

ENVIRONMENTAL FRIENDLY MACHINABILITY EVALUATION ON DUPLEX STAINLESS STEEL

by

RAJEEV SHARMA

Submitted

In Partial Fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the



BHARTIYA SKILL DEVELOPMENT UNIVERSITY, JAIPUR

2023

Declaration of Originality of Research Work and Thesis by the Scholar and Supervisor

I have not committed plagiarism in any of the forms described in the ‘Promotion of Academic Integrity and Prevention of Plagiarism in Bhartiya Skill Development University (BSDU)’. I have documented all methods, data, and processes truthfully and I have not manipulated any data. I have mentioned all persons who were significant facilitators of the work. The work has been screened electronically for plagiarism.

Signature

Name of the Scholar: Rajeev Sharma

Place: Jaipur

Registration Number: 190150W001

Date: 12/04/2023

I, Dr. **Binit Kumar Jha** certify and attest that the work done by my Ph.D. candidate Mr. **Rajeev Sharma** is original and vouch that there is no plagiarisms. The work has not been submitted for the award of any other degree/diploma of the same university / school where the work was carried out, or to any other university / Institution.

Signature:

Name of the Research Supervisor: Prof. B.K. Jha

Designation: Principal & Professor

Place: Jaipur

School/ Department: S.M.S

Date: 12/04/2023

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere gratitude and thanks to my supervisor and co-supervisor, **Prof. (Dr.) B.K. Jha & Dr. Vipin Pahuja**, without whom this thesis wouldn't have been possible. Their support and commitment in all phases of my academic journey; pre, during, and post peace crops was unmatched by anyone and greatly appreciated. I feel so lucky to have them as my supervisors and your dedication and hard work have not gone unnoticed.

I would thank my family for their unconditional support and a steady stream of mail which kept me going throughout my journey. I would mention my special gratitude to my wife for keeping me motivated and always being supportive to pursue my work with dedication. Thank you for allowing me to embrace my wandering curiosity and always supporting my sense of adventure and curious nature. I would like to thank the faculty of the library, who helped with the resources I needed. I would like to thank to my committee members, Dr. Sandeep Kumar Tomar, Dr. Prerna Srivastava, Dr. Sheetal Kumar Jain, Dr. Satyendra Singh, and Dr. Kunji Lal Meena, for your time and assistance during the process.

Lastly, I would like to acknowledge my sincere gratitude to peer research scholars for helping me to learn new concepts and techniques throughout my journey.

Name: Rajeev Sharma

Registration No.: 190150W001

Discipline: Mechanical

Date: 15/02/2023

Place: Jaipur

LIST OF FIGURES

| | Title | Page No. |
|------|--|-----------------|
| 1.1 | Specification of Solid Carbide Drill | 1 |
| 1.2 | Drilling Process | 2 |
| 1.3 | Fishbone Diagram | 3 |
| 1.4 | The Independent Variables | 3 |
| 1.5 | The Dependent Variables | 4 |
| 1.6 | Microstructure of Duplex Stainless Steel | 5 |
| 1.7 | Continuous Chip | 6 |
| 1.8 | Discontinuous Chip | 7 |
| 1.9 | Built-Up Edge | 7 |
| 1.10 | Serrated Chip | 8 |
| 1.11 | Surface Roughness | 8 |
| 1.12 | Tool Wear Analysis | 9 |
| 1.13 | Hole Deviation Error | 10 |
| 1.14 | Environmental-Friendly Machining | 12 |
| 1.15 | Basic Process of Dry Machining | 13 |
| 1.16 | Basic Process of MQL Machining | 14 |
| 1.17 | Basic Process of MQL-Nano Machining | 14 |
| 1.18 | Basic Process of Cryogenic Machining | 15 |
| 1.19 | Basic Process of High-Pressure Cooling | 16 |
| 1.20 | Types of Optimization Techniques | 17 |
| 1.21 | Plan of Action | 19 |
| 2.1 | Summary of Literature | 54 |
| 3.1 | Flow Chart of GA Methodology | 63 |
| 3.2 | ANN Model Structure | 64 |
| 3.3 | Operation of Fuzzy Logic System | 65 |
| 3.4 | Membership Function | 66 |
| 3.5 | ANFIS Model Structure | 68 |

