

LIST OF FIGURES

Figure Number	Page No.
Figure 1.1: Schematic diagram of Continuous Extrusion process[Green et al. (1974)]	1
Figure 1.2: Principle of Continuous Extrusion process [Bridewater and Maddock, (1992)]	2
Figure 1.3: Schematic Diagram of Design Developed and Fabricated Continuous Extrusion Setup for 9.5 mm Aluminum feedstock material	4
Figure 1.4: Radial extrusion [IR 1, (BWE Ltd, UK)]	6
Figure 1.4(a): Single groove radial	7
Figure 1.4(b):Twin groove radial	7
Figure 1.5: Tangential Extrusion process [IR 1, (BWE Ltd, UK)]	7
Figure 1.6: Pattern of Material flow in process of Extrusion [Lau and Stranger, 1981]	8
Figure 1.7: Extrusion defects (a) Internal cracking[Cocks and Ashby, 1980](b) Piping [Tang et al., (1994)] (c) Surface cracking [Lee et al., (1973)]	11
Figure 1.8: Process variables in continuous extrusion process	11
Figure 3.1: Implementation of CAE process, [Fu et al. (2006)]	36
Figure 3.2: (a) and (b) FEA Simulation mesh model for 8mm diameter Aluminum feedstock	41
Figure 3.3: X-Load distribution for 8 mm Aluminum feedstock	42
Figure 3.4: Y-Load distribution for 8 mm Aluminum feedstock	43
Figure 3.5: Z Load distribution for 8 mm Aluminum feedstock	43
Figure 3.6: Effective stress distribution for 8 mm Aluminum feedstock	44
Figure 3.7: Effective strain distribution for 8 mm Aluminum feedstock	44
Figure 3.8: Damage distribution for 8 mm Aluminum feedstock	45
Figure 3.9: Temperature distribution for 8 mm Aluminum feedstock	45

Figure 3.10: Velocity distribution for 8 mm Aluminum feedstock	46
Figure 3.11: Torque distribution for 8 mm Aluminum feedstock	46
Figure 3.12: X Load distribution for 9.5 mm Aluminum feedstock	51
Figure 3.13: Y Load distribution for 9.5 mm Aluminum feedstock	51
Figure 3.14: Z Load distribution for 9.5 mm Aluminum feedstock	52
Figure 3.15: Torque distribution for 9.5 mm Aluminum feedstock	52
Figure 3.16: Effective stress distribution for 9.5 mm Aluminum feedstock	53
Figure 3.17: Effective strain distribution for 9.5 mm Aluminum feedstock	53
Figure 3.18: Effective strain rate distribution for 9.5 mm Aluminum feedstock	54
Figure 3.19: Velocity distribution for 9.5 mm Aluminum feedstock	54
Figure 3.20: Damage distribution for 9.5 mm Aluminum feedstock	55
Figure 3.21: Temperature distribution for 9.5 mm Aluminum feedstock	55
Figure 3.22: Effective stress distribution at 100 °C for 9.5 mm Aluminum feedstock	56
Figure 3.23: Effective stress distribution at 300 °C for 9.5 mm Aluminum feedstock	56
Figure 3.24: Effective stress distribution at 700 °C for 9.5 mm Aluminum feedstock	57
Figure 3.25: Torque distribution at 100 °C for 9.5 mm Aluminum feedstock	58
Figure 3.26: Torque distribution at 300 °C for 9.5 mm Aluminum feedstock	58
Figure 3.27: Torque distribution at 700 °C for 9.5 mm Aluminum feedstock	59
Figure 3.28: Damage distribution at 100 °C for 9.5 mm Aluminum feedstock	60
Figure 3.29: Damage distribution at 300 °C for 9.5 mm Aluminum feedstock	61
Figure 3.30: Damage distribution at 700 °C for 9.5 mm Aluminum feedstock	61
Figure 3.31: Temperature distribution at 100 °C for 9.5 mm Aluminum feedstock	62
Figure 3.32: Temperature distribution at 300 °C for 9.5 mm Aluminum feedstock	63

