

***Design of an Integrated Process Chain to
Support the Manufacturing of Ti6Al4V Components***

**Von der Fakultät für Maschinenbau, Elektrotechnik und Wirtschaftsingenieurwesen
der Brandenburgischen Technischen Universität Cottbus
zur Erlangung des akademischen Grades eines Doktor-Ingenieurs (Dr.- Ing.)**

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Vorwort des Herausgebers

Die Automatisierungstechnik bildet eine Schlüsseltechnologie für die Steigerung der Produktinnovation und die Verbesserung von Wertschöpfungsprozessen. Als Konsequenz einer globalen Wirtschaftsstruktur müssen alle Unternehmensbereiche wie Entwicklung, Produktion und Güterverkehr in einen übergreifenden Kontext gestellt und behandelt werden. Dabei steht die informationstechnische Verknüpfung verbundener Unternehmen und Unternehmensbereiche bei stetig veränderlichen Aufgabenstellungen und Randbedingungen eine besondere Herausforderung dar. Die Automatisierung des betrieblichen und betriebsübergreifenden Informationsflusses sowie die Einbindung des Menschen in allen Phasen des Entwicklungs- und Leistungsprozesses bildet daher die vordringliche Aufgabenstellung für Forschung und Entwicklung. Durch den zielgerichteten, systematischen Einsatz und die ständig aktualisierte Beurteilung und Bewertung automatisierungstechnischer Lösungen wird die schnelle Umsetzung und Einführung hochwertiger und zukunftsweisender Innovationen gesichert.

Ziel der Forschungsarbeiten am Lehrstuhl Automatisierungstechnik der Brandenburgischen Technischen Universität Cottbus (BTU) ist die kontinuierliche Verbesserung der automatisierungstechnischen Methoden und Verfahren im Hinblick auf fortgeschrittene Produktionsstrukturen. Ein weiterer Schwerpunkt ist die Entwicklung integrierter Fertigungs- und Montagesysteme unter Einsatz neuartiger Steuerungstechnik. Dazu werden leistungsfähige Entwurfswerkzeuge der *Digitalen Fabrik* erprobt und weiterentwickelt. Durch die Bereitstellung modernster Laborausstattung und die Zusammenarbeit mit industriellen und institutionellen Technologieführern wird der Stand der Technik in Wissenschaft und Forschung aktualisiert abgebildet. Nationale und internationale Forschungsarbeiten zu ganzheitlichen Automatisierungskonzepten, den *Industrial Life Cycle Automation*, runden das Aufgaben- und Leistungsspektrum des Lehrstuhls ab.

Die in dieser Buchreihe erscheinenden Bände stammen aus den Forschungsarbeiten des Lehrstuhls Automatisierungstechnik der BTU Cottbus. In diesen Bänden werden neue Resultate und Erkenntnisse aus Forschung und Entwicklung veröffentlicht. Die Berichte aus dem Lehrstuhl Automatisierungstechnik sollen Forschung, Entwicklung und Anwendung zu automatisierungstechnischen Fragestellungen enger verknüpfen und daraus Potential für zukünftige Innovationen erzeugen.

Ulrich Berger

Kurzfassung

Komplexe Mehrwerterzeugnisse, die aus Materialien mit attraktiven Eigenschaften, wie hohe Festigkeit, niedrige Dichte und eine gute Korrosionsbeständigkeit gefertigt werden, sind für die effektive Herstellung innovativer Produkte von besonderer Bedeutung. Dazu wurden in letzter Zeit vornehmlich in der Fahrzeugindustrie Titanlegierungen eingeführt, um leichtere und umweltfreundliche Fahrzeuge produzieren zu können. In der Flugzeugindustrie werden beispielsweise für die Herstellung von Triebwerken Vierzig Prozent Titanlegierungen verwendet. Gegenwärtig ist das Design des Flugzeugtriebwerkes so ausgereift, dass sich die Hersteller auf die Produktivitätssteigerung und die Entwicklung neuer Technologien und Prozesse konzentriert haben. Das beinhaltet insbesondere die Schaffung neuen Fertigungsstrategien und Prozessketten.

