOPMENT OF LASER MICROMACHINING SYSTEM WITH INTEGRATED IN-SITU METROLOGY	40
2.1 Introduction	40
2.2 Development of laser micromachining system	40
2.2.1 Selection of laser beam source	41
2.2.1.1 Comparison of laser source from different manufacturers	43
2.2.2 Optics selection	44
2.2.2.1 Collimator	44
2.2.2.2 Beam Expander	44
2.2.2.3 Fine cutter with focusing lens	45
2.2.3 Integration in AMMS	48
2.2.3.1 High-speed micromachining tool	48
2.2.4 In-situ metrology system	50
2.2.4.1 Microscope	51
2.2.4.2 Confocal sensor	51
2.2.4.3 Calibration and validation of confocal sensor	52
2.5 In-situ measurements comparison between confocal sensor and microscope	53
2.5.1 Experimental procedure	53
2.5.2 Measurement method	55
2.6 Result and discussion	58
2.6.1 Comparison of width measurement between confocal sensor and microscope	58

2.6.2 Comparison of depth measurement by confocal sensor and microscope	59
2.6.3 Surface roughness measurement by the confocal sensor	60
2.6.4 MRR analysis	61
2.7 Conclusion	63
 CHAPTER 3	 65
 MODELING AND SIMULATION OF TEMPERATURE IN LASER MICRO	
MILLING PROCESS	65
3.1 Introduction	65
3.2 Mechanism of LBM machining	66
3.3 Computational modeling of temperature	68
3.3.1 Initial condition and assumptions	68
3.3.2 Numerical simulation	69
3.3.3 Finite element model	73
3.4 Experimentation work	75
3.4.1 Laser micro milling experimentation	75
3.4.2 Profile measurement	75
3.5 Result and discussion	77
3.5.1 Temperature distribution along the width and depth direction of microchannel	78
3.5.2 Simulation result	79
3.5.3 Validation of simulated result	82
3.6 Conclusion	85

CHAPTER 4	87
PARAMETRIC STUDY OF LASER MICRO MILLING PROCESS	87
4.1 Introduction	87
4.2 Materials and methods	87
4.2.1 Methodology	87
4.2.2 Design of experiments	89
4.3 Results and discussion	92
4.3.1 Regression analysis	92
4.3.2 Effect of process parameters on MRR	96
4.3.2.1 Interaction effect of process parameter on MRR	98
4.3.3 Effect of process parameters on average surface roughness	99
4.3.3.1 Interaction effect of process parameters on surface roughness (Ra)	101
4.3.4 Effect of process parameters on taper (θ)	103
4.3.4.1 Interaction effect of process parameters on taper	104
4.3.5 Effect plot of process parameters on top kerf width	106
4.3.5.1 Interaction effect of process parameters on top kerf width	107
4.3.6 Validation of regression Model	108
4.3.7 Surface characterization	109
4.3.7.1 Oxidation zone width	109
4.3.7.2 Surface Morphology	109
4.4 Conclusion	112

CHAPTER 5	114
SEQUENTIAL LASER MICRO MILLING AND CONVENTIONAL MICRO MILLING	114
5.1 Introduction	114
5.2 Materials and methods	116
5.3 Comparison between CMM, LPCMM and LASMM methods	119
5.3.1 Force	120
5.3.2 Top burr width	121
5.3.3 Surface roughness	124
5.3.4 Surface morphology	125
5.3.5 Tool wear	128
5.4 Comparison of LASMM and LPCMM methods with varying cutting speed and tool feed	130
5.4.1 Effect of cutting speed and tool feed on down burr width	131
5.4.2 Effect of cutting speed and tool feed on up burr width	133
5.4.3 Effect of cutting speed and tool feed on surface roughness	134
5.4.4 Effect of cutting speed and tool feed on tool diameter	136
5.4.5 Effect of cutting speed and tool feed on tool wear	137
5.5 Conclusion	139
CHAPTER 6	142

SEQUENTIAL LASER MICRO MILLING AND CONVENTIONAL MICRO GRINDING METHOD	142
6.1 Introduction	142
6.2 Materials and methods	143
6.2.1 Sequential grinding method and parameters	143
6.2.2 Laser scan strategy	145
6.2.3 Grinding tool and workpiece	146
6.2.4 Experimentation	146
6.3 Result and discussion	147
6.3.1 Laser structuring	147
6.3.2 Effect of laser structuring on cutting forces in micro grinding	149
6.3.3 Effect of laser structuring on surface roughness	151
6.3.4 Effect of laser input energy density on cutting forces	152
6.3.5 Effect of laser input energy density on surface roughness	154
6.3.5 Surface morphology analysis	155
6.4 Conclusion	158
CHAPTER 7	160
CONCLUSION AND FUTURE SCOPE	160
7.1 Conclusion	160
7.2 Future Scope	162

