

CERTIFICATE

It is certified that the work contained in the thesis “FLOW FORMING OF ALUMINIUM BASED ALLOYS” by “ASHUTOSH KUMAR SRIVASTWA” has been carried out under my supervision and that this work has not been submitted elsewhere for a 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.

Signature: Prof. Santosh Kumar
Professor
Department of Mechanical Engineering
Indian Institute of Technology (BHU), Varanasi
Varanasi-221005

DECLARATION BY THE CANDIDATE

I, ASHUTOSH KUMAR SRIVASTWA certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of Prof. Santosh Kumar from July 2014 to Jan-2022, at the Department of Mechanical Engineering, Indian Institute of Technology (Banaras Hindu University) Varanasi. 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, rted in journals, books, magazines, reports dissertations, theses, etc:, or available at websites and have not included them in this thesis or cited as my own work.

Date :

Signature of the Student

Place :

(ASHUTOSH KUMAR SRIVASTWA)

CERTIFICATE BY THE SUPERVISOR

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

Signature of Supervisor

(Prof. Santosh Kumar)

Signature of Head of Department

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis: FLOW FORMING OF ALUMINIUM ALLOYS

Name of the Student: ASHUTOSH KUMAR SRIVASTWA

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 :

Place :

Signature of the Student

(ASHUTOSH KUMAR SRIVASTWA)

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.

ACKNOWLEDGEMENTS

I take this opportunity to express my sincere thanks and gratitude beyond words to my supervisors, Prof. Santosh Kumar for their consistent help, encouragement and valuable discussions during the entire period of my research work. I would also like to express my deepest sense of gratitude to Prof. Vakil Singh, whose words have inspired me a lot while tackling day-to-day technical problems. I would not have been able to complete the thesis without their utmost involvement and invaluable efforts. They motivated me to pursue research problems and the need for persistent effort to accomplish the goal. I am truly indebted to them. They are the real definition of the best teacher being friendly and behind for all problems of not only mine but all the students.

I sincerely thank Prof A. P. Harsha, former Head of the Department of Mechanical Engineering, Prof. Rajneesh Tyagi, Dr. Mohd Zaheer Khan Yusufzai, Dr. Uppu Srinivas Rao for providing all the research facilities to successfully accomplish my research in the Department.

Besides my supervisor, I would like to thank other members of RPEC: Dr. R. Manna, Department of Metallurgical Engineering and Prof. S.K. Sinha Department of Mechanical Engineering, for their insightful comments and encouragement.

I am also thankful to Prof. I. Samajdar, IIT Bombay for residual stress and EBSD analysis, and Prof. Sudhanshu Shekhar Singh IIT Kanpur for tensile testing.

I am thankful to my all friends, Ravi, Pankaj, Meraz, Avnish Singh, Roop Chandra, Aman, Ashutosh Roushan, Jitendra, and Asgar for their constant encouragement, support, and making joyful and memorable moments at IIT (BHU),

Varanasi. They are the persons who were always behind me when I was feeling low when things were not going well during the corona pandemic.

I am also thankful to all my junior students of M.Tech and Ph.D. of our group from 2015 to 2021 for their constant support during my research work.

I am also thankful to all the Lab and workshop staff especially Rajendra Ji, Lal Ji Vishkarma, B Rai Ji, Harishankar Ji, Ravi Ji, and all others who have not only helped and at times taught me whenever I faced issues during experimentation.

Last but not the least, I wish to thanks my friends Sandeep Mishra, Abhishek Shukla and all others whose name have not been mentioned on this piece of paper for extending their cooperation directly or indirectly.