| | Title | Page No. |
|------|--|-----------------|
| 4.1 | CNC Machine | 70 |
| 4.2 | Machined Workpiece | 71 |
| 4.3 | Cutting Tool | 71 |
| 4.4 | Geometry of Tool Holder | 72 |
| 4.5 | Tool Holder | 72 |
| 4.6 | Design of MQL Setup | 73 |
| 4.7 | Attachment of LCO ₂ Setup | 76 |
| 4.8 | Surface Roughness Tester | 77 |
| 4.9 | Setup of CMM | 78 |
| 4.10 | Tool Pre-Setting Device | 78 |
| 4.11 | Hybrid MQL-LCO ₂ Setup | 85 |
| 4.12 | Shows Surface Roughness | 87 |
| 4.13 | Principle of Hole Deviation | 88 |
| 4.14 | Basic concept of cylindricity error | 88 |
| 4.15 | Basic concept of circularity error | 89 |
| 5.1 | Main Effect Plot for Means of Ra | 91 |
| 5.2 | Interaction Plot for Ra | 92 |
| 5.3 | The Best Value of Ra | 93 |
| 5.4 | Graphical Representation of Response Table | 94 |
| 5.5 | Graphical Representation of Contribution of Parameters | 95 |
| 5.6 | Residual Plot for Ra | 96 |
| 5.7 | Contour Plot Between Input Variables to Response | 97 |
| 5.8 | Chart of The Confirmation Test | 98 |
| 5.9 | Main Effect Plot for Means of Ra | 100 |
| 5.10 | Main Effect Plot for Means of Hole Deviation | 101 |
| 5.11 | Interaction Plot for Ra | 102 |
| 5.12 | The Best Value for Ra | 103 |
| 5.13 | Interaction Plot for Hole Deviation | 103 |
| 5.14 | The Best Value of Hole Deviation | 104 |

| | Title | Page No. |
|------|---|-----------------|
| 5.15 | Graphical Representation of Responses for Ra | 105 |
| 5.16 | Graphical Representation of Response for Hole Deviation | 107 |
| 5.17 | Graphical Representation of Contribution of Process Parameters for Ra | 108 |
| 5.18 | Graphical Representation of Contribution of Process Parameters for Hole Deviation | 109 |
| 5.19 | Residual Plot for Ra | 111 |
| 5.20 | Residual Plot for Hole Deviation | 111 |
| 5.21 | Contour Plot | 112 |
| 5.22 | Comparison Chart for Ra | 116 |
| 5.23 | Comparison Chart for Hole Deviation | 117 |
| 5.24 | The Optimized Value of Ra | 119 |
| 5.25 | The Optimized Value of Hole Deviation | 120 |
| 5.26 | Tool Wear Analysis | 121 |
| 5.27 | Main Effect Plot for Hole Deviation | 123 |
| 5.28 | Main Effect Plot for Cylindricity Error | 124 |
| 5.29 | Main Effect Plot for Circularity Error | 125 |
| 5.30 | Interaction Plot for Hole Deviation | 125 |
| 5.31 | The Best Value of Hole Deviation | 126 |
| 5.32 | Interaction Plot of Cylindricity Error | 127 |
| 5.33 | The Best Value of Cylindricity Error | 128 |
| 5.34 | Interaction Plot of Circularity Error | 128 |
| 5.35 | The Best Value of Circularity Error | 129 |
| 5.36 | Graphical Representation of Contribution of Process Parameters for Hole Deviation | 130 |
| 5.37 | Graphical Representation of Contribution of Process Parameters for Cylindricity Error | 132 |
| 5.38 | Graphical Representation of Contribution of Process Parameters for Circularity Error | 133 |
| 5.39 | Normal Residual Plot for Responses | 134 |
| 5.40 | Contour Plot for Responses | 137 |

| | Title | Page No. |
|------|--|-----------------|
| 5.41 | ANN Model Structure | 138 |
| 5.42 | Input Window | 139 |
| 5.43 | Regression Plot & Mean Square Error for Responses | 140 |
| 5.44 | The Surface Plot of the Hole Deviation | 142 |
| 5.45 | The Surface Plot of the Cylindricity Error | 142 |
| 5.46 | The Surface Plot of the Circularity Error | 143 |
| 5.47 | FIS File | 144 |
| 5.48 | Membership Function for Drill Diameter | 144 |
| 5.49 | Membership Function of Spindle Speed | 145 |
| 5.50 | Membership Function of Feed Rate | 145 |
| 5.51 | Membership Function of Hole Deviation | 146 |
| 5.52 | Membership Function of Cylindricity Error | 146 |
| 5.53 | Membership Function of Circularity Error | 147 |
| 5.54 | Rules File | 148 |
| 5.55 | Shows the Predicated Value for Hole Deviation | 149 |
| 5.56 | 3-D Surface Plot for Responses | 150 |
| 5.57 | General Structure of ANFIS | 153 |
| 5.58 | Neural Network Model for Responses | 154 |
| 5.59 | Input Window | 154 |
| 5.60 | Initial Loading of Training Data for Hole Deviation | 155 |
| 5.61 | Initial Loading of Testing Data for Hole Deviation | 155 |
| 5.62 | Comparison of Experimental to Predicated for Hole Deviation | 156 |
| 5.63 | Initial Loading of Training Data for Cylindricity Error | 156 |
| 5.64 | Initial Loading of Testing Data for Cylindricity Error | 156 |
| 5.65 | Comparison of Experimental to Predicated for Cylindricity | 157 |
| 5.66 | Initial Loading of Training Data for Circularity Error | 157 |
| 5.67 | Initial Loading of Testing Data for Circularity Error | 158 |
| 5.68 | Comparison of Experimental to Predicated for Circularity | 158 |
| 5.69 | Comparison Chart Experimental Value to Predicated Value for Hole Deviation | 160 |

