

STRETCH FLANGEABILITY OF ALUMINIUM ALLOYS IN CIRCULAR AND SQUARE HOLE FLANGING PROCESSES

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by

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Dedicated to

My Parents

and

Grandparents

CERTIFICATE

This is to certify that the thesis entitled “**Stretch Flangeability of Aluminium Alloys in Circular and Square Hole Flanging Processes**” being submitted by **Mr. Vinay Kumar** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** in Department of Mechanical Engineering is a bonafide research work carried out by him under my supervision and guidance. To the best of my knowledge the thesis has reached the requisite standard. The research reports and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.

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IIT DELHI

ABSTRACT

The growing emphasis on fuel efficiency and environmental sustainability has significantly propelled the demand for lightweight materials in the automotive industry. Aluminium alloys, known for their high strength-to-weight ratio, have a high potential for replacing steel in manufacturing various sheet metal parts for automobiles. However, formability of aluminium alloys is a critical factor in the success of sheet metal forming operations. In the assessment of formability of sheet metals, stretch flangeability is an important aspect. The stretch flangeability refers to the local edge formability to avoid cracking during the expansion of a hole in a sheet metal part to form a flange. It is evaluated by determination of hole expansion ratio (HER), which is the ratio of final hole diameter to initial hole diameter in a hole expansion test and it is a measure of the local formability at the edge of the hole. Besides the material properties, hole making method also influences the stretch flangeability of sheet metals. While the stretch flangeability of steels has been well reported, it has been studied only to a very limited extent in the case of aluminium alloys. In view of this, the present work is aimed at an investigation into the hole expansion test and stretch flanging processes, particularly focusing on aluminium alloys of different grades and comparing their performance with steels.

In the first part of the work, stretch flangeability of five different aluminium alloys (AA2024, AA5083, AA5754, AA6061 and AA7075) and two grades of steel (DP600 steel and EDD Steel) has been investigated by numerical simulation of the hole expansion test (HET) along with characterisation of their tensile properties, anisotropy and forming limits. The HET experiments were carried out on a customised formability testing machine to validate the predicted hole expansion ratio, and strain and thinning at failure. It has been found that AA5754 and AA6061 exhibited the highest hole expansion ratio ($HER \approx 67\%$) among the Al alloys studied in the present work and it is significantly higher than that of DP600 steel also. AA2024 and AA5083 also exhibited higher stretch flangeability than DP600 steel in HET making these four alloys potentially suitable for lightweighting of sheet metals parts involving stretch flanging operations.

The quality of the hole edge plays a major role in the determination of stretch flangeability of sheet metals. Therefore, the effect of hole making method on HER has been studied in the second part of the work by preparing the samples using three different hole making methods (punching, abrasive waterjet cutting and laser cutting) from two aluminium alloys (AA5083 and AA5754) and DP600 steel. A hydro-pneumatic press along with a suitable die assembly has been

developed for punching the holes. The hole edge quality has been found to be very high in laser cut samples resulting in the highest HER in all the three materials. An improvement of 36.8% and 22.5% has been obtained with laser cutting when compared to punching in the case of AA5083 and AA5754, respectively. Though WJC produced a better-quality hole edge than punching, the presence of a small notch resulted in early cracking resulting in lower HER when compared to laser cutting. However, in the case of DP600 steel, WJC resulted in a much higher improvement. In punched holes, presence of voids and microcracks and work hardening due to plastic deformation caused lower HER.