Figure 3.33: Temperature distribution at 700 °C for 9.5 mm Aluminum feedstock	63
Figure 3.34: Velocity distribution at 100 °C for 9.5 mm Aluminum feedstock	64
Figure 3.35: Velocity distribution at 300 °C for 9.5 mm Aluminum feedstock	65
Figure 3.36: Velocity distribution at 700 °C for 9.5 mm Aluminum feedstock	65
Figure 3.37: X-Load distribution for 12.5 mm Copper feedstock	67
Figure 3.38: Y-Load distribution for 12.5 mm Copper feedstock	68
Figure 3.39: Z-Load distribution for 12.5 mm Copper feedstock	68
Figure 3.40: Torque distribution for 12.5 mm Copper feedstock	69
Figure 3.41: Effective stress distribution for 12.5 mm Copper feedstock	69
Figure 3.42: Effective strain distribution for 12.5 mm Copper feedstock	70
Figure 3.43: Effective strain rate distribution for 12.5 mm Copper feedstock	70
Figure 3.44: Damage distribution for 12.5 mm Copper feedstock	71
Figure 3.45: Temperature distribution for 12.5 mm Copper feedstock	71
Figure 3.46: Velocity distribution for 12.5 mm Copper feedstock	72
Figure 3.47: Effect of die temperature on total Load for 9.5 mm Aluminum feedstock	73
Figure 3.48: Effect of die temperature on Torque required for 9.5 mm Aluminum feedstock	73
Figure 3.49: Effect of die temperature Effective stress for 9.5 mm Aluminum feedstock	74
Figure 3.50: Effect of die temperature on effective strains for 9.5 mm Aluminum feedstock	74
Figure 3.51: Effect of die temperature on Damage value for 9.5 mm Aluminum feedstock	75
Figure 3.52: Effect of die temperature on Product temperature for 9.5 mm Aluminum feedstock	75
Figure 3.53: Effect of die temperature on strain rate for 9.5 mm Aluminum feedstock	77
Figure 3.54: Effect of feedstock temperature on total Load for 9.5 mm Aluminum feedstock	77
Figure 3.55: Effect of feedstock temperature on Torque for 9.5 mm Aluminum feedstock	78

Figure 3.56: Effect of feedstock temperature on Effective stresses for 9.5 mm Aluminum feedstock	78
Figure 3.57: Effect of feedstock temperature on effective strains for 9.5 mm Aluminum	79
Figure 3.58: Effect of feedstock temperature on Damage value for 9.5 mm Aluminum	79
Figure 3.59: Effect of feedstock temperature on Product temperature for 9.5mm Aluminum	80
Figure 3.60: Effect of feedstock temperature on strain rate for 9.5 mm Aluminum feedstock	80
Figure 3.61: Effect of extrusion ratio on total Load for 9.5 mm Aluminum feedstock	83
Figure 3.62: Effect of extrusion ratio on Torque required for 9.5 mm Aluminum feedstock	83
Figure 3.63: Effect of extrusion ratio on Effective stresses for 9.5 mm Aluminum feedstock	84
Figure 3.64: Effect of extrusion ratio on effective strains for 9.5 mm Aluminum feedstock	84
Figure 3.65: Effect of extrusion ratio on Damage value for 9.5 mm Aluminum feedstock	85
Figure 3.66: Effect of extrusion ratio on Product temperature for 9.5 mm Aluminum feedstock	85
Figure 3.67: Effect of extrusion ratio on strain rate for 9.5 mm Aluminum feedstock	86
Figure 3.68: Effect of extrusion wheel velocity on total Load required for 9.5 mm Aluminum feedstock	86
Figure 3.69: Effect of extrusion wheel velocity on Torque Load required for 9.5 mm Aluminum feedstock	87
Figure 3.70: Effect of extrusion wheel velocity on Effective stresses for 9.5 mm Aluminum feedstock	87
Figure 3.71: Effect of extrusion wheel velocity on effective strains for 9.5 mm Aluminum feedstock	88
Figure 3.72: Effect of extrusion wheel velocity on Damage value for 9.5 mm Aluminum Feedstock	88
Figure 3.73: Effect of extrusion wheel velocity on Product temperature for 9.5 mm Aluminum feedstock	89

