CHAPTER 1: INTRODUCTION AND LITERATURE SURVEY

This chapter is divided into three sections. The first section discusses aluminium and its alloys which are the materials that have been used in the present investigation. The second section introduces the flow forming processes, and discusses the literature available on methodologies adopted by various researchers to investigate the process, their findings and important factors that affect the process, and the product characteristics.

The third section summarizes the gaps present and aim of the investigation.

1.1 Aluminium and its Alloys

Aluminium alloys are one of the most important materials for making structures due to their high strength-to-weight ratio. These alloys are widely used in automobile, aerospace, construction equipment. Other than the high strength to weight ratio, aluminium has excellent corrosion resistance, high specific stiffness, high electrical and thermal conductivity, and good formability. However, the limitations of the aluminium alloys are their low modulus of elasticity, high susceptibility to stress corrosion cracking, and lower properties at elevated temperatures.[1]. To overcome the limitations, there has been continued research aimed at improving the strength of the alloys. Figure 1.1 shows the improved aluminium alloys along with their year of introduction and their yield strength in ksi.

Aluminium is widely used in the aerospace industry due to its high specific strength. These alloys were initially used in making main airframe materials and replaced wood. Continuous research in aluminium alloys have greatly improved their properties, improving the chemical composition, and having better control on impurities**.** Table 1.3 shows the chemical composition of aluminium used in aerospace industries.