In the actual manufacturing of sheet metal parts involving stretch flanging, circular hole flanging and square hole flanging processes are commonly used. Therefore, in the third part of the work, stretch flangeability of Al alloys has been investigated in circular hole flanging and square hole flanging processes by numerical simulation and experimental validation and the results of formability, strain distribution, thinning and flange height are compared with steels. Among the aluminium alloys, AA5754 and AA5083 alloys showed highest formability in circular hole flanging indicated by their lowest minimum hole flanging coefficient (HFC_{min}) and AA7075 exhibited the highest HFC_{min} . It has been observed that HFC_{min} of AA5754 and AA5083 alloys is nearly equal to that of DP600 steel. The final flange thickness in circular hole flanging has been analytically predicted incorporating the anisotropy of sheet metals. AA5754, AA5083 and AA6061 showed better formability in square hole flanging process as indicated by their HFC_{min} values which are lower than or equal to that of DP600 steel. But in general, all the materials showed lower formability in square hole flanging than in circular hole flanging due to very high strain localization causing severe thinning and failure at the corners of the hole as indicated by the effective strain and thinning (%) distributions in the simulation.

It can be concluded that AA5083, AA5754 and AA6061 have high stretch flangeability in both circular hole flanging and square hole flanging processes and these alloys could be considered as potential materials to replace steel for stretch flanging applications where very high strength is not an essential requirement.

Key Words: Stretch flanging, Aluminium alloys, Lightweighting, Formability, Simulation

सार

ईंधन दक्षता और पर्यावरणीय स्थिरता पर बढ़ते जोर ने ऑटोमोटिव उद्योग में हल्के सामग्रियों की मांग को काफी हद तक बढ़ा दिया है। उच्च शक्ति-से-वजन अनुपात के लिए प्रसिद्ध एल्युमिनियम मिश्र धातुओं में ऑटोमोटिव के विभिन्न शीट मेटल हिस्सों के निर्माण में स्टील को प्रतिस्थापित करने की उच्च क्षमता है। हालांकि, एल्युमिनियम मिश्र धातुओं की फॉर्मिबिलिटी शीट मेटल फॉर्मिंग ऑपरेशनों की सफलता में एक महत्वपूर्ण कारक है। शीट मेटल की फॉर्मिबिलिटी के आकलन में, स्ट्रेच फ्लैन्जेबिलिटी एक महत्वपूर्ण पहलू है। स्ट्रेच फ्लैन्जेबिलिटी एक शीट मेटल भाग में फ्लैज बनाने के लिए होल के विस्तार के दौरान क्रैकिंग से बचने के लिए स्थानीय किनारे की फॉर्मिबिलिटी को संदर्भित करती है। इसे होल एक्सपेंशन रेशियो (HER) के निर्धारण द्वारा मापा जाता है, जो होल एक्सपेंशन टेस्ट में अंतिम होल के व्यास और प्रारंभिक होल के व्यास का अनुपात है, और यह होल के किनारे की स्थानीय फॉर्मिबिलिटी का माप है। मटेरियल गुणों के अलावा, होल बनाने की विधि भी शीट मेटल की स्ट्रेच फ्लैन्जेबिलिटी को प्रभावित करती है। जबकि स्टील की स्ट्रेच फ्लैन्जेबिलिटी को अच्छी तरह से रिपोर्ट किया गया है, एल्युमिनियम मिश्र धातुओं के मामले में इसे बहुत सीमित रूप से अध्ययन किया गया है। इसे ध्यान में रखते हुए, वर्तमान कार्य का उद्देश्य होल एक्सपेंशन टेस्ट और स्ट्रेच फ्लैन्जिंग प्रक्रियाओं की जांच करना है, विशेष रूप से विभिन्न ग्रेड की एल्युमिनियम मिश्र धातुओं पर ध्यान केंद्रित करते हुए और उनके प्रदर्शन की तुलना स्टील से करना है।