Ashutosh Kumar Srivastwa

DEDICATED

To

My Teachers

&

My Beloved Family Members

TABLE OF CONTENTS

1	CHAPTER 1: INTRODUCTION AND LITERATURE SURVEY.....	1
1.1	Aluminium and its Alloys	1
1.2	Aluminium Alloy designation System	2
1.3	Temper designation of Aluminium alloys.....	5
1.4	Introduction to flow forming.....	6
1.5	Components in Flow forming	8
1.6	Types of flow forming process	10
1.7	Factors affecting the Flow forming process.....	12
1.8	Researches based on Experimental investigation.....	14
1.8.1	Design of Experiments (DOE).....	19
1.8.2	Numerical Analysis.....	20
1.9	THE PREDICTIVE MODELS: THE MECHANICS OF FLOW FORMING ...	21
1.9.1	Models for predicting product geometry	22
1.9.2	Model for Prediction model for Surface Properties.....	24
1.9.3	Model for prediction of mechanical proprieties.....	25
1.9.4	Model for Prediction of Product Microstructure and its Effects:	28
1.9.5	Model for Prediction of Power and Tool Forces	30
1.10	Stress and Strain in Flow forming.....	35

1.11	STATE OF STRESS	37
1.12	Defect and failure of flow formed samples	38
1.12.1	Diametral growth:	41
1.12.2	Ovality or out of roundness:	42
1.12.3	Wrinkling:	43
1.12.4	Fish Scaling :	43
1.13	Flow forming Roller geometry	44
1.13.1	Tool Path Design:	47
1.14	Effect of Lubrication	47
1.15	Preform designing	48
1.16	Heat Treatments	48
1.17	Scope and Aim of the Thesis:	49
2	CHAPTER 2: EXPERIMENTAL SET UP OF FLOW FORMING	51
2.1	Planning of Flow forming	51
2.2	Selection of Machine Tool:	52
2.3	Design of Preform	52
2.3.1	Process plan of fabrication of Preform of Al6101 T6.....	54
2.4	Design of Mandrel.....	55
2.5	Design of Roller assembly	57
2.5.1	Roller Wheel Assembly	57
2.5.2	Process plan for fabrication of Roller wheel.....	59
2.5.3	Design of bolt and Sleeve arrangement	59

2.6	Design of Y Frame (Roller holder):	60
2.6.1	Assembly of Roller Assembly	61
2.7	Flow forming Set up.....	65
2.8	Data acquisition system.....	65
2.9	Heat treatment of Preform.....	68
2.10	Experimental plan and analysis.....	68
2.11	Mechanical and metallurgical testing of preform and flow formed samples:	70
3	CHAPTER 3: MATHEMATICAL MODELLING	73
3.1	Generalized Upper Bound Method	73
3.1.1	Generalized Kinetically Admissible Velocity	73
3.2	Developing a generalized kinetically admissible velocity fields.	76
3.3	Conditions on choice of suitable flow lines	78
3.4	Upper bound formulation	79
3.4.1	Power for internal deformation over the volume of deforming body.....	79
3.4.2	Power loss due to velocity discontinuity	85
3.4.3	Power loss due to friction	86
3.4.4	Power loss at work piece- roller contact region.....	87
3.4.5	Power loss at workpiece- mandrel contact region	88
3.5	Calculation of average force	89
3.5.1	Validation of Mathematical model for Al6101 T6.....	90
3.5.2	Validation of the mathematical model for 7075	91
3.5.3	Validation of the mathematical model for Al2014	94

4	CHAPTER 4: RESULTS OF FLOW FORMING	97
4.1	Results of flow Forming of Al6101	97
4.1.1	Thickness reduction	98
4.1.2	Temperature Variation	100
4.1.3	Radial force, circumferential force, and axial force	100
4.1.4	Thickness Variation	109
4.1.5	Diametral growth	109
4.1.6	Ovality.....	110
4.1.7	Surface Roughness:.....	111
4.1.8	Microhardness Variation:.....	112
4.1.9	Tensile Test.....	115
4.1.10	XRD plots:	116
4.1.11	EBSD Analysis :	118
4.1.12	Defect Analysis	122
4.2	Results of Flow forming of Al7075	124
4.2.1	Geometrical Characteristics	124
4.2.2	Force Measurement.....	130
4.2.3	XRD analysis	131
4.2.4	EBSD Analysis	133
4.2.5	Defects in Flow forming	137
4.2.6	Microhardness.....	144
4.3	EXPERIMENTAL RESULTS OF FLOW FORMED AL2014 SAMPLES	146