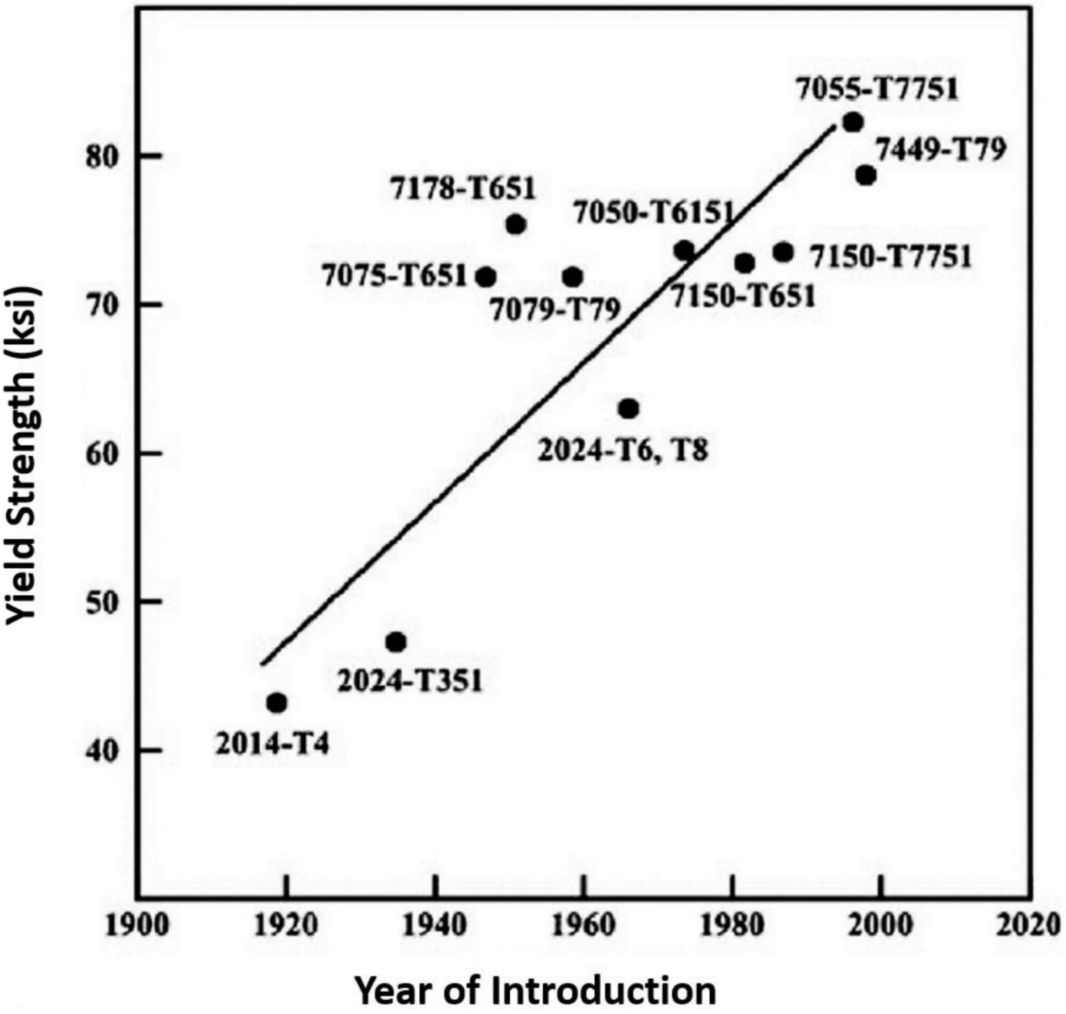

Figure 1.1: Yield Strength (YS) versus Year of Introduction [1]

1.2 Aluminium Alloy designation System

As per the Aluminum Association, the wrought aluminium alloy are normally designated by 4 digit system XXXX, where the first digit indicates the alloy group, or major alloy addition. The second digit represents modification of original alloy or impurity limits and the last two digits identify the specific aluminum alloy. Experimental alloys also use this system, but are indicated as experimental by the prefix X. The designation system for wrought aluminum alloys and cast alloys are given in Table 1.1 and

Table 1.2 respectively.

Table 1.1: Four digit aluminium alloy designation system for wrought alloys [3]

Four digit series	Al content or main alloying elements
1XXX	99.00% minimum
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Magnesium and Silicon
7XXX	Zinc (most also contain Mg)
8XXX	Others eg. Lithium
9XXX	Unused

Table 1.2: Three digit aluminium alloy designation for cast alloys [3]

Three digit series	Al content or main alloying elements
1XX.0	99.00% minimum
2XX.0	Copper
3XX.0	Silicon, with added Cu and/or Mg
4XX.0	Silicon
5XX.0	Magnesium
6XX.0	Used
7XX.0	Zinc
8XX.0	tin
9XX.0	Others

Aluminum alloys can be broadly classified into two groups : heat treatable and non- heat treatable alloys. An alloy is considered as heat treatable only when it can be precipitation hardened else it is considered as non- heat treatable.[4]

As wrought alloys tend to develop high specific strength, the alloys such as 2XXX, 6XXX , 7XXX and 8XXX that are age hardened, are generally used in airframes. These alloys contains elements whose solubility decreases with decreasing temperature, and in concentration much greater than equilibrium solid solubility but moderately higher temperature. Cr, Mn or Zr is added to age hardenable wrought alloys to form dispersoids for controlling the grain structure. The most important alloying elements are Cu, Zn, Mg and Li. The predominant alloys that are used 2XXX and 7XXX.

Some cast alloys are non- heat –treatable and not affected by solutionizing or precipitation effects. Most of the alloys are work hardening alloy.