Die Einführung von Materialien mit hohen Leistungsfähigkeiten ist eine neue Herausforderung für die Fertigungstechnologie, da diese Materialien schwer zu zerspannen sind und die Prozesse durch ein hohes Wissen über die Materialeistung gekennzeichnet sind. Eine Kostreduzierung ist nur möglich, wenn das Erfahrungswissen für die Prozessplanung systematisch erfasst und damit wieder verwendbar wird.

Zurzeit ist ein Trend zur Herstellung von Industrieprodukten mit Mikro-Komponenten und Mikro-Features in verschiedenen Bereichen, wie zum Beispiel in der Fahrzeugindustrie, in der Flugzeugindustrie und in der Biomedizintechnik, zu beobachten. Die Komplexität der Prozessplanung wird allein schon durch die Mikrobearbeitung erhöht, da viele dieser Prozesse, wenn es um die Fertigung von 3D-Freiformen auf hartem Metall geht, eingeschränkt sind.

In der vorliegenden Arbeit wurde eine Systematik zur Unterstützung der Planung von Fertigungsprozessen entwickelt, die speziell auf die kostengünstige Herstellung von Titankomponenten abzielt. Dazu wurden folgenden Schwerpunkte untersucht:

- Analyse der Fertigungsprozesse zur Herstellung von Verdichterschaufeln aus Titanlegierungen und Entwurf einer Prozesskette für die kostenoptimierten Produktion dieser Komponenten.
- Untersuchung des Fertigungsprozesses zur Herstellung von Mikrofeatures, die beispielsweise die Eigenschaften von Verdichterschaufeln verbessern können.
- Entwicklung einer integrierten Methodologie auf Basis des Axiomatik-Designs zur Steigerung der Produktivität und damit der Reduktion der Kosten zur Herstellung von Makrokomponenten und Mikrofeatures.
- Schaffung einer Datenbasis zur Erfassung von Fertigungswissen, welches bei der Entwicklung der Prozesskette benutzt wird. Diese Datenbasis wird mithilfe eines semantischen Netzes benutzerfreundlich dargestellt.

Im Ergebnis dieser Arbeit lassen sich verschiedene integrierte Prozesse zur Herstellung von Titankomponenten hinsichtlich der Produktivität, der Technologie, des Ressourceneinsatzes und der Prozessparameter optimieren.

Abstract

Nowadays, the industry evolves towards the production of complex components with added value; most of them are made of materials with higher capabilities, such as the titanium alloys. Titanium alloys have attractive characteristics, e.g. high strength, low density and good corrosion resistance, which offer many potential applications. In the automotive industry, titanium alloys have been recently introduced with the aim of developing new vehicles with reduced weight, and thus optimized fuel consumption. In the aerospace industry, titanium alloys are currently the most used materials in aero engines, with a volume fraction of approximately 40%. On the one hand, the maturity in the aero engine design has been reached to a point where the manufacturers are focusing more on productivity, which implies the development of new technologies and processes, thus the development of new manufacturing strategies and new process chains. The introduction of materials with new capabilities represents challenges for the manufacturing technologies as these materials are difficult to machine. Their processes are defined and characterised only when knowledge and deep understanding about the material performance is available. And cost minimisation can take place when manufacturing knowledge is retrieved and reused in the process planning. On the other hand, more and more micro components and micro features have been introduced into diverse types of industrial products and market sectors. Micro components and micro features are used in the aerospace and automotive industry and for medical and biomedical applications. There are several micro manufacturing processes but they are quite limited to machine 3D free-form micro structures in a wide range of materials, mainly hard metals. Thus, a combination and integration of micro manufacturing processes is required.

Thus, facing these challenges, the aim of this work is to design an integrated process chain to support the manufacturing of titanium components using a formal approach. Such approach may include a scientific method to fulfil design and quality requirements and minimise costs; and a tool to retrieve, characterise and share relevant engineering data, generated during the manufacturing process in order to avoid the loss of manufacturing knowledge. Summarising, this research is focus on the following issues.

- Analysis of the machining processes to manufacture titanium compressor airfoils and the design of an integrated process chain to reduce manufacturing costs.
- Research on diverse technologies to manufacture micro features which, for instance, may add functionality to compressor components.
- Development of an integrated methodology, based on axiomatic system design, to enhance productivity and reduce manufacturing costs.
- Design and development of a technology data catalogue to characterise manufacturing knowledge necessary for the development of process chains. And development of semantic nets, components of the technology data catalogue, which enable the dynamic navigation through the information assuring the easy sharing of knowledge.