| | Title | Page No. |
|------|--|-----------------|
| 5.70 | % of Error Experimental Value to Predicated Value for Hole Deviation | 161 |
| 5.71 | Comparison Chart Experimental Value to Predicated Value for Cylindricity Error | 163 |
| 5.72 | % of Error Experimental Value to Predicated Value for Cylindricity Error | 164 |
| 5.73 | Comparison Chart Experimental Value to Predicated Value for Circularity Error | 166 |
| 5.74 | % of Error Experimental Value to Predicated Value for Circularity Error | 168 |
| 5.75 | Total % of error | 169 |
| 5.76 | Closeness Coefficient of the Experimental Run | 173 |

LIST OF TABLES

| | Page No. | |
|------|--|----|
| 2.1 | Brief overview of literature on cooling techniques | 40 |
| 2.2 | Brief overview of literature on optimization techniques & modelling | 50 |
| 3.1 | Types of Design | 58 |
| 3.2 | Types of Observation | 60 |
| 3.3 | Types of Response Table | 60 |
| 3.4 | Membership Function | 66 |
| 4.1 | Specification of CNC Machine | 69 |
| 4.2 | Chemical Composition of DSS 2205 | 70 |
| 4.3 | Specifications of MQL Setup | 74 |
| 4.4 | Characteristics of Vegetable Oil | 74 |
| 4.5 | Specifications of LCO ₂ Setup | 75 |
| 4.6 | Characteristics of LCO ₂ Setup | 76 |
| 4.7 | Level of Process Parameters | 79 |
| 4.8 | Set of Experiments | 80 |
| 4.9 | Experimental Conditions Details | 81 |
| 4.10 | Level of Process Parameters | 82 |
| 4.11 | Set of Experiments Under Dry, MQL, and LCO ₂ Conditions | 82 |
| 4.12 | The Characteristics of the MQL-LCO ₂ Setup | 83 |
| 4.13 | Chemical Composition of DSS 2205 | 84 |
| 4.14 | Level of Process Parameters | 84 |
| 4.15 | Set of Experiments Under the Hybrid Cooling Condition | 86 |
| 5.1 | Experimental Results for Ra Under Dry, and Wet Conditions | 90 |
| 5.2 | Response Table | 93 |
| 5.3 | ANOVA Analysis for Ra | 94 |
| 5.4 | Confirmation Test | 98 |
| 5.5 | Experimental Results for Responses Under Dry, MQL, and LCO ₂ Conditions | 99 |

| | Page No. | |
|------|--|-----|
| 5.6 | Response Table for S/N Ratio of Ra | 105 |
| 5.7 | Response Table for S/N Ratio of Hole Deviation | 106 |
| 5.8 | ANOVA Analysis for Ra | 108 |
| 5.9 | ANOVA Analysis for Hole Deviation | 109 |
| 5.10 | Level of Process Parameter for a Confirmation Test | 116 |
| 5.11 | Comparison of Experimental Value and Predicated Value | 116 |
| 5.12 | Confirmation Test in Term of S/N Ratio of Ra and Hole Deviation | 117 |
| 5.13 | Experimental Results Under Hybrid MQL-LCO ₂ Condition | 122 |
| 5.14 | ANOVA Analysis for Hole Deviation | 130 |
| 5.15 | ANOVA Analysis for Cylindricity Error | 131 |
| 5.16 | ANOVA Analysis for Circularity Error | 133 |
| 5.17 | ANN Model Parameters | 139 |
| 5.18 | The Rules Applied for Response Value Prediction | 147 |
| 5.19 | Experimental Value and Predicated Value for Hole Deviation | 160 |
| 5.20 | % of Error for Hole Deviation | 161 |
| 5.21 | Experimental Value and Predicated Value for Cylindricity Error | 162 |
| 5.22 | % of Error for Cylindricity Error | 164 |
| 5.23 | Experimental Value and Predicated Value for Circularity Error | 165 |
| 5.24 | % of Error for Circularity Error | 167 |
| 5.25 | Total % of error | 168 |
| 5.26 | Normalised Matrix | 170 |
| 5.27 | Normalised Weighted Matrix | 171 |
| 5.28 | Closeness Coefficient and Ranking of Alternatives | 173 |

CERTIFICATE

This is to certify that the thesis titled “ **ENVIRONMETALFRIENDLY MACHINABILITY EVALUATION ON DUPLEX STAINLESS STEEL**” being submitted by “ **RAJEEV SHARMA**” (190150W001) to the Bhartiya Skill Development University, for the award of degree of Doctor of Philosophy is a bonafiderecord of original research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which has reached the required standard.

The results contained 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.

Signature:

Name of the Supervisor:

Prof. B.K. Jha

Date: 12/04/2023

Place: Jaipur

Signature:

Name of the Co-Supervisor:

Dr. Vipin Pahuja

Date: 12/04/2023

Place: Jaipur