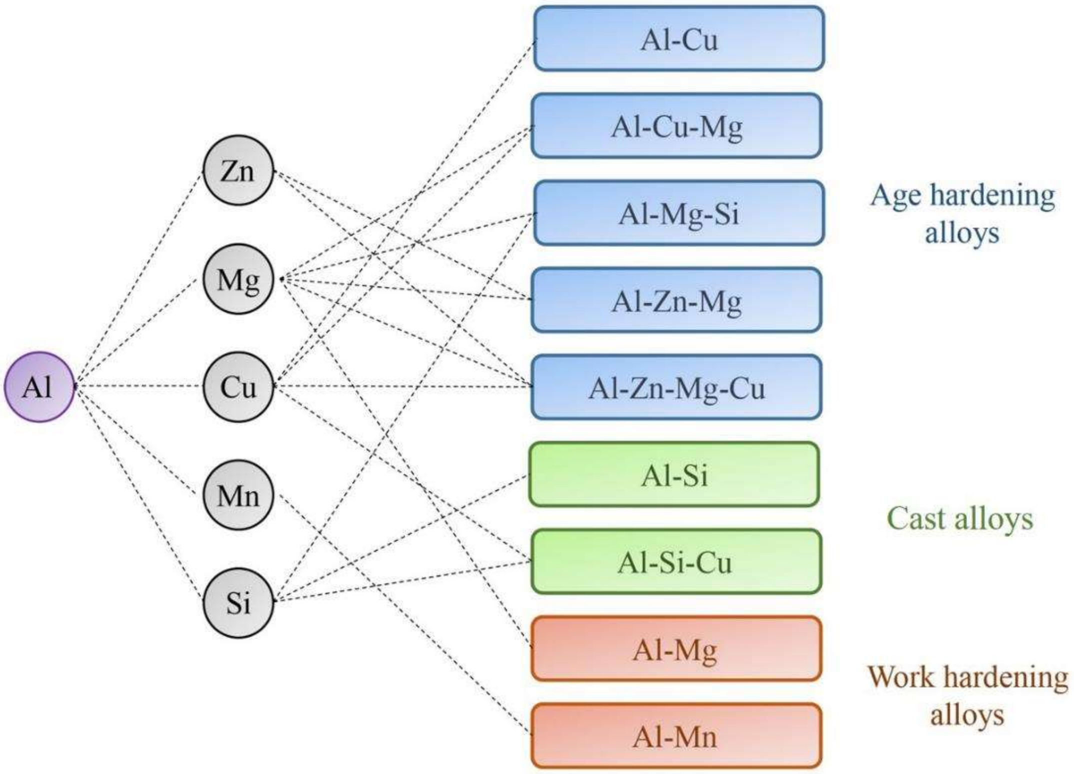

Figure 1.2: Main type of Aluminium alloys and their Alloying Elements [5]

The basic requirement of aluminium alloy to be responsive to age hardening is that there should be decrease in solid solubility of one or more elements with decreasing temperature. The chemical composition of some important aircraft aluminium alloys are given in Table 1.3.

Table 1.3: Nominal composition of Aluminium aerospace alloy[3]

Alloy	Zn	Mg	Cu	Mn	Cr	Zr	Fe	Si	Li	O	Other
1420@	–	5.2	–	–	–	0.1			2.0	–	–
2004	–	–	6.0	–	–	0.4	–	–	–	–	–
2014	–	0.5	4.4	0.8	–	–	0.7*	0.8	–	–	–
2017	–	0.6	4.0	0.7	–	–	0.7*	0.5	–	–	–
2020	–	–	4.5	0.55	–	–	0.4*	0.4*	1.3	–	0.25 Cd
2024	–	1.5	4.4	0.6	–	–	0.5*	0.5*	–	–	–
X2080	1.85	3.7	–	–	0.2	0.20*	0.10*	–	0.2	–	–
2090	–	–	2.7	–	–	0.1	0.12*	0.10*	2.2	–	–
2091	–	1.5	2.1	–	–	0.1	0.30*	0.20*	2.0	–	–
X2095	0.25*	0.4	4.2	–	–	0.1	0.15*	0.12*	1.3	–	0.4 Ag
2219	–	–	6.3	0.3	–	0.2	0.3*	0.2*	–	–	0.1 V
2224	–	1.5	4.1	0.6	–	–	0.15*	0.12*	–	–	–
2324	–	1.5	4.1	0.6	–	–	0.12*	0.10*	–	–	–
2519	–	0.2	5.8	0	–	0.2	0.3*	0.2*	–	–	0.1 V
6013	–	1.0	0.8	0.35	–	–	0.30*	0.8	–	–	–
6113	–	1.0	0.8	0.35	–	–	0.30*	0.8	–	0.2	–
7010	6.2	2.35	1.7	–	–	0.1	0.15*	0.12*	–	–	–
7049	7.7	2.45	1.6	–	0.15	–	0.35*	0.25*	–	–	–
7050	6.2	2.25	2.3	–	–	0.1	0.15*	0.12*	–	–	–
7055	8.0	2.05	2.3	–	–	0.1	0.15*	0.1*	–	–	–
7075	5.6	2.5	1.6	–	0.23	–	0.4*	0.4*	–	–	–
7079	4.3	3.2	0.6	0.2	0.15	–	0.4*	0.3*	–	–	–
X7093	9.0	2.5	1.5	–	–	0.1	0.15*	0.12*		0.2	–
7150	6.4	2.35	2.2	–	–	0.1	0.15*	0.12*	–	–	–
7178	6.8	2.8	2.0	–	0.23	–	0.5*	0.4*	–	–	–
7475	5.7	2.25	1.6	–	0.21	–	0.12*	0.10*	–	–	–
8009	–	–	–	–	–	–	8.65	1.8	–	0.30*	1.3 V
X8019	–	–	–	–	–	–	8.3	0.2*	–	0.2	4.0 Ce
8090	–	0.9	1.3	–	–	0.1	0.30*	0.20*	2.4	–	–