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Contents

1	Introduction	1
1.1	Manufacturing of titanium components.....	1
1.2	Macro components.....	6
1.3	Micro components and micro features.....	10
1.4	Needs for process chains for manufacturing macro and micro features.....	13
1.5	The role of CAD/CAM and manufacturing knowledge.....	15
1.6	Research motivation and objectives.....	17
1.7	Organisation of the dissertation.....	18
2	Literature Review.....	19
2.1	Research on process design methods and models, and knowledge management.....	19
2.1.1	Research on process design and process modelling.....	19
2.1.2	Research on knowledge management systems.....	24
2.1.3	Summary of the research on process design, process modelling and knowledge management.....	25
2.2	Research on system design methodologies.....	27
2.2.1	TRIZ methodology.....	27
2.2.2	Robust design.....	29
2.2.3	Engineering design, systematic approach.....	31
2.2.4	Systematic approach, VDI 2221 guideline.....	33
2.2.5	Axiomatic design.....	35
2.2.6	Summary of the research on system design methodologies.....	39
3	Fundamentals and Analysis of Knowledge Sharing.....	41
3.1	Knowledge in geometry modelling (features).....	41
3.2	Relevance of knowledge sharing.....	42
3.3	Problems of knowledge sharing and needs for ontology.....	45
3.3.1	Definition of ontology.....	46
3.3.2	Criteria for designing ontologies.....	46
3.3.3	Classification and development of ontologies.....	47
3.4	Advantages of knowledge representation and semantic nets.....	48
3.5	Summary of fundamentals and analysis of knowledge sharing.....	50
4	Design of the Integrated Process Chain.....	51
4.1	Integrated design methodology.....	51
4.2	Process chain developer.....	53
4.2.1	Process chain design for conventional cutting conditions.....	53
4.2.2	Process chain design for dynamic cutting conditions.....	64
4.2.3	Differences among process chain designs.....	70
4.3	Development of the technology data catalogue.....	71
4.4	Summary of the development of the integrated process chain design.....	89

5	Validation of the Integrated Design Methodology.....	90
5.1	Machining of Ti6Al4V alloy.....	90
5.1.1	Face milling of Ti6Al4V alloy.....	91
5.1.2	Characterisation of information and optimal process parameters selection...	95
5.1.3	Summary of the validation of the integrated design for machining of Ti6Al4V alloy.....	100
5.2	Micro machining of Ti6Al4V alloy.....	101
5.2.1	Micro drilling of Ti6Al4V alloy.....	102
5.2.2	Micro laser drilling of Ti6Al4V alloy.....	111
5.2.3	Micro electric discharge machining of Ti6Al4V alloy.....	117
5.2.4	Characterisation of information and optimum technology selection.....	124
5.2.5	Summary of the validation of the integrated design for micro machining of Ti6Al4V alloy.....	131
6	Conclusions and Suggestions for Future Work.....	132
6.1	Concluding remarks.....	132
6.2	Suggestions for future work.....	134
	Bibliography.....	136
	Appendix A: State of the Art on Manufacturing Technologies.....	150
	Appendix B: Axiomatic System Design.....	167
	Appendix C: Measurement Instruments and Results.....	169
	Appendix D: Part Draw for the Machining of Micro Features.....	196

