

# LIST OF FIGURES

	<i>Page No.</i>
1.1 Classifications of Sheet Metal Forming operations	1
1.2 Rubber Based Sheet Hydroforming Set-up [6]	2
1.3 Symmetric and Non-symmetric drawn components	3
1.4 Stages in deep drawing process [7]	4
1.5 Three sections x, y, z[8]	5
1.6 Workpiece stresses during deep drawing	5
1.7 Flow of material during deep drawing [9]	7
1.8 Effect of Blank Holding force on wrinkles and tearing [9]	7
1.9 Common defects in deep drawn parts [7]	8
1.10 A schematic plot of forming limit diagram [11]	10
1.11 Forming limit diagram showing different failure zones [11]	11
1.12 Forming limit diagram and other failure limits [11]	12
1.13 Sheet hydroforming: (a) blank setting (b) blank holding; (c) drawing and (d) finishing [15]	13
1.14 Hydro mechanical deep drawing [15]	14
1.15 Hydroforming using a membrane diaphragm [15]	15
1.16 Schematic Representation of Rubber Based Sheet Forming [7]	15
1.17 Set up for rubber forming by Guerin Process [6]	16
1.18 Marform Process [18]	17

1.19	Verson-Hydroform process [6]	18
1.20	Maslennikov's process [19]	18
1.21	Flow chart for Finite Element Analysis	22
2.1	Tensile test specimen for pure Copper	31
2.2	Load vs. displacement plot for Copper	32
2.3	Stress-strain diagram of Copper Sheet	32
2.4	Decomposition of total strain into elastic and plastic components [42]	33
2.5	True stress vs. Plastic strain for Copper	33
2.6	Engineering strains based Forming Limit Curve for pure copper	35
2.7	True strains based Forming Limit Curve for pure copper	35
2.8	Plastic stress vs. Flow stress for SS-304	37
2.9	Rubber classification	37
2.10	Composition of Natural Rubber	41
2.11	Stress-Strain diagram for Natural Rubber	42
2.12	Composition of Nitrile Rubber	42
2.13	Composition of Silicone Rubber	43
2.14	Comparison of load displacement curve for three rubbers	44
2.15	Comparison stress-strain curves for three rubbers	44
3.1	Flow Diagram for Product Design	46
3.2	Family Tree of RBSH Setup	47
3.3	Design stages [48]	49
3.4	Schematic diagram of process in rubber assisted sheet Hydro-forming	50

3.5	Process flow diagram for fabrication of Upper & Lower adapter, Punch and Die Block	57
3.6	Process flow diagram for fabrication of Blank Holder, Base plate and Fluid Chamber	58
3.7	Die Setup Assembly	59
3.8	Upper Adapter	60
3.9	Lower Adaptor	61
3.10	Punch	62
3.11	Die Block	63
3.12	Blank Holder	64
3.13	Base Plate	65
3.14	Fluid Chamber	66
3.15	Schematic diagram of a typical load cell [63]	68
3.16	Schematic diagram of Pressure Transducer [64]	69
3.17	Block diagram of Data Acquisition Module [65]	70
3.18	Experimental setup in rubber assisted sheet Hydro-forming	72
3.19	Die Punch Set-Up	73
3.20	Data Acquisition system	73
3.21	Rubber assisted sheet Hydro-forming Set Up	74
3.22	Plot showing peak load and pressure rise in chamber (T1)	76
3.23	Plot showing peak load and pressure rise in chamber (T2)	77
3.24	Plot showing peak load and pressure rise in chamber (T11)	78
3.25	Plot showing peak load and pressure rise in chamber (T4)	79
3.26	Plot showing peak load and pressure rise in chamber (T5)	79

3.27	Plot showing peak load and pressure rise in chamber (T6)	80
3.28	Plot showing peak load and pressure rise in chamber (T8)	80
3.29	Plot showing peak load and pressure rise in chamber (T10)	81
3.30	Plot showing peak load and pressure rise in chamber (T12)	82
3.31	Plot showing peak load and pressure rise in chamber (T14)	83
3.32	Plot showing peak load and pressure rise in chamber (T16)	83
4.1	3D CAD model of the trial component (SS304)	86
4.2	CAD model of Tool assembly for conventional Drawing Process	87
4.3	CAD model of Tool assembly for Rubber Based Drawing Process	87
4.4	Die assembly and formed components	88
4.5	Reference points to measure stress	89
4.6	Max Principle Stress Variation in Component formed without Rubber Pad	89
4.7	Max Principle Stress Variation in Component formed with Rubber Pad	90
4.8	Natural Rubber	91
4.9	Tool Assemblies for both the Processes (SS304)	92
4.10	Components formed using both Processes (SS304)	92
4.11	Increase in Bulk Hardness Comparison (SS304)	94
4.12	3D model for Sample location (SS304)	95
4.13	Samples for Microstructure (SS304)	95
4.14	Locations for Microstructure analysis (SS304)	96
4.15	Microstructures (Rubber Assisted Process (SS304))	96
4.16	Microstructures (Without Rubber Process)	97
4.17	Comparison of Microstructures (SS304)	97