Figure 3.74: Effect of extrusion wheel velocity on strain rate for 9.5 mm Aluminum feedstock	89
Figure 3.75: Effect of wheel groove friction on total Load required for 9.5 mm Aluminum Feedstock	91
Figure 3.76: Effect of wheel groove friction on Torque required for 9.5 mm Aluminum Feedstock	91
Figure 3.77: Effect of wheel groove friction on effective stress for 9.5 mm Aluminum Feedstock	92
Figure 3.78: Effect of wheel groove friction on effective strains for 9.5 mm Aluminum Feedstock	92
Figure 3.79: Effect of wheel groove friction on Damage value for 9.5 mm Aluminum feedstock	93
Figure 3.80: Effect of wheel groove friction on effective stress for 9.5 mm Aluminum feedstock	93
Figure 3.81: Effect of wheel groove friction on strain rate for 9.5 mm Aluminum feedstock	95
Figure 3.82: Contact area and grip length in continuous extrusion process	97
Figure 3.83: Detail showing grip lengths	98
Figure 3.84: Extrusion grip length showing contact pressure	99
Figure 3.85: Graphical comparison of Analytical and Simulation power for Aluminum feedstock	113
Figure 4.1 : Virtual designed developed and fabricated Continuous Extrusion machine setup	116
Figure 4.2 : CAE model of Continuous Extrusion machine setup designed developed and Fabricated	116
Figure 4.3: Continuous Extrusion machine setup for 8 mm Aluminum feedstock material	117
Figure 4.4: Modified Continuous Extrusion machine setup for 8 mm Aluminum feedstock material after several stages of modification	117
Figure 4.5: Designed Developed and Fabricated Continuous Extrusion machine setup for 9.5 mm Aluminum feedstock material.	118

Figure 4.6 : Extrusion Wheel with circular groove for 8 mm feedstock material	119
Figure 4.7 : Coining Wheel for 8 mm feedstock material	120
Figure 4.8: Grooved Extrusion shoe for 8 mm feedstock material	120
Figure 4.9: Extrusion die block for 8 mm feedstock Continuous Extrusion machine setup	121
Figure 4.10: Abutment before modification for 8 mm feedstock Continuous Extrusion machine setup	121
Figure 4.11: Additional gearbox incorporated for modification of 8 mm feedstock Continuous Extrusion machine setup	123
Figure 4.12: A pair of spur gear for modification of 8mm feedstock Continuous Extrusion machine setup	123
Figure 4.13: Modified abutment for 8 mm feedstock Continuous Extrusion machine setup	124
Figure 4.14: Modified for 8 mm feedstock Continuous Extrusion machine setup	124
Figure 4.15: Modified Continuous Extrusion machine setup for 8 mm feedstock material	125
Figure 4.16: Material coming out of the abutment hole	125
Figure 4.17: Extrusion Wheel for 9.5 mm feedstock Continuous Extrusion machine setup	131
Figure 4.18: Coining Wheel for 9.5 mm feedstock Continuous Extrusion machine setup	131
Figure 4.19: Extrusion Shoe for 9.5 mm feedstock Continuous Extrusion machine setup	132
Figure 4.20: Abutment Die Chamber for 9.5 mm feedstock Continuous Extrusion setup	132
Figure 4.21: Extrusion Die for 9.5 mm feedstock Continuous Extrusion machine setup	133
Figure 4.22: Scraper for 9.5 mm feedstock Continuous Extrusion machine setup	133
Figure 4.23: Variable Frequency Drive for 9.5 mm feedstock Continuous Extrusion setup	134
Figure 4.24: Die Chamber heating arrangement device for 9.5 mm feedstock Continuous Extrusion setup	134