काम के पहले भाग में, पांच अलग-अलग एल्युमिनियम मिश्र धातुओं (AA2024, AA5083, AA5754, AA6061 और AA7075) और दो ग्रेड के स्टील (DP600 स्टील और EDD स्टील) की स्ट्रेच फ्लैन्जेबिलिटी की होल एक्सपेंशन टेस्ट (HET) के संख्यात्मक अनुकरण द्वारा जाँच की गई है, साथ ही उनके तन्यता गुणों, एनीसोट्रॉपी और फॉर्मिंग लिमिट्स के गुणों का वर्णन किया गया है। HET प्रयोगों को होल एक्सपेंशन अनुपात की भविष्यवाणी को मान्य करने के लिए और विफलता के समय तनाव और थिनिंग को सत्यापित करने के लिए एक कस्टमाइज्ड फॉर्मिबिलिटी टेस्टिंग मशीन पर किया गया। यह पाया गया कि AA5754 और AA6061 ने अध्ययन में शामिल एल्युमिनियम मिश्र धातुओं में से सबसे उच्च होल एक्सपेंशन अनुपात ($HER \approx 67\%$) प्रदर्शित किया, जो DP600 स्टील से भी काफी अधिक है। AA2024 और AA5083 ने भी HET में DP600 स्टील से अधिक स्ट्रेच फ्लैन्जेबिलिटी दिखाई, जिससे ये चार मिश्र धातुएं स्ट्रेच फ्लैन्जिंग ऑपरेशनों में शामिल शीट मेटल पार्ट्स के हल्के वजन के लिए संभावित रूप से उपयुक्त हैं।

होल के किनारे की गुणवत्ता शीट मेटल की स्ट्रेच फ्लैन्जेबिलिटी के निर्धारण में एक प्रमुख भूमिका निभाती है। इसलिए, काम के दूसरे भाग में तीन अलग-अलग होल बनाने की विधियों (पंचिंग, एब्रेसिव वॉटरजेट कटिंग और लेजर कटिंग) का उपयोग करके दो एल्युमिनियम मिश्र धातुओं (AA5083 और AA5754) और DP600 स्टील से नमूने तैयार करके HER पर होल बनाने की विधि का प्रभाव अध्ययन किया गया। पंचिंग के लिए हाइड्रो-न्यूमैटिक प्रेस और एक उपयुक्त डाई असेंबली विकसित की गई है। लेजर कटे हुए नमूनों में होल के किनारे की गुणवत्ता बहुत अधिक पाई गई, जिससे तीनों सामग्रियों में उच्चतम HER प्राप्त हुआ। AA5083 और AA5754 के मामले में लेजर कटिंग की तुलना में पंचिंग की तुलना में क्रमशः 36.8% और 22.5% सुधार

हुआ। यद्यपि WJC ने पंचिंग से बेहतर गुणवत्ता वाला होल का किनारा उत्पन्न किया, लेकिन एक छोटे से कटाव की उपस्थिति ने जल्दी दरार का कारण बना, जिसके परिणामस्वरूप लेजर कटिंग की तुलना में कम HER प्राप्त हुआ। हालांकि, DP600 स्टील के मामले में, WJC में काफी सुधार हुआ। पंच किए गए होल्स में voids और माइक्रोक्रेक्स की उपस्थिति और प्लास्टिक विरूपण के कारण वर्क हार्डनिंग के कारण कम HER हुआ।