4.3.1	Introduction.....	146
4.3.2	Material Specification:.....	146
4.3.3	Flow forming forces.....	147
4.3.4	Microhardness Test.....	150
4.3.5	XRD Analysis	151
4.3.6	EBSD Analysis	153
4.3.7	Defects encountered in Al2014 samples:.....	156
4.4	Fractography analysis of tensile test specimen	157
5	CHAPTER 5: DISCUSSIONS	161
5.1	Experimental Forces and validation of mathematical model.....	161
5.2	X- ray diffraction results	165
5.3	EBSD Analysis.....	166
5.4	Microhardness test analysis:.....	167
5.5	Defects in Flow forming	168
5.5.1	Diametral growth	168
5.5.2	Chip formation.....	168
5.5.3	Distortion of the tube	169
5.6	SEM Fractography of tensile specimen and cracked specimen	170
6	CHAPTER 6: CONCLUSIONS AND FUTURE SCOPE OF WORK	171
	REFERENCES	175
	List of Publications	188
	APPENDICES	189

APPENDIX- 1	189
APPENDIX- 2	191

LIST OF TABLES

Table 1.1: Four digit aluminium alloy designation system for wrought alloys [3]	3
Table 1.2: Three digit aluminium alloy designation for cast alloys [3].....	3
Table 1.3: Nominal composition of Aluminium aerospace alloy[3]	5
Table 1.4: Temper designation of Al alloys [3].....	6
Table 1.5: Material Used in flow forming	12
Table 1.6: Summary of defects and their probable influencing factors. Table adapted from Marini et. al.[72]	40
Table 2.1: Lathe Dynamometer specifications	67
Table 2.2: Preform Condition and experimental process parameters for Al6101	68
Table 2.3: Temper Condition and Process parameters used in flow forming Al7075.....	69
Table 2.4: Temper Condition and Process parameters used in flow forming Al2014.....	69
Table 3.1: Calculating value of $\eta\alpha$ and ηr	90
Table 3.2: Validation of mathematical model for Al6101 T6	91
Table 3.3: Calculating value of $\eta\alpha$ and ηr for heat treated samples of Al7075	92
Table 3.4: Validation of mathematical model using $\eta\alpha = 0.3$ and $\eta r = 0.96$ for 7075 heat treated 7F04 (Figure 4.25)	94
Table 3.5: Calculation of mathematical model using $\eta\alpha$ and ηr for 2014 heat treated samples.....	95
Table 4.1: Summary of mean radial force, mean circumferential force and mean axial force variation in each pass	103
Table 4.2: Process Parameter for FF02.....	105
Table 4.3: Thickness reduction and Average flow forming Forces in FF02	106

Table 4.4: Thickness reduction and average flow forming forces in FF03, FF04 and FF05	106
Table 4.5: Surface roughness measurement.....	112
Table 4.6: Hardness variation in different sections of FF01.....	114
Table 4.7: Grain Size distribution in Preform Al6101.....	119
Table 4.8: Grain size distribution in flow formed FF01 IA.....	121
Table 4.9: Chemical composition of Al7075.....	124
Table 4.10: Heat-treated Condition of samples of 7075.....	124
Table 4.11: The dimensions of the flow formed products.....	125
Table 4.12: Summary of geometrical characteristics of the preform(undeformed) and deformed 7F04.....	129
Table 4.13: Chemical Composition of Al2014.....	146
Table 5.1: Lattice microstrain, crystallite size, and dislocation density of the various heat treatable aluminum alloys.....	166
Table 7.1: Dimensional relationships of tensile specimens used in different countries (Dieter).....	190