List of Figures

Figure 1: Applications of titanium alloys in different market sectors [Helm04].....	1
Figure 2: Potential automotive applications for titanium [Froes04].....	2
Figure 3: Volume fraction of titanium alloy classes in aero engines [Esslin03].....	3
Figure 4: Characteristics and machinability problems of titanium alloys [Janssen03].....	4
Figure 5: Cutting speed range for different materials, from conventional range to high speed cutting (HSC) range [Rahman06].....	4
Figure 6: Decrease in Ti6Al4V price reported in the last three years [Metal09].....	5
Figure 7: Compressor blisk [Bußmann05].....	6
Figure 8: Airfoiling processes forecast [Bußmann05].....	7
Figure 9: Core airfoiling processes for blisk [Bußmann05].....	8
Figure 10: Instrumentation holes on blisk (left), and 61 holes of $\varnothing=0.2\text{mm}$ on blade trailing edge (right) [Steffens02].....	10
Figure 11: Laser drilling techniques [Richter08].....	12
Figure 12: Six-axis flank milling [Steffens02].....	13
Figure 13: The role of CAD/CAM and operator knowledge.....	15
Figure 14: The two main elements of the proposed methodology.....	17
Figure 15: Basic structure of TRIZ.....	28
Figure 16: Technical system; and energy, material and signal transformation.....	29
Figure 17: Design process by Pahl and Beitz.....	32
Figure 18: Steps of design process, VDI 2221.....	34
Figure 19: Axiomatic design domains.....	35
Figure 20: Zigzagging to decompose FRs and DPs.....	36
Figure 21: Schematic representation of the information axiom.....	38
Figure 22: Schematic representation of the integrated methodology.....	52
Figure 23: Top level FR/DP.....	53
Figure 24: Decomposition of FR_1/DP_1	54
Figure 25: Decomposition of $\text{FR}_{11}/\text{DP}_{11}$; integrated process chain design.....	56
Figure 26: Decomposition of $\text{FR}_{114}/\text{DP}_{114}$	59
Figure 27: Decomposition of $\text{FR}_{115}/\text{DP}_{115}$	60
Figure 28: Decomposition of $\text{FR}_{13}/\text{DP}_{13}$	63
Figure 29: Top level FR/DP.....	64
Figure 30: Decomposition of FR_1/DP_1	65
Figure 31: Decomposition of $\text{FR}_{114}/\text{DP}_{114}$	68
Figure 32: Decomposition of $\text{FR}_{117}/\text{DP}_{117}$	69
Figure 33: Schematic representation of the technology data catalogue.....	72
Figure 34: Development of the manufacturing ontology and semantic net.....	73
Figure 35: Semantic net of class <i>Feature</i> retrieved in a web environment (K-infinity).....	75
Figure 36: Semantic net illustrating the relationship between Feature and Machining operation (Graph editor/ K-infinity).....	77
Figure 37: Semantic net illustrating the relationship between Feature, Machining operation, Cutting tool, and Machine (Graph editor/ K-infinity).....	79

Figure 38: Semantic net illustrating the relationship between Feature, Workpiece material, Machining operation, Cutting tool, and Machine (Graph editor/ K-infinity).....	81
Figure 39: Semantic net illustrating the relationship between multiple classes, subclasses, and individual instances (Graph editor/ K-infinity).....	85
Figure 40: Semantic net of hole feature retrieved in a web environment (K-infinity).....	88
Figure 41: Schematic representation of the workpiece and tool path.....	91
Figure 42: Workpiece in the milling machine LPZ 500.....	93
Figure 43: Process parameters to obtain max. $Q_{12}=1180 \text{ cm}^3/\text{min}$ (experiment 12)..	96
Figure 44: Process parameters to obtain min. $Ra_5= 0.25\mu\text{m}$ (experiment 5).....	96
Figure 45: Process chain to obtain max. $Q_{12}=1180\text{cm}^3/\text{min}$ and $Ra_{12}=0.50\mu\text{m}$ (experiment 12).....	99
Figure 46: Schematic representation of the rough machining	101
Figure 47: Pictures of pre-drilled hole of $\varnothing=0.3\text{mm}$; DeMeet picture (left) and SEM picture (right).....	102
Figure 48: Milling machine Cincinnati 750 Arrow 2 Series used for experiments...	103
Figure 49: Workpiece being drilled.....	104
Figure 50: Tool breakage in hole 8, $\varnothing= 0.3\text{mm}$, and depth= 7.20mm (right); and hole eccentricity (left), $\varnothing= 0.5\text{mm}$, and depth= 9.20mm.....	105
Figure 51: Workpiece mill lay patterns and measured areas (1 and 2).....	106
Figure 52: Roughness measurement on silicone replica; the line shows the profile..	107
Figure 53: 3D-picture of pin 1mm.....	107
Figure 54: Roughness measurement on pin 1mm.....	107
Figure 55: Roughness measurement on silicone replica; the line shows the profile sampled on pin 0.5mm.....	107
Figure 56: 3D-picture of pin 0.5mm.....	108
Figure 57: Roughness measurement on pin 0.5mm.....	108
Figure 58: Roughness measurement on silicone replica; the line shows the profile sampled on pin 0.3mm.....	108
Figure 59: 3D-picture of pin 0.3mm.....	109
Figure 60: Roughness measurement on pin 0.3mm.....	109
Figure 61: Holes of $\varnothing= 0.3$ and 0.5mm ; Pictures made with DeMeet with ring top light (left) and bottom light (right).....	109
Figure 62: Holes of $\varnothing= 1\text{mm}$; Pictures made with DeMeet with two light sources: ring top light (left) and bottom light (right).....	110
Figure 63: SEM picture of hole of diameters of 0.3mm , 0.5mm , and 1mm (left to right).....	110
Figure 64: SEM pictures of drill tools, nominal $\varnothing= 1\text{mm}$, before (left) and after drilling (right).....	110
Figure 65: Schematic representation of (a) two lines of holes of different diameters and (b) the wobbling movement used to machine holes of 1mm diameter.....	111
Figure 66: Pictures of lines 1, 4 and 5 made with Alicona.....	112
Figure 67: Workpiece being laser drilled.....	112