शीट मेटल पार्ट्स के वास्तविक निर्माण में जिसमें स्ट्रेच फ्लैन्जिंग शामिल है, सर्कुलर होल फ्लैन्जिंग और स्क्रायर होल फ्लैन्जिंग प्रक्रियाओं का सामान्य रूप से उपयोग किया जाता है। इसलिए, काम के तीसरे भाग में, स्ट्रेच फ्लैन्जेबिलिटी का अध्ययन संख्यात्मक अनुकरण और प्रयोगात्मक सत्यापन द्वारा किया गया और स्ट्रेच वितरण, थिनिंग और फ्लैन्ज की ऊँचाई के परिणामों की तुलना स्टील्स के साथ की गई। एल्युमिनियम मिश्र धातुओं में, AA5754 और AA5083 मिश्र धातुओं ने सर्कुलर होल फ्लैन्जिंग में सर्वोच्च फॉर्मैबिलिटी दिखाई, जिसे उनके सबसे न्यूनतम होल फ्लैन्जिंग कोफिसिएंट (HFC_{min}) द्वारा इंगित किया गया और AA7075 ने सबसे अधिक HFC_{min} प्रदर्शित किया। यह देखा गया कि AA5754 और AA5083 मिश्र धातुओं का HFC_{min} लगभग DP600 स्टील के बराबर है। सर्कुलर होल फ्लैन्जिंग में अंतिम फ्लैन्ज की मोटाई का विश्लेषणात्मक रूप से पूर्वानुमान किया गया है जिसमें शीट मेटल्स की एनीसोट्रॉपी को शामिल किया गया है। AA5754, AA5083 और AA6061 ने स्क्रायर होल फ्लैन्जिंग प्रक्रिया में बेहतर फॉर्मैबिलिटी दिखाई, जैसा कि उनके HFC_{min} मूल्यों द्वारा इंगित किया गया है जो कि DP600 स्टील के बराबर या उससे कम हैं। लेकिन सामान्य तौर पर, सभी सामग्रियों ने स्क्रायर होल फ्लैन्जिंग में सर्कुलर होल फ्लैन्जिंग की तुलना में कम फॉर्मैबिलिटी दिखाई, क्योंकि कोनों पर उच्च तनाव स्थानीयकरण के कारण तीव्र थिनिंग और विफलता होती है, जैसा कि सिमुलेशन में प्रभावी तनाव और थिनिंग (%) वितरण द्वारा इंगित किया गया है।

यह निष्कर्ष निकाला जा सकता है कि AA5083, AA5754 और AA6061 दोनों सर्कुलर और स्क्रायर होल फ्लैन्जिंग प्रक्रियाओं में उच्च स्ट्रेच फ्लैन्जेबिलिटी रखते हैं और इन मिश्र धातुओं को उन स्ट्रेच फ्लैन्जिंग अनुप्रयोगों के लिए स्टील के प्रतिस्थापन के रूप में संभावित सामग्रियों के रूप में माना जा सकता है जहाँ बहुत अधिक शक्ति की आवश्यकता नहीं है।

मुख्य शब्द: स्ट्रेच फ्लैन्जिंग, एल्युमिनियम मिश्र धातुएं, हल्के वजन, फॉर्मैबिलिटी, अनुकरण.

ABBREVIATIONS

AHSS	Advanced High Strength Steel
BCC	Body-Centred Cubic
BH	Bake Hardened
BHF	Blank Holder Force
CNC	Computerised Numerical Control
CP	Complex Phase
CT	Coldwork Tool Steel
DAQ	Data Acquisition
DH	Differential Hardening
DP	Dual-Phase
EDD	Extra-Deep Drawing
EDM	Electric Discharge Machining
FB	Ferrite and Bainite
FCC	Face-Centred Cubic
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
FLC	Forming Limit Curve
FLD	Forming Limit Diagram
GPA	Grid Pattern Analyser
HAZ	Heat Affected Zone
HB	Hyper Burring
HER	Hole Expansion Ratio
HET	Hole Expansion Test
HFC _{min}	Minimum Hole Flanging Coefficient
HRC	Rockwell Hardness C
IF	Interstitial-Free
IH	Isotropic Hardening
LC	Laser Cutting

LDH	Limiting Dome Height
LDR	Limiting Draw Ratio
LVDT	Linear Variable Differential Transformer
ND	Normal Direction
PHS	Press Hardening Steel
PLC	Programmable Logic Controller
RD	Rolling Direction
SAZ	Shear Affected Zone
SEM	Scanning Electron Microscope
SF	Super Formable Steel
SPIF	Single Point Incremental Forming
SRS	Strain Rate Sensitivity
SS	Stainless Steel
TD	Transverse Direction
TE	Total Elongation
TRIP	Transformation Induced Plasticity
TWIP	Twinning Induced Plasticity
UAT	Uniaxial Tensile Test
UE	Uniform Elongation
UTS	Ultimate Tensile Strength
WJC	Waterjet Cutting
YS	Yield Strength