Figure 4.25: Design Developed and Fabricated Continuous Extrusion machine setup for 9.5 mm feedstock material	135
Figure 4.26: Close view of Design Developed and Fabricated Continuous Extrusion machine setup for 9.5 mm feedstock material	135
Figure 4.27: View of Gearbox coupled with Continuous Extrusion machine setup for 9.5 mm feedstock material	136
Figure 4.28: Close view of Extrusion Wheel, Coining Wheel and Scraper of Continuous Extrusion machine setup for 9.5 mm feedstock material	136
Figure 4.29: View of Extruded material from Design Developed and Fabricated Continuous Extrusion machine setup for 9.5 mm feedstock material	137
Figure 4.30: Schematic Diagram of Design Developed and Fabricated Continuous Extrusion Setup for 9.5 mm Aluminum feedstock material	139
Figure 4.31 Sectional View of design developed and fabricated setup for 9.5 mm Aluminum feedstock	140
Figure 4.32: Table of parts of 2D model (schematic) of Continuous Extrusion setup	141
Figure 4.33: All View of design developed and fabricated setup for 9.5 mm Aluminum Feedstock	142
Figure 5.1: Commercial Continuous Extrusion machine setup 1	145
Figure 5.2: Fabricated Continuous Extrusion machine setup for 9.5 mm feedstock material	145
Figure 5.3: Extruded product of Copper alloy	146
Figure 5.4: Extruded product of Aluminum alloy	146
Figure 5.5: Extruded product of Aluminum alloy 6mm diameter at 6 rpm, extrusion ratio 2.5	147
Figure 5.6: Extruded product of Aluminum alloy of 6mm diameter at 6 rpm, extrusion ratio 1.84	148
Figure 5.7: Extruded product of 8mm diameter at 6 rpm, extrusion ratio 1.41	148
Figure 5.8: Pure Copper rod feedstock before extrusion of 12.5 mm diameter	150

Figure 5.9: Extruded Copper product of 6mm diameter at 6rpm, extrusion ratio 4.34	150
Figure 5.10: Extruded Copper rod of 7mm diameter at 6 rpm, extrusion ratio 3.18	150
Figure 5.11: Graphical comparison of experimental and simulation results for effect of wheel speed on total power required for Aluminum alloy	152
Figure 5.12: Graphical comparison of experimental and simulation results for effect of wheel speed on total power required for Aluminum alloy	152
Figure 5.13: Graphical comparison of experimental and simulation results for effect of wheel speed on total power required for Aluminum alloy	153
Figure 5.14: Graphical comparison of experimental and simulation results for effect of extrusion ratio on total power required	153
Figure 5.15: Graphical comparison of experimental and simulation results for effect of wheel speed on total power required for Copper alloy	154
Figure 5.16: Microstructure samples of Aluminum rod before and after extrusion	155
Figure 5.17: Microstructure samples of Copper rod before and after extrusion	155
Figure 5.18: (a), (b), (c) Microstructures of Aluminum samples of 6mm size at 6 rpm at 50x, 100x and 200x respectively	158
Figure 5.19 : (a) and (b) Microstructures of Aluminum samples of 7mm size at 6rpm at 50x, 100x and 200x respectively	158
Figure 5.20 :(a), (b), (c) shows the microstructures of Aluminum samples of 8mm size at 6rpm at 50x, 100x and 200x respectively	159
Figure 5.21:(a), (b), (c) shows the microstructures of Aluminum samples of 6mm size at 8rpm at 50x, 100x and 200x respectively	159
Figure 5.22:(a),(b), (c) shows the microstructures of Aluminum samples of 7 mm size at 8 rpm at 50x, 100x and 200x respectively	159