TABLE OF FIGURES

Figure 1.1: Yield Strength (YS) versus Year of Introduction [1]	2
Figure 1.2: Main type of Aluminium alloys and their Alloying Elements [5]	4
Figure 1.3: Schematic illustration of flow forming process [6].....	7
Figure 1.4: A typical flow forming machine [8].....	9
Figure 1.5: Schematic diagram of Forward flow forming process [9]	10
Figure 1.6: Schematic diagram of backward flow forming process. [9]	11
Figure 1.7: Flowchart showing the interdependence of research aim and knowledge available [1]	13
Figure 1.8: Flow chart depicting the process used for flow forming of the preform and Testing [20]	16
Figure 1.9: Tensile Strength in axial direction in 7075-O,2024-O and Al2024-S [18].....	27
Figure 1.10: Radial force variation with \sqrt{v} (v is feed in mm/rev).[11].....	31
Figure 1.11: Deformation zone in flow forming[40].....	37
Figure 1.12: Deformation zone and the state of stress (a) axial direction (b) radial direction and tangential direction [40]	38
Figure 1.13: Wrinkling defect Gupta et al. [23].....	43
Figure 1.14: Fish Scales on flow formed component. [79].....	43
Figure 1.15: (a) Effect of attack angle on circumferential contact length (S) and axial contact length (L) Gur and Tirosh [14] (b) Variation of S/L ratio with attack angle . Parsa et. al.[44].....	46
Figure 1.16: (a) Correlation between critical attack angle and thickness reduction. [14] (b) Correlation of attack angle and thickness reduction [13]	47
Figure 2.1: Preform dimension of Al6101	52
Figure 2.2: Preform dimension for Al7075 and Al2014.....	53

Figure 2.3: Fabricated preform (a) Al2014 (b) Al6101	55
Figure 2.4: (a) Design of Mandrel (b) Design of Mandrel for Al7075 and Al2014 specimen	56
Figure 2.5: Initial design of roller assembly	57
Figure 2.6: (a) Design of Roller (b) Modified design of roller.....	58
Figure 2.7: Fabrication Setup for Machining Roller.....	59
Figure 2.8: (a) Drawing of bolt (b) Drawing of sleeve	60
Figure 2.9: Design of Y Frame	61
Figure 2.10: Roller assembly used for initial flow forming operation.	62
Figure 2.11: Modified design of Y frame	63
Figure 2.12: Parts of the modified roller assembly.....	64
Figure 2.13: Modified Roller assembly	64
Figure 2.14: Flow Forming setup developed at IIT (BHU), Varanasi.....	65
Figure 2.15: Lathe dynamometer (supplied by M/s Testmaster).....	66
Figure 2.16: (a) Layout of data acquisition system (b) Actual measuring setup used during investigation with Lathe dynamometer.....	67
Figure 2.17 Flowchart for mechanical and metallurgical testing of flow formed product.	71
Figure 3.1: Schematic diagram for developing generalized upper bound mathematical model.....	74
Figure 3.2: Schematic diagram showing Surface of discontinuities S_1 , S_2 , S_3 and S_4	81
Figure 3.3: (a) Schematic diagram representing front view showing interaction zone between the roller and the workpiece (b) contact area taken in investigation.....	84
Figure 3.4: Roller – Workpiece contact region approximated as ellipse.....	87
Figure 4.1: Al6101 samples (a) Preform (b) FF02 (c) FF01 (d) FF03.....	97

Figure 4.2: The preform and the flow formed product showing the different regions. IE represents the initial region (not flow formed) while regions 1A-1D denote the thickness reduction obtained in 4 different passes.....	99
Figure 4.3: Thickness reduction per pass and cumulative thickness reduction. Pass 1 refers to 1D, pass 2 refers to region 1C and so on. Pass 4 refers to 1A.....	99
Figure 4.4: Variation of radial force during flow forming operation of sample FF01 ...	101
Figure 4.5: Variation of axial force during flow forming operation of sample FF01	101
Figure 4.6: Variation of circumferential force during flow forming operation of sample FF01.....	102
Figure 4.7: Flow formed FF02-Multistep flow formed sample (a) preform (b) Flow formed product.....	105
Figure 4.8: Preform and Flow formed FF03	107
Figure 4.9: Flow formed samples FF04 and FF05.....	109
Figure 4.10: Ovality in FF05 (a) Flow formed Sample FF05 (b) enlarged view of the end section	111
Figure 4.11: Variation of Vickers hardness with cumulative percentage thickness reduction.....	113
Figure 4.12: (a) Tensile specimen cut out from flow formed FF04. (b) One Tensile specimen	115
Figure 4.13: Engineering Stress- engineering strain curve of sample FF04.....	116
Figure 4.14: X-ray diffraction pattern of as received 6101 T6 Al alloy.....	117
Figure 4.15: X-ray diffraction of flow formed sample.....	117
Figure 4.16: EBSD result of preform Al6101. (a) Inverse pole figure map (b) Image quality map.....	118