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENT	ii
ABSTRACT.....	iv
ABBREVIATIONS	vi
TABLE OF CONTENTS.....	viii
LIST OF FIGURES	xii
LIST OF TABLES	xviii
CHAPTER 1 INTRODUCTION	1
1.1 Sheet metal forming.....	1
1.2 Lightweighting of sheet metal parts for automotive applications.....	2
1.3 Importance of aluminium alloys for lightweighting	3
1.4 Types of aluminium alloys and their applications	4
1.5 Formability.....	6
1.5.1 Formability tests.....	6
1.5.2 Forming limit diagram	8
1.5.3 Factors influencing formability.....	10
1.5.3.1 Design variables.....	11
1.5.3.2 Process parameters.....	11
1.5.3.3 Material properties	12
1.6 Stretch flangeability	13
CHAPTER 2 LITERATURE REVIEW AND OBJECTIVES OF THE PRESENT WORK	17

2.1	Stretch flangeability of steels.....	17
2.1.1	Hole expansion ratio	17
2.1.2	Prediction of HER using ductile fracture models	21
2.1.3	Effect of microstructure and constitutive laws in HER prediction.....	22
2.1.4	Effect of punch geometry.....	24
2.1.5	Effect of hole edge quality	26
2.2	Stretch flangeability of aluminium alloys.....	30
2.3	Hole flanging processes	32
2.3.1	Circular hole flanging	33
2.3.2	Square hole flanging	35
2.4	Research gaps and motivation	40
2.5	Objectives of the present work	41
2.6	Overall methodology	41
CHAPTER 3 STRETCH FLANGEABILITY OF ALUMINIUM ALLOYS AND ITS COMPARISON WITH STEELS.....		43
3.1	Material selection and characterisation of mechanical properties and formability	43
3.1.1	Material selection.....	43
3.1.2	Tensile properties.....	46
3.1.3	Anisotropic parameters	51
3.1.4	Forming limit diagrams.....	53
3.2	Prediction of HER by FE simulation	58
3.3	Experimental validation of HER.....	63
3.4	Results and discussion	66
3.4.1	Hole expansion ratio (HER).....	66
3.4.2	Thinning and strains at failure	71

3.5	Summary	74
CHAPTER 4 EFFECT OF HOLE PREPARATION TECHNIQUE ON STRETCH FLANGEABILITY..... 76		
4.1	Hole preparation techniques	76
4.1.1	Punching	77
4.1.2	Water jet cutting (WJC).....	78
4.1.3	Laser cutting (LC).....	79
4.2	Results and discussion	82
4.2.1	Hole expansion ratio	82
4.2.2	Major and minor strains	84
4.2.3	Surface roughness	85
4.2.4	Microstructural analysis using scanning electron microscopy (SEM)	88
4.2.5	Microhardness.....	92
4.3	Summary	94
CHAPTER 5 FORMABILITY OF ALUMINIUM ALLOYS IN CIRCULAR AND SQUARE HOLE FLANGING PROCESSES 95		
5.1	Methodology	95
5.1.1	Simulation procedure	97
5.1.2	Experimental work.....	100
5.1.2.1	Circular hole flanging	100
5.1.2.2	Square Hole Flanging	103
5.2	Results and discussion	104
5.2.1	Circular hole flanging	105
5.2.1.1	Minimum hole flanging coefficient	105

5.2.1.2	Stress and strain distributions and thinning	108
5.2.1.3	Analytical prediction of flange thickness	114
5.2.1.4	Flange height and punch load	120
5.2.2	Square hole flanging	124
5.2.2.1	Minimum hole flanging coefficient	124
5.2.2.2	Strain distribution and thinning	127
5.2.2.3	Analytical prediction of flange thickness	133
5.2.2.4	Flange height and punch load	137
5.3	Summary	141
CHAPTER 6 CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK		142
6.1	Conclusions	142
6.2	Suggestions for further work	145
REFERENCES		146
PUBLICATIONS BASED ON PRESENT WORK		155
BIODATA		156