Figure 68: Diagram of line 1, machined holes with nominal diameters= 0.3, 0.5 and 1mm (left to right), and nominal depth= 1.6mm.....	113
Figure 69: Diagram of line 4, machined holes with nominal diameters= 0.3, 0.5 and 1mm (left to right), and nominal depth= 3.53mm.....	114
Figure 70: Diagram of line 5, machined holes with nominal diameters= 0.3, 0.5 and 1mm, and nominal depth= 3.99mm.....	115
Figure 71: Workpiece mill lay patterns and measured areas (1 and 2).....	115
Figure 72: SEM picture of EDMed holes ($\varnothing$ =0.3, 0.5 and 1mm, and depth $\approx$ 1mm).....	117
Figure 73: Workpiece in the Sarix SX-200 HPM machine.....	118
Figure 74: Workpiece mill lay patterns and measured areas (1 and 2).....	118
Figure 75: Roughness measurement on silicone replica; the line shows the profile sampled on the pin 1mm.....	119
Figure 76: 3D-picture of pin 1mm.....	119
Figure 77: Roughness measurement on pin 1mm.....	120
Figure 78: Roughness measurement on silicone replica; the line shows the profile sampled on pin 0.5mm.....	120
Figure 79: 3D-picture of pin 0.5mm.....	120
Figure 80: Roughness measurement on pin 0.5mm.....	121
Figure 81: Roughness measurement on silicone replica; the line shows the profile sampled on pin 0.3mm.....	121
Figure 82: 3D-picture of pin 0.3mm.....	121
Figure 83: Roughness measurement on pin 0.3mm.....	122
Figure 84: Holes of $\varnothing$ = 0.3 and 0.5mm; DeMeet pictures taken with ring top light (left) and bottom light (right).....	122
Figure 85: Holes of $\varnothing$ =1mm; DeMeet pictures taken with ring top light (left) and bottom light (right).....	122
Figure 86: SEM picture of hole of $\varnothing$ = 0.3mm.....	123
Figure 87: Drilling parameters to produce a hole through of diameter=1.013mm and hole-wall Ra= 0.231 μ m.....	125
Figure 88: Laser parameters to produce a hole through of diameter=0.996mm and surface Ra= 0.437 μ m around the holes.....	125
Figure 89: EDM parameters to produce a hole through of diameter=0.9696mm and hole-wall Ra= 0.460 μ m.....	126
Figure 90: Integrated methodology incorporated in a CAD/CAM environment.....	135
Figure A-1: Achievable machining accuracy ([Byrne03] based on [Corbett00]).....	150
Figure A-2: Reduction of the cycle time for machining a model workpiece [Byrne03].....	151
Figure A-3: Material removal rates for different materials and processes ([Byrne03] based on [Lung93]).....	152
Figure A-4: Current achievable cutting speeds ([Byrne03] based on [Schulz81])....	153
Figure A-5: Factors which influence machining performance ([Byrne03] based on [Jawa02]).....	164
Figure C-1: Schematic representation of measurements on the master.....	169
Figure C-2: Surface roughness measured on the master, profile 2.....	170
Figure C-3: Surface roughness, experiment 3, profile 10.....	171