Figure 4.17: EBSD result of flow formed Al6101 FF01 IA (a) Inverse pole figure map (b) Image quality map.....	120
Figure 4.18: (a) Misorientation angle in undeformed samples (b) Misorientation angle in flow formed samples FF01 IA.	122
Figure 4.19: Defects in flow formed Al6101sample FF05	123
Figure 4.20: Flow formed 7F01 samples (a) 7F01 (without lubrication) (b) undeformed (c) 7F01-2 without lubrication (d) 7F01-3L (with lubrication.), (e) 7F01-4L(with lubrication)	126
Figure 4.21: Flow formed 7F02 showing crack formation in the middle of the specimen.	127
Figure 4.22: Flow formed 7F03 (a) Experimental view (b) defects present.....	128
Figure 4.23 Flow formed Al7075 annealed sample 7F04	129
Figure 4.24: Flow formed 7F05	130
Figure 4.25: Flow forming forces in Al7075 –O (7F04) (a) radial force (b) axial force (c) circumferential force	131
Figure 4.26: X-ray diffraction pattern of the Al7075-T6 Aluminum alloy	132
Figure 4.27: X-ray diffraction pattern of the 7F02 Aluminum alloy.....	132
Figure 4.28: EBSD result of flow formed Al7075 T6 (a) Inverse pole figure map (b) Image quality map.....	133
Figure 4.29: (a) Grain size distribution in annealed undeformed Al7075 sample (7075-T6) (b) Misorientation angle distribution in 7075-T6	134
Figure 4.30: EBSD result of annealed Al7075 preform (a) Inverse pole figure map (b) Image quality map.....	134
Figure 4.31: (a) Grain size distribution in annealed undeformed Al7075 sample (7075-O) (b) Misorientation angle distribution in 7075-O.....	135

Figure 4.32: EBSD result of flow formed 7F03 (a) Inverse pole figure map (b) Image quality map.....	136
Figure 4.33: (a) Grain Size distribution in sample 7F03 (b) Misorientation angle distribution.....	136
Figure 4.34: EBSD result of flow formed 7F04 (a) Inverse pole figure map (b) Image quality map.....	137
Figure 4.35: (a) Grain Size distribution in sample 7F04 (b) Misorientation angle distribution.....	137
Figure 4.36: Backward flow defect leading to flange formation.....	138
Figure 4.37: Defect: Chip formation during flow formation.....	139
Figure 4.38: Defect: Circular marks in Roller.....	140
Figure 4.39: Bending of Job Flow formed Aluminium 6061(as received) with Roller attack angle of 30°. Rotation speed of 420 RPM.....	140
Figure 4.40: Defect: Crack formation in flow formed samples (a) 7F02 (b) 7F03 and (c) 7F05.....	141
Figure 4.41: Fractograph of 7F02.....	142
Figure 4.42: (a) Fractured portion of 7F03. Sample for fractograph has been taken from encircled region. (b) SEM fractograph of 7F03.....	142
Figure 4.43: Flow formed 7F05 (a) preform and flow formed product (b) crack near the end and ovality at end section.....	143
Figure 4.44: Fractograph of a cracked portion of 7F05.....	144
Figure 4.45: Hardness of undeformed and flow formed samples.....	145
Figure 4.46: Flow formed Al2014 Samples (a) 2014-05 (b) 2014-04 (lower) (c) 2014-03 (d) 2014-04 (upper) (e) 2014-02 (f) 2014-01.....	147
Figure 4.47: Axial force variation during flow formation of Al2014.....	148