LIST OF FIGURES

Figure 1.1: Some typical parts manufactured by sheet metal forming processes [1].	1
Figure 1.2: Growth of aluminium usage (in kg per vehicle) in North America and forecast.	4
Figure 1.3: Applications of aluminium alloys in manufacturing automotive components [11].	5
Figure 1.4: Schematic of (a) Erichsen and Olsen tests [16], (b) Limiting dome height test [17], (c) Hydraulic bulge test [18], and (d) Swift cup test [19].	7
Figure 1.5: Samples of different geometry used in Nakazima method for FLD determination [25].	9
Figure 1.6: A typical forming limit diagram [26].	10
Figure 1.7: Applications of stretch flanging.	14
Figure 1.8: Edge cracking in stretch flanging [35].	14
Figure 1.9: Schematic of HET (a) before the test and (b) after the test [36].	15
Figure 2.1: FE simulation of hole expansion test of EDD steel: (a) distribution of circumferential strain at failure and (b) variation of major and minor strain on inner, mid and outer edges [50].	20
Figure 2.2: Fracture in hole expansion of CP590 steel sample by (a) flat bottom cylindrical punch and (b) conical punch [43].	25
Figure 2.3: Different shapes of the punch used in hole expansion test [80].	25
Figure 2.4: Strain paths obtained in hole expansion test by using (a) conical punch, (b) flat bottom punch, and (c) hemispherical punch [80].	26
Figure 2.5: Sheared edge surface with shear-affected zone [83].	27
Figure 2.6: (a) Cutting path of the waterjet, (b) fracture location, and (c) a small notch at the end of the water jet path [88].	29

Figure 2.7: (a) Schematic of edge cracking due to tensile stress in stretch flanging and (b) fracture in a stretch flanged component of DP780 steel [98].	33
Figure 2.8: (a) Fracture, (b) necking, and (c) perfect periphery around the hole of the finished lip after the hole flanging process with different initial hole diameters [92].	34
Figure 2.9: Load-displacement curves in hole flanging of (a) TRIP steel and (b) F+B steel with different hole diameters [45].	34
Figure 2.10: Punch load variation with displacement in square hole flanging [95].	36
Figure 2.11: Stainless steel (SUS304) specimens of different size after square hole flanging. ...	37
Figure 2.12: Schematic of tooling arrangement of SPIF experiments with a pre-cut hole blank and a square flange with a round corner [100].	37
Figure 2.13: Square hole flanged sample [100].	38
Figure 2.14: Failure by tearing at the corner [100].	38
Figure 2.15: Strain paths in square hole flanging at different zones on the hole periphery [100].	39
Figure 3.1: (a) Dimensions of a tensile test specimen and (b) specimen orientations (0° , 45° , and 90°) to the rolling direction.	47
Figure 3.2: Instron universal testing machine used for uniaxial tensile tests.	47
Figure 3.3: True stress-true strain curves of all the materials used.	49
Figure 3.4: Plot of $\ln(\sigma)$ – $\ln(\epsilon)$ of AA6061 to determine the coefficients of Swift hardening law.	50
Figure 3.5: Dimensions of the FLD test samples.	54
Figure 3.6: (a) Laser grid marking machine and (b) a grid marked sample.	54
Figure 3.7: A 150-ton double action hydraulic press used for FLD determination.	55
Figure 3.8: Schematic of tooling used for FLD tests [108].	55