Figure C-4: Surface roughness, experiment 4, profile 12.....	172
Figure C-5: Surface roughness, experiment 5, profile 12.....	173
Figure C-6: Surface roughness, experiment 6, profile 6.....	174
Figure C-7: Surface roughness, experiment 9, profile 11.....	175
Figure C-8: Surface roughness, experiment 12, profile 10.....	176
Figure C-9: Surface roughness measured on the master, profile 5.....	177
Figure C-10: Infinite Focus Alicona (left) and optical CMM DeMeet 220 (right)....	178
Figure C-11: SEM microscope JEOL JSM-5900.....	179
Figure C-12: Roughness measurements on area 1, profile 10 before drilling.....	181
Figure C-13: Surface roughness measurements on area 2, profile 10 before drilling.	182
Figure C-14: Surface roughness measurements on area 1, profile 8 after drilling.....	183
Figure C-15: Surface roughness measurements on area 2, profile 2 after drilling.....	184
Figure C-16: Surface roughness on area 1, profile 3 before laser drilling.....	187
Figure C-17: Surface roughness on area 2, profile 9 before laser drilling.....	188
Figure C-18: Surface roughness on area 1, profile 7 after laser drilling.....	189
Figure C-19: Surface roughness on area 2, profile 8 after laser drilling.....	190
Figure C-20: Roughness measurements on area 1, profile 7, before EDM.....	191
Figure C-21: Roughness measurements on area 2, profile 7, before EDM.....	192
Figure C-22: Roughness measurements on area 1, profile 8, after EDM.....	193
Figure C-23: Roughness measurements on area 2, profile 4 after EDM.....	194

List of Tables

Table 1: Components manufactured from Ti6Al4V in the automotive industry [Froes04].....	2
Table 2: Toolbox approach as a component of a process chain generation [Bußmann05].....	9
Table 3: Summary of state of the art tools and knowledge management systems.....	26
Table 4: Comparison between system design methodologies.....	39
Table 5: System design range obtained from different experiments or used cases...	61
Table 6: Calculation of information contents.....	62
Table 7: Actual processes capabilities (system design).....	66
Table 8: Calculation of information contents.....	66
Table 9: Slots and facets of the class <i>Feature</i>	74
Table 10: Examples of instances from class <i>Feature</i> and its slot <i>Tool access directions</i>	75
Table 11: Slots of the class <i>Machining_operation</i>	76
Table 12: Slots of the class <i>Machine_tool</i>	78
Table 13: Slots of the class <i>Cutting_tool</i>	78
Table 14: Slots of the class <i>Cooling_lubricant</i>	79
Table 15: Slots of the class <i>Fixture</i>	80
Table 16: Slots of the class <i>Workpiece_material</i>	80
Table 17: Slots of the class <i>Cutting_speed</i>	82
Table 18: Slots of the class <i>Feed_per_tooth</i>	82
Table 19: Slots of the class <i>Spindle_speed</i>	82
Table 20: Slots of the class <i>Feed_rate</i>	83
Table 21: Slots of the class <i>Depth_of_cut</i>	83
Table 22: Slots of the class <i>Width_of_cut</i>	84
Table 23: Slots of the class <i>Machining_productivity</i>	84
Table 24: Slots of the class <i>Surface_quality</i>	85
Table 25: Slots of the class <i>Burr_formation</i>	86
Table 26: Slots of the class <i>Chatter_vibration</i>	86
Table 27: Slots of the class <i>Tool_wear</i>	87
Table 28: Slots of the class <i>Tool_life</i>	88
Table 29: Composition of Ti6Al4V alloy in accordance with DIN 17851 [Boyer94].....	90
Table 30: Mechanical properties of Ti6Al4V alloy [Boyer94].....	90
Table 31: Machining experiments on titanium alloys (partially based on [Rahman06]).....	92
Table 32: Milling machine tool specifications [MAP08].....	93
Table 33: Tool and insert specifications.....	93
Table 34: Summary of milling parameters for the twelve experiments.....	94
Table 35: Summary of surface roughness measurements.....	95
Table 36: System design range obtained from different experiments.....	97
Table 37: Calculation of information content for satisfying FR ₁	97
Table 38: Calculation of information content for satisfying FR ₂	98