References	164
 APPENDIX-A	 176
(Related to Simulation of laser micro milling)	
APPENDIX-B	181
(Related to parametric analysis of laser micro milling)	
PATENTS, PUBLICATIONS AND AWARDS	183
AUTHOR BIOGRAPHY	186

LIST OF FIGURES

Fig. 1.1(a) Embossing(b) Imprinting	5
Fig. 1.2 Mechanism of the laser pulse and material interaction	7
Fig. 1.3 LBM process parameters and responses.....	10
Fig. 1.4 Laser-based hybrid machining processes classification.....	13
Fig. 1.5 Schematics laser assisted turning method	16
Fig. 1.6 Schematic of laser assisted milling method.....	17
Fig. 1.7 Laser assisted grinding	18
Fig. 1.8 LAJECM process mechanism.....	19
Fig. 1.9 Sequential laser drilling and conventional drilling method.....	21
Fig. 1.10 Sequential LBM and EDM machining method.....	22
Fig. 2.1 Optics component (a) Beam delivery optics with F50 collimator (b) Beam expander (c) Fine cutting head	45
Fig. 2.2 (a) CAD drawing of optic system (b) laser beam flow diagram	47
Fig. 2.3 Developed AMMS system (a) CAD of AMMS (b) AMMS(c) Integrated CNC system	50
Fig. 2.4 Roughness standard of Taylor Hobson.....	53
Fig. 2.5(a) Schematic of laser micromachining (b) Measurement method by confocal sensor ..	55
Fig. 2.6(a) Positions of the confocal sensor for width and depth measurements (b) Surface roughness measurement.....	56
Fig. 2.7 Algorithm to calculate average surface roughness from the data obtained by confocal sensor	57

Fig. 2.8 Comparison of measurement of width by confocal sensor and microscope	59
Fig. 2.9 Comparison of measurement of depth by confocal sensor and microscope	60
Fig. 2.10 Roughness variation with scanning speed and no of scans	61
Fig. 2.11 (a) Cross-section area measurement method of microchannel by 3D profilometer	62
Fig.3.1 Mechanism of machining	67
Fig. 3.2 Finite element mesh of 3D geometry in the coordinate system	73
Fig. 3.3 Channel profile at 81.38 kW/mm^2 measured with the confocal sensor.....	77
Fig. 3.4 Temperature variation with flux along width direction from the center of the laser beam.....	78
Fig. 3.5 Temperature variation with flux along depth direction from the top surface.....	79
Fig. 3.6 Simulated microchannel profile of ablated material at laser flux 54.27 kW/mm^2	81
Fig. 3.7 Simulated microchannel profile of ablated material at laser flux 108.52 kW/mm^2	81
Fig. 3.8 Comparison of predicted and experimental result for crater width.....	84
Fig. 3.9 Comparison of predicted and experimental result for ablation depth	84
Fig .4.1 (a) Geometrical dimension of microchannel (b) Measurement of responses.....	88
Fig. 4.2 Main effect plot on MRR	97
Fig. 4.3 Factor contribution on MRR	97
Fig. 4.4 Impact of SV and PRR on MRR	99
Fig. 4.5 Impact of SV and air pressure on MRR	99
Fig. 4.6 Influence of air pressure and PRR.....	99
Fig. 4.7 Main effect plot of Ra.....	100
Fig. 4.8 Factor contribution on Ra.....	101

Fig. 4.9 Effect of Air pressure and PRR on Ra.....	102
Fig. 4.10 Effect of No of scans and PRR on Ra	102
Fig. 4.11 Effect of SV and PRR on Ra	102
Fig. 4.12 Effect of scanning times and velocity	102
Fig. 4.13 Main effect plot for taper angle(θ)	103
Fig. 4.14 Factor contribution on taper	104
Fig. 4.15 Effect of air Pressure and PRR on taper(θ)	105
Fig. 4.16 Effect of scanning times and PRR on taper.....	105
Fig. 4.17 Effect of air pressure and scanning times on taper(θ)	105
Fig. 4.18 Mean effect plot for microchannel width(θ)	106
Fig. 4.19 Factor contribution on the width	107
Fig. 4.20 Interaction effect of air pressure and SV on W_t	108
Fig. 4.21 Oxidation zone width analysis.....	109
Fig. 4.22 Surface morphology variation with machining parameters.....	111
Fig. 5.1(a) Schematics of hybrid micro milling method (b) Machining setup (c) Strategies for channel fabrication	117
Fig. 5.2(a)Laser scanning strategy (b)Profiles of channels fabricated by different methods (c)Burr measurement method s(d)Profile of LMM removed material in LASMM from each layer	119
Fig. 5.3 Comparison of Methods (a) Cutting force (b)Down burr width (c)Up burr width(d) Burr ratio	122
Fig. 5.4 Surface roughness comparison	125