Figure 3.9: Tested FLD specimens of AA5754.	56
Figure 3.10: (a) Automated strain measurement system (Grid pattern analyser) and (b) fitting an ellipse on the deformed grid	56
Figure 3.11: Experimentally determined forming limit curve of AA2024-O.....	57
Figure 3.12: Experimentally determined forming limit diagrams of all the materials used in the present work.....	59
Figure 3.13: An FE model of tools and blank for hole expansion test simulation.	61
Figure 3.14: (a) Hardening curve, (b) yield locus, and (c) FLD of AA5754 used in the simulation of HET.	63
Figure 3.15: (a) Conical punch and (b) die used in HET experiments.	64
Figure 3.16: Dimensions of the tools used in HET experiments.	65
Figure 3.17: Experimental setup for HET.....	65
Figure 3.18: Final hole diameter measurement by PROCAM software.	65
Figure 3.19: Thickness measurement near the crack using a pointed anvil micrometer.	66
Figure 3.20: Prediction of failure in hole expansion test simulation of AA5754-O.....	66
Figure 3.21: HET samples before test and after test.	67
Figure 3.22: Tested samples of all the materials used in HET experiments.....	67
Figure 3.23: Predicted thinning (%) variation in HET simulation of AA5754-O.	71
Figure 4.1: (a) Hydro-pneumatic punching press and (b) Die setup.....	78
Figure 4.2: Waterjet cutting machine.....	79
Figure 4.3: Laser cutting machine.	80
Figure 4.4: Images of the HET specimens in which the holes were made by (a) Punching, (b) Waterjet cutting, and (c) Laser cutting.	81

Figure 4.5: A notch at the hole edge in the HET sample prepared by WJC of AA5754.....	81
Figure 4.6: Tested HET specimens of AA5083, AA5754 and DP600 steel using three different hole making techniques.....	83
Figure 4.7: Surface roughness profiles at the hole edge of AA5754 HET samples prepared by (a) Punching, (b) WJC, and (c) LC.	86
Figure 4.8: Surface roughness profiles at the hole edge of DP600 steel HET samples prepared by (a) Punching, (b) WJC, and (c) LC.	87
Figure 4.9: SEM images of the hole edge of HET samples of AA5754 - (a) Punching, (b) waterjet cutting, and (c) laser cutting.....	88
Figure 4.10: SEM images of the hole edge of HET samples of DP600 steel - (a) Punching, (b) waterjet cutting, and (c) laser cutting.....	88
Figure 4.11: SEM images of the hole edge (by punching) of HET sample of (a) AA5754 and (b) DP600 steel.	89
Figure 4.12: SEM images of the hole edge (by waterjet cutting) of HET sample of (a) AA5754 and (b) DP600 steel.	90
Figure 4.13: EDX analysis of a particle in the HET sample of AA5754 made by WJC.....	91
Figure 4.14: EDX analysis of a particle in the HET sample of DP 600 steel made by WJC.	91
Figure 4.15: SEM image of the hole edge of HET sample of (a) AA5754 and (b) DP600 steel made by laser cutting.....	92
Figure 5.1: Parts manufactured by circular hole flanging and square hole flanging processes [118].	96
Figure 5.2: Circular hole flanging process - (a) before forming and (b) after forming.	96
Figure 5.3: Square hole flanging process - (a) before forming and (b) after forming.	97