Table 39: Calculation of information content of the system to identify the best combination of parameters for satisfying both FRs simultaneously.....	98
Table 40: Summary of the rough machining and finishing information.....	101
Table 41: Hole diameters and depths of cut of pre-drilled holes.....	102
Table 42: Milling machine Cincinnati 750 Arrow 2 Series specifications.....	102
Table 43: Drilling tool specifications.....	103
Table 44: Summary of drilling information.....	104
Table 45: Summary of tool diameters measurements.....	105
Table 46: Summary of measurements before drilling.....	106
Table 47: Summary of measurements after drilling.....	106
Table 48: Summary of surface roughness measurement on pin 1mm.....	107
Table 49: Summary of surface roughness measurement on pin 0.5mm.....	108
Table 50: Summary of surface roughness measurement on pin 0.3mm.....	109
Table 51: Summary of measurements.....	110
Table 52: Laser specifications.....	111
Table 53: Photon Properties of Nd-YAG laser [Steen05].....	111
Table 54: Summary of machining parameters, line 1.....	112
Table 55: Measurement of holes diameter and depth, line 1.....	112
Table 56: Summary of machining parameters, line 4.....	113
Table 57: Measurement of holes diameter and depth, line 4.....	113
Table 58: Summary of machining parameters, line 5.....	114
Table 59: Measurement of holes diameter and depth, line 5.....	114
Table 60: Summary of diameter measurements.....	115
Table 61: Summary of measurements before laser drilling.....	116
Table 62: Summary of measurements after laser drilling.....	116
Table 63: EDM machine specifications.....	117
Table 64: Tool specifications.....	117
Table 65: EDM parameters.....	117
Table 66: Summary of measurements before EDM.....	119
Table 67: Summary of measurements after EDM.....	119
Table 68: Summary of surface roughness measurement on pin 1mm.....	119
Table 69: Summary of surface roughness measurement on pin 0.5mm.....	120
Table 70: Summary of surface roughness measurement on pin 0.3mm.....	121
Table 71: Summary of measurements.....	123
Table 72: Technologies capabilities for micro holes of $\varnothing = 1\text{mm}$	126
Table 73: Calculation of the information content for FR_1	127
Table 74: Calculation of the information content for FR_2	127
Table 75: Calculation of the information content for FR_3	127
Table 76: Calculation of the total information content.....	127
Table 77: Technologies capabilities for micro holes of $\varnothing = 0.5\text{mm}$	128
Table 78: Calculation of the information content for FR_4	128
Table 79: Calculation of the information content for FR_5	128
Table 80: Calculation of the total information content.....	128
Table 81: Technologies capabilities for micro holes of $\varnothing = 0.5\text{mm}$	129
Table 82: Calculation of the information content for FR_6	129