Fig. 5.5 SEM micrograph of burrs, the bottom surface, tool morphology and EDX analysis of bottom surface.....	127
Fig. 5.6 Down burr width comparison (a) LASMM(b) LPCMM.....	132
Fig. 5.7 Top burr comparison (a)LASMM(b) LPCMM	133
Fig. 5.8 Roughness parameters Sa and Sq comparison (a) LASMM(b) LPCMM	135
Fig. 5.9 Tool dia. comparison (a) LASMM(b) LPCMM.....	136
Fig. 5.10 Tool wear comparison with machining length at 80,000RPM amd 40mm/min tool feed (a) LASMM (b) LPCMM	139
Fig. 6.1(a) Sequential micro grinding process and laser path(b) Experiment steps.....	144
Fig. 6.2 Laser scan pattern for laser structuring	145
Fig. 6.3 Laser structured surface 20W	148
Fig. 6.4 Effect of laser power with pattern 1 at tool $f=2\text{mm/min}$, $a_p=5\mu\text{m}$ and $v_s=80\text{mm/min}$ on cutting forces.....	150
Fig. 6.5 Effect of laser power with pattern 1 at tool $f=2\text{mm/min}$, $a_p=5\mu\text{m}$ and $v_s=80\text{mm/min}$ on roughness	151
Fig. 6.6 Effect of laser input energy density on pattern 1 and 2 at $f=2\text{mm/min}$, $a_p=5\mu\text{m}$ and $v_s=80\text{mm/min}$, Laser power 15W (a) Normal force (a) Tangential force.....	153
Fig. 6.7 Effect of laser input energy density on pattern 1 and 2 at $f=2\text{mm/min}$, $a_p=5\mu\text{m}$ and $v_s=80\text{mm/min}$, Laser power 15W surface roughness	154
Fig. 6.8 CMG process SEM micrograph $v_s=80\text{mm/min}$, $f=2\text{ mm/min}$ and $a_p=5\mu\text{m}$	155

LIST OF TABLES

Table 2. 1 Laser selection based on literature review	42
Table 2.2 Laser model available with different manufacturers	43
Table 2.3 Specifications of high-speed aerostatic spindle	50
Table 2. 4 Confocal sensor specifications	52
Table 2.5 Experimental conditions	54
Table 3.1 Properties of Ti6Al4V used in simulation.....	73
Table 3.2 Comparison of experimental and simulated results.....	82
Table 4.1 Factor considered and their levels.....	90
Table 4.2 Experiment run and responses.....	91
Table 4.3 Other ANOVA parameters.....	93
Table 4.4 Sequential model sum of square of responses.....	93
Table 4.5 ANOVA for MRR (after filtering insignificant terms).....	94
Table 4.6 ANOVA for surface roughness (after filtering insignificant terms).....	95
Table 4.7 ANOVA for Taper (after filtering insignificant terms).....	95
Table 4.8 ANOVA for Top kerf width (after filtering insignificant terms).....	95
Table 4. 9 Confirmation run for the developed models.....	108
Table 5.1: Micro milling tool specification CMTec CESS 2p.....	118
Table 5.2 Experimental Condition and tool specifications.....	120
Table 5.3 Hybrid machining parameters	130
Table 5.4 Experimental plan	131
Table 6.1 Micro grinding tool specification Nakanishi diamond burr 12005	144

Table 6.2 Hybrid machining parameters.....	147
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Abbreviation

LMM laser micro milling

HMG hybrid micro grinding

LASMM laser assisted sequential micro milling

LPCMM pre laser channel micro milling

CMM conventional micro milling

LHMM Laser-based hybrid micromachining

ns nanosecond

CMG conventional micro grinding

LBM laser beam machining

HAZ heat affected zone

PRR pulse repetition rate

LAM laser assisted milling

LAG laser assisted grinding

LAECM laser assisted electro chemical machining

CW continuous wave

FEA finite element analysis

AMMS advanced micromachining system

ANOVA analysis of variance

SV scanning velocity

LAMG laser assisted micro grinding