Figure 5.23: (a), (b), (c) shows the microstructures of Aluminum samples of 8 mm size at 8 rpm at 50x, 100x and 200x respectively	160
Figure 5.24: (a), (b), (c) shows the microstructures of Aluminum samples of 8 mm size at 10 rpm at 50x, 100x and 200x respectively	160
Figure 5.25: (a) and (b) shows the microstructures of Aluminum samples of raw feedstock of 9.5 mm size at 6rpm at 50x and 100x respectively	160
Figure 5.26: (a), (b), (c) shows the microstructures of Copper samples of 6mm size at 4rpm at 50x, 100x and 200x respectively	162
Figure 5.27: (a), (b), (c) shows the microstructures of Copper samples of 6mm size at 6 rpm at 50x, 100x and 200x respectively	162
Figure 5.28 : (a), (b), (c) shows the microstructures of Copper samples of 6 mm size at 8 rpm at 50x, 100x and 200x respectively	162
Figure 5.29: (a), (b), (c) shows the microstructures of Copper samples of 6 mm size at 10 rpm at 50x, 100x and 200x respectively	163
Figure 5.30: (a), (b), (c) shows the microstructures of Copper samples of 7 mm size at 4 rpm at 50x, 100x and 200x respectively	163
Figure 5.31: (a), (b), (c) shows the microstructures of Copper samples of 7mm size at 6 rpm at 50x, 100x and 200x respectively	163
Figure 5.32: (a), (b), (c) shows the microstructures of Copper samples of 7 mm size at 8 rpm at 50x, 100x and 200x respectively	164
Figure 5.33: (a),(b), (c) shows the microstructures of Copper samples of 7mm size at 10rpm at 50x, 100x and 200x respectively	164
Figure 5.34: (a),(b), (c) shows the microstructures of Copper samples of raw feedstock of 12.5 mm size at 50x, 100x and 200x respectively	164
Figure 5.35: Tensile sample Gauge Length = 15.6 mm, Gauge diameter =4.5 mm	165

Figure 5.36: Tensile sample for 7mm and 8mm extruded Aluminum rod Gauge length=15.6 mm, Gauge diameter=4.5 mm	165
Figure 5.37: Fractured tensile test sample of extruded Aluminum alloy	166
Figure 5.38: Tensile sample of extruded Copper rod (Gauge Length=15.6 mm, Gauge diameter =4.5 mm)	169
Figure 5.39: Fractured tensile sample of extruded Copper rod	169
Figure 5.40: Hardness test sample of Aluminum alloy before and after extrusion	170
Figure 5.41: Hardness test samples of Copper rod before and after extrusion	170
Figure 5.42: Variation of Hardness with wheel velocity for Aluminum alloy	173
Figure 5.43: Variation of Hardness with extrusion ratio for Aluminum alloy	173
Figure 5.44: Variation of energy break with extrusion wheel velocity for Aluminum alloy	174
Figure 5.45: Variation of Maximum strength with extrusion wheel velocity for Aluminum Alloy	174
Figure 5.46: Variation of breaking Load with extrusion wheel velocity for Aluminum alloy	175
Figure 5.47: Variation of % elongation with extrusion wheel velocity for Aluminum alloy	175
Figure 5.48: Variation of % elongation with extrusion ratio for Aluminum alloy	176
Figure 5.49: Variation of energy break with extrusion ratio for Aluminum alloy	177
Figure 5.50: Variation of 0.2% Yield strength with extrusion ratio for Aluminum alloy	177
Figure 5.51: Variation of energy break with extrusion ratio for Aluminum alloy	178
Figure 5.52: Variation of maximum strength with extrusion ratio for Aluminum alloy	178
Figure 5.53: Variation of 0.2% Yield strength with extrusion wheel velocity for Aluminum Alloy	179
Figure 5.54: Variation of Hardness with extrusion wheel velocity for Copper alloy	180