Table 83: Calculation of the information content for FR ₇	129
Table 84: Calculation of the total information content.....	130
Table 85: Calculation of the total information content.....	130
Table 86: Summary of solutions provided by this research.....	133
Table A-1: High speed milling of titanium alloys [Steffens08].....	154
Table A-2: Linear friction welding of titanium alloys [Steffens08].....	154
Table A-3: Electro chemical machining of titanium alloys [Steffens08].....	155
Table A-4: Classification of machining processes according to their characteristics [Masu00].....	156
Table A-5: State of the art on cutting materials.....	161
Table B-1: Characteristics of the domains for different designs [Suh01].....	167
Table B-2: Axioms, corollaries and theorems [Suh90].....	167
Table C-1: Instrument specifications.....	169
Table C-2: Master references.....	169
Table C-3: Surface roughness measurements on the master.....	170
Table C-4: Roughness measurements from experiment 3.....	171
Table C-5: Roughness measurements from experiment 4.....	172
Table C-6: Roughness measurements from experiment 5.....	173
Table C-7: Roughness measurements from experiment 6.....	174
Table C-8: Roughness measurements from experiment 9.....	175
Table C-9: Roughness measurements from experiment 12.....	176
Table C-10: Surface roughness measurements on the master.....	177
Table C-11: Hole wall replication system RepliSet specifications.....	178
Table C-12: Scanning electron microscope (SEM) specifications.....	179
Table C-13: Tool diameter measurements, nominal Ø= 1mm.....	180
Table C-14: Tool diameter measurements, nominal Ø= 0.5mm.....	180
Table C-15: Tool diameter measurements, nominal Ø= 0.3mm.....	180
Table C-16: Surface roughness measurements on area 1 before drilling.....	181
Table C-17: Surface roughness measurements on area 2 before drilling.....	182
Table C-18: Surface roughness measurements on area 1 after drilling.....	183
Table C-19: Surface roughness measurements on area 2 after drilling.....	184
Table C-20: Hole diameter measurements, nominal Ø=0.3mm.....	185
Table C-21: Hole diameter measurements, nominal Ø=0.5mm.....	185
Table C-22: Hole diameter measurements, nominal Ø=1mm.....	186
Table C-23: Surface roughness measured on area 1 before laser drilling.....	187
Table C-24: Surface roughness measured on area 2 before laser drilling.....	188
Table C-25: Surface roughness measured on area 1 after laser drilling.....	189
Table C-26: Surface roughness measured on area 2 after laser drilling.....	190
Table C-27: Surface roughness measurements on area 1 before EDM.....	191
Table C-28: Surface roughness measurements on area 2 before EDM.....	192
Table C-29: Surface roughness measurements on area 1 after EDM.....	193
Table C-30: Surface roughness measurements on area 2 after EDM.....	194
Table C-31: Hole diameter measurements, nominal Ø=0.3mm.....	195
Table C-32: Hole diameter measurements, nominal Ø=0.5mm.....	195
Table C-33: Hole diameter measurements, nominal Ø=1mm.....	195

List of abbreviations and formula symbols

Abbreviations

ARIZ	Algorithm to solve an inventive problem
BCBN	Binder-less cubic boron nitride
Blik	Integrally bladed disk
BUE	Build up edge
CA	Customer attributes
CAD	Computer aided design
CAM	Computer aided manufacturing
CBN	Cubic boron nitride
CCD	Charge coupled device
CMM	Coordinate measurement machine
CNC	Computerized numerical control
Co	Cobalt
Cs	Constraints
DP	Design parameter
EBD	Electron beam drilling
EBM	Electron beam machining
ECD	Electro chemical drilling
ECF	Electro chemical milling with ultra short pulses
ECM	Electro chemical machining
EDM	Electric discharge machining
EOS	Exit order sequence
ERP	Enterprise resource planning
FEM	Finite element modelling
FR	Functional requirement
HPC	High pressure compressor
HSC	High speed cutting
HSS	High speed steel
IBR	Integrally bladed rotor
IHFP	Inductive high frequency pressure welding
IPC	Integrated process chain
ISO	International organization for standardization
IT	Information technology
KV	Knowledge visualization
LBM	Laser beam machining
LFW	Linear friction welding
LPC	Low pressure compressor
Mo	Molybdenum
MCD	Monocrystalline diamond
MQL	Minimal quantity lubricant
NaCl	Sodium chloride
NC	Numerical control
NDM	Near dry machining

NDT	Non destructive testing
Ni	Nickel
NPT	Non productive times
PCD	Polycrystalline diamond
pdf	probability density function
PDM	Product data management
PECM	Precise electrochemical machining
PVD	Physical vapour deposition
PV	Process variable
ROI	Return of investment
SED	Sinking electro discharge machining
SEM	Scanning electron microscope
SiC	Silicon carbide
Ta	Tantalum
TDC	Technology data catalogue
Ti	Titanium
TiAlN	Titanium aluminium nitride
TiCN	Titanium carbon nitride
TiN	Titanium nitride
TRIZ	Theory of inventive problem solving
UR	Unite removal
USM	Ultrasonic machining
VDI	Verein Deutscher Ingenieure
W	Tungsten
WC	Tungsten carbide
WEDM	Wire electric discharge machining

Formula symbols

[A]	Design matrix
a_c	Contact width
a_p	Depth of cut
f_z	Tooth feed rate
l	Evaluation length
L_c	Filter cut-off
Q, Q_w	Material removal rate
R_a	Arithmetical mean deviation
R_z	Average height of roughness profile
R_{zmax}	Maximum height of roughness profile
S	Spindle speed
STD	Standard deviation
V_B	Tool flank wear
V_c	Cutting speed
V_f	Feed rate
$\varnothing$	Diameter