4.18	Tool Assemblies for both the Processes (pure Copper)	98
4.19	Components formed using both Processes (pure Copper)	98
4.20	Increase in Bulk Hardness Comparison (pure Copper)	100
4.21	3D model for Sample location (pure Copper)	101
4.22	Samples for Micro-hardness (pure Copper)	101
4.23	Locations for Microstructure analysis (pure Copper)	102
4.24	Microstructures (Rubber Assisted Process (pure Copper))	102
4.25	Microstructures (Without Rubber Process (pure Copper))	103
4.26	Comparison of Microstructures (pure Copper)	104
4.27	Die Assembly for Conical Component	106
4.28	Die assembly and Punch for forming of Conical Shape	106
4.29	Deep Drawing Setup On Press Machine	107
4.30	Components formed using both Processes	107
4.31	Comparison Of Thickness for Both Processes	108
4.32	Thickness Comparison at 5 Location	108
4.33	Die Assembly for Hemispherical shape Rubber-based deep drawing process	109
4.34	CAD model of Hemispherical Cone	110
4.35	Comparative percentage thinning in X-section	111
4.36	Comparative percentage thinning in Y-section	112
4.37	Pattern of circular grid [73]	113
4.38	Theoretical FLC of Copper	117
4.39	Grid marking using Chemical Analysis	118
4.40	Experimental Set up for forming	118

4.41	Formed cones and deformation of circle into ellipse	118
4.42	Grid deformation before and after forming [72]	119
4.43	Deformation in circle under various forming conditions [87]	120
4.44	Strain measurement location	121
4.45	Comparison of FLD Plots	122
4.46	Hemispherical Cups formed with assistance of Rubbers	124
4.47	Comparative thickness variation in cup (X-section)	125
4.48	Comparative thickness variation in cup (Y-section)	125
5.1	Finite element model of Conventional Deep Drawing	131
5.2	Finite element model of Rubber assisted deep drawing	131
5.3	Component formed by conventional deep drawing	132
5.4	Component formed by rubber assisted deep drawing	133
5.5	Thickness distribution in conventional deep drawing	133
5.6	Thickness distribution in rubber assisted deep drawing	134
5.7	Thickness distribution along the distance from cup centre in rubber assisted deep drawing	134
5.8	Von-Mises stress in conventional deep drawing	135
5.9	Von-Mises stress in Rubber assisted deep drawing	135
5.10	Von-Mises stress comparison	136
5.11	Plastic strain in conventional deep drawing	136
5.12	Plastic strain in Rubber assisted deep drawing	137
5.13	Comparative plot for Plastic strain	137
5.14	Finite element model of Rubber assisted Deep Drawing Operation	139
5.15	Loads and boundary conditions for sheet hydro-forming process	141

5.16	Model validation: Deformed shape	142
5.17	Comparison of shell thickness	142
5.18	Variation of thickness along cone wall for cone angle $84^\circ$	143
5.19	Variation of thickness along cup wall for different cone angle (conventional sheet forming process)	144
5.20	Variation of thickness along cup wall for different cone angle (rubber assisted sheet forming process)	145
5.21	Variation of thickness along cup wall for different cone angle (rubber assisted sheet hydro forming process)	145
5.22	Variation of von-Mises stresses with cup cone angle [Conventional forming process]	147
5.23	Variation of von-Mises stresses with cup cone angle [Rubber assisted forming process]	147
5.24	Variation of von-Mises stresses with cup cone angle [Rubber assisted hydro-forming process]	148
5.25	Assembly of rubber assisted sheet Hydro-forming	150
5.26	Distribution of Pressure in Simulation as per experimental data	151
5.27	Formed cup in Simulation and actual Hardware	151
5.28	Various FEM plots	152
5.29	Comparison of shell thickness in simulation and experiment	153
5.30	Variation of Plastic strain	153
5.31	Variation of von-Mises stress	154
5.32	Tool Assembly for forming of Non-symmetric Component	155
5.33	FEM model of Die assembly	156
5.34	Max. Principle Stress Plot	156
5.35	Von-Mises Plot	157

5.36 Thickness Plot	157
5.37 Model Showing Rubber Deformation	158
A.1 Base Plate	178
A.2 Blank Holder	179
A.3 Cone ( $84^\circ$ )	180
A.4 SS-304 Cup	181
A.5 Die Block	182
A.6 Fluid Chamber	183
A.7 Lower adaptor	184
A.8 Upper Adaptor	185
A.9 Punch ( $84^\circ$ )	186
A.10 Punch ( $95^\circ$ )	187
A.11 Spherical Cup	188
A.12 Spherical Punch	189
A.13 RBSH test set-up	190
A.14 RBSH test set-up (Top and Front View)	191