Figure 5.4: An FE model of tools and blank for circular hole flanging simulation.....	99
Figure 5.5: An FE model of tools and blank for square hole flanging simulation.	99
Figure 5.6: Dimensions of (a) tools and (b) blank used in circular hole flanging.	100
Figure 5.7: (a) Die, (b) blank holder, and (c) punch used in circular hole flanging.	101
Figure 5.8: A 20-ton load cell used in hole flanging experiments.....	102
Figure 5.9: Flange height measurement by a Vernier height gauge.	103
Figure 5.10: Dimensions of (a) tools and (b) blank used in square hole flanging.	103
Figure 5.11: (a) Die, (b) blank holder, and (c) punch used in square hole flanging.	104
Figure 5.12: Simulation results of circular hole flanging of AA5083 with a hole diameter of (a) 33 mm (successful) and (b) 30 mm (failure).	105
Figure 5.13: Successfully formed and failed samples in circular hole flanging.	107
Figure 5.14: Effective stress and effective strain distributions with minimum successful hole diameter in circular hole flanging.	109
Figure 5.15: Major and minor principal strain distributions with minimum successful hole diameter in circular hole flanging.	111
Figure 5.16: Predicted thinning (%) distribution in circular hole flanging of (a) AA5083, (b) AA5754, (c) DP600 steel, and (d) EDD steel.	112
Figure 5.17: Change in thickness in circular hole flanging [94].....	115
Figure 5.18: Predicted and experimental load-displacement curves in circular hole flanging of AA5083.....	123
Figure 5.19: Predicted and experimental load-displacement curves in circular hole flanging of DP600 steel.	123

Figure 5.20: Simulation results of square hole flanging of AA5083 with a hole size of (a) 42 mm × 42 mm (successful) and (b) 39 mm × 39 mm (failure).....	124
Figure 5.21: Successfully formed and failed samples in square hole flanging of different materials.	126
Figure 5.22: Effective stress and effective strain distributions with minimum successful hole size in square hole flanging.....	128
Figure 5.23: Major and minor strain distribution with minimum successful hole size in square hole flanging.	130
Figure 5.24: Predicted thinning (%) distribution with minimum successful hole size in square hole flanging.	131
Figure 5.25: Final cross section of the flange in square hole flanging.	134
Figure 5.26: Predicted and experimental load-displacement curves in square hole flanging of AA5083 steel.	140
Figure 5.27: Predicted and experimental load-displacement curves in square hole flanging of EDD steel.	140

LIST OF TABLES

Table 3.1: Materials used in the present work.	44
Table 3.2: Chemical composition of Al alloys (in wt %).	45
Table 3.3: Chemical composition of DP600 and EDD steel sheets (in wt %).	46
Table 3.4: Tensile properties of the materials used.	50
Table 3.5: Anisotropic parameters of all the materials used.	52
Table 3.6: Comparison of predicted and experimental values of HER.	68
Table 3.7: Comparison of HER (%) value calculated using correlation and experimental value.	70
Table 3.8: Comparison of predicted and experimental values of maximum thinning.	72
Table 3.9: Comparison of predicted and experimental values of maximum major and maximum minor strains.	73
Table 4.1: Effect of hole preparation technique on HER (%) of Al alloys and DP steel	82
Table 4.2: Maximum major and maximum minor engineering strains near the cracks in HET specimens made with different hole making techniques.	84
Table 4.3: Comparison of average surface roughness of the hole edge of HET specimens of AA5754 and DP600 steel.	87
Table 4.4: Comparison of Vickers microhardness values.	92
Table 5.1: Comparison of predicted and experimental HFC_{min} in circular hole flanging.	106
Table 5.2: Experimental values of maximum strains and thinning in circular hole flanging.	113
Table 5.3: Comparison of predicted and experimental values of maximum strains and thinning.	114
Table 5.4: Comparison of analytically predicted and experimental flange thickness (t).	119
Table 5.5: Comparison of flange height obtained from simulation and experiments.	120

Table 5.6: Flange height and maximum punch load obtained from circular hole flanging experiments.	122
Table 5.7: Comparison of predicted and experimental results of HFC_{min} in square hole flanging.	127
Table 5.8: Experimental values of maximum strains and thinning (%) at the corner.	132
Table 5.9: Comparison of predicted and experimental values of maximum strains and % thinning in square hole flanging.	133
Table 5.10: Comparison of analytically predicted thickness with experimental values.	136
Table 5.11: Comparison of flange height obtained from simulation and experiments in square hole flanging.	137
Table 5.12: Comparison of maximum punch load obtained from simulation and experiments in square hole flanging.	139