Figure 4.48: Radial Force variation in Al2014 flow formed sample.....	148
Figure 4.49: Circumferential Force variation in Al2014 flow formed sample.	149
Figure 4.50: Diametral growth along the fixed end of the workpiece	150
Figure 4.51: Hardness variation of preformed and flow formed samples	151
Figure 4.52: X-ray diffraction pattern of the as annealed Al2014 preform	152
Figure 4.53: X-ray diffraction pattern of the flow formed 2014 Aluminum alloy 2014-05	152
Figure 4.54: EBSD inverse pole figure map of undeformed 2014-O annealed sample (a) Inverse pole figure map (b) Image quality map.....	153
Figure 4.55: (a) Grain size distribution in 2014-O (b) Misorientation angle in 2014-heat treated at 413°C for 2 hour.....	154
Figure 4.56: EBSD result: inverse pole figure for flow formed 2014-T6 sample (a) Inverse pole figure map (b) Image quality map (c) (001) inverse pole figure	154
Figure 4.57: (a) Grain Size distribution in 2014-T6 (b) Misorientation angle in 2014-T6	155
Figure 4.58: EBSD result of flow formed 2014-2 sample (a) Inverse pole figure map (b) Image quality map (c) (001) inverse pole figure	156
Figure 4.59: (a) Grain Size distribution in 2014-2 (b) Misorientation angle in 2014-2 ..	156
Figure 4.60: Defects in flow formed Al2014 product.....	156
Figure 4.61: Fractograph of Al2014 T6 flow formed sample at two different positions.	157
Figure 4.62: Tensile specimen after failure.	158
Figure 4.63: SEM fractograph (a) Al6101 T6 + flow formed (FF04) (b) Al6101 not flow formed (c) Al7075 as received material in T6 condition, heated at 470°C for 3 hours and furnace cooled and not flow formed (d) Al7075 as received material in T6 condition, heated at 470°C for 3 hours and furnace cooled and flow formed (e) Al7075 heat treated +flow	

formed (7F03) (f) Al7075 heat treated +flow formed (7F04) (g) 2014-F04 ; Al2014 heat treated + flow formed (h) Al2014 heat treated but not flow formed.	158
Figure 5.1: Mandrel Support at tail support (a) initial design (b) modified design by introducing a support	169

Abbreviations

EBS	Electron Back Scattered Diffraction
FCC	Face Centred Cubic
GP	Guinier Preston
SAE	Society of Automotive Engineers
UTS	Ultimate tensile strength
HAGB	High Angle Grain boundary
LAGB	Low Angle Grain boundary
XRD	X-Ray diffraction

Symbols

ε_U	plastic strain when stress equals UTS
F_r	Radial force
F_a	Axial force
F_t	Circumferential force
f	Feed in mm/rev
H	Hardness
ε_p	Plastic strain
S	Circumferential contact length
L	Axial contact length
α	Attack angle of roller
V_z	Axial velocity
V_r	Radial velocity
V_θ	Circumferential velocity
$\dot{\varepsilon}_{rr}$	Normal Strain rate in radial direction
$\dot{\varepsilon}_{zz}$	Normal Strain rate in axial direction
$\dot{\varepsilon}_{\theta\theta}$	Normal Strain rate in θ direction
$\bar{\varepsilon}$	Effective strain rate
Δt	Thickness reduction
r_0	Initial thickness, measured along r axis
r_f	Final thickness, measured along r axis
β	Angle subtended by contact region at centre of mandrel
R_m	Radius of mandrel
R_o	Outer radius of preform

R_r	Radius of roller
τ	Shear stress
P_{vd_1}	Power loss due to velocity discontinuity at surface 1
P_{vd_2}	Power loss due to velocity discontinuity at surface 2
P_{vd_3}	Power loss due to velocity discontinuity at surface 3
P_{vd_4}	Power loss due to velocity discontinuity at surface 4
$P_{fric,TW}$	Power loss due to friction at tool- workpiece contact
$P_{fric,mw}$	Power loss due to friction at mandrel- workpiece contact
η_a	Process efficiency factor in axial direction
η_r	Process efficiency factor in radial direction
F_{axial}	Net axial force after incorporating η_a
F_{radial}	Net axial force after incorporating η_r
$T6$	Temper designation
$\%TR$	Percentage thickness reduction