Figure 5.55: Variation of maximum strength with extrusion wheel velocity for Copper alloy	180
Figure 5.56: Variation of % elongation with extrusion wheel velocity for Copper alloy	181
Figure 5.57: Variation of 0.2% yield strength with extrusion wheel velocity for Copper alloy	182
Figure 5.58: Variation of breaking Load with extrusion wheel velocity for Copper alloy	182
Figure 5.59: Variation of energy break with extrusion wheel velocity for Copper alloy	183
Figure 6.1: Residual plots for UTS	193
Figure 6.2: Contour plot of UTS with variation of wheel velocity and product diameter	194
Figure 6.3: Surface plot of UTS with variation of wheel velocity and product diameter	194
Figure 6.4: Optimization plot for UTS with respect to wheel velocity and product diameter	195
Figure 6.5: Residual plots for Hardness	199
Figure 6.6: Contour plot of Hardness with variation of wheel velocity and product diameter	199
Figure 6.7: Surface plot of Hardness with variation in wheel velocity and product diameter	200
Figure 6.8: Optimization plot for Hardness with respect to wheel velocity and product diameter	200
Figure 6.9: Residual plots for YIELD STRENGTH	204
Figure 6.10: Contour plot of YS with variation in wheel velocity and product diameter	204
Figure 6.11: Surface plot of YS with variation in wheel velocity and product diameter	205
Figure 6.12: Optimization plot for Yield strength with respect to wheel velocity and product diameter	205
Figure 6.13: Residual plots for % ELONGATION	210
Figure 6.14: Contour plot of % Elongation with variation in wheel velocity and product diameter	210
Figure 6.15: Surface plot of % Elongation with variation in wheel velocity and product diameter	211

Figure 6.16: Optimization plot for % Elongation with respect to wheel velocity and product diameter	211
Figure 6.17: Residual plots for UTS	217
Figure 6.18: Contour plot for UTS	217
Figure 6.19: Contour plot for UTS	218
Figure 6.20: Optimization plot for UTS	218
Figure 6.21: Residual plots for Hardness	223
Figure 6.22: Contour plot for Hardness	223
Figure 6.23: Surface plot for Hardness	224
Figure 6.24: Optimization plot for Hardness	224
Figure 6.25: Residual plots for Yield Strength	227
Figure 6.26: Contour plot for Yield Strength	228
Figure 6.27: Surface plot for YS	228
Figure 6.28: Optimization plot for Yield Strength	229
Figure 6.29: Residual plots for % Elongation	232
Figure 6.30: Contour plot for % Elongation	232
Figure 6.31: Surface plot for % Elongation	233
Figure 6.32: Optimization plot for % Elongation	233
Figure 6.33: Residual plots for Load required	242
Figure 6.34: Surface plots for Load required	242
Figure 6.35: Contour plots for Load required	243
Figure 6.36: Optimization plot for Load required	243
Figure 6.37: Residual plots for Torque required	247
Figure 6.38: Surface plots for Torque required	247

Figure 6.39: Contour plots for Torque required	248
Figure 6.40: Optimization plot for Torque required	248
Figure 6.41: Residual plots for Effective stress	252
Figure 6.42: Surface plots for Effective stresses	252
Figure 6.43: Contour plots for Effective stresses	253
Figure 6.44: Optimization plot for Effective stresses	253
Figure 6.45: Residual plots for Damage value	257
Figure 6.46: Surface plots for Damage value	257
Figure 6.47: Contour plots for Damage value	258
Figure 6.48: Optimization plot for Damage value	258
Figure 6.49: Residual plots for Product temperature	262
Figure 6.50: Surface plots for Product temperature	262
Figure 6.51: Contour plots for Product temperature	263
Figure 6.52: Optimization plot for Product temperature	263
Figure 6.53: Training epoch cycles vs. calculated mean square error of the supervised training for the designed ANN	266
Figure 6.54: Correlation chart for experimental and predicted Load required for Continuous Extrusion	267
Figure 6.55: Best fitness plot showing the progressive performance (for Load required) of GA over generations till the achievement of optimum solution (upper plot). Variables (in lower plot) showing the level of wheel velocity, product diameter, friction condition, feedstock temperature and die temperature.	269