1.3 Temper designation of Aluminium alloys

The heat treatment or temper designation applicable to aerospace alloys are given in Table 1.4 In general, the aluminium alloys are supplied in form of as fabricated, annealed, heat treated form. The temper designation provides information about the processing condition of the material. The temper condition gives a rough idea about the hardness, material strength, ductility and other mechanical and metallurgical parameters.

Table 1.4: Temper designation of Al alloys [3]

Suffix letter F,O,H,T or W indicates basic treatment condition	First Letter digit indicates secondary treatment used to influence properties	Second suffix digit for condition only indicates residual hardening
F- fabricated		
O- Annealed wrought products only		
H- Cold worked strain hardened	1- Cold Worked only 2- Cold Worked and partially annealed 3- Cold worked and Stabilized	2-1/2 hard 4-1/2 hard 6- ¾ hard 8- hard 9 –extra hard
W- Solution heat treated		
T- Heat treated stable	1- Partial solution plus natural aging 2- Annealed cast products only 3-Solution+ cold worked 4- Solution+ natural aging 5- Artificially aged only 6- Solution+ artificial aging 7- Solution + Stabilizing 8- Solution+ Cold worked +artificial aging 9- Solution+ Artificial aging+ cold worked	

1.4 Introduction to flow forming

Flow forming is an incremental cold/hot forming process in which a ductile material is plastically displaced axially along a given mandrel, while the internal diameter remains constant and fixed with the mandrel. It is bulk plastic deformation under a compressive stress of rollers without fracture. The schematic diagram of the flow forming process is shown in Figure 1.3. Flow forming results in elongation of the preform with a simultaneous reduction in the thickness.

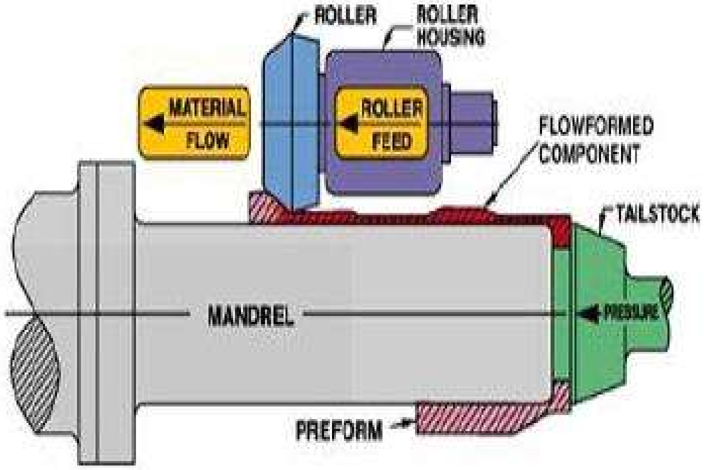

Figure 1.3: Schematic illustration of flow forming process [6]

Flow forming can be considered as a variant of the metal spinning process, which is a well-established metal forming process. In the metal spinning process, the material is mounted on one end of a rotating mandrel and a pivot is used to push the material over the mandrel. The process is suited for a simple axisymmetric jobs such as cooking pots. However, the repeatability of finished product is largely dependent on the skills of workers. Unlike the conventional metal spinning process which uses a pivoted pointer to push the material along the axis of mandrel, the flow forming process uses a roller for deforming materials. The movement of rollers pushes the material in radial and axial directions resulting in the formation of an axisymmetric product. One of the most striking features of flow forming operation is that it can produce products with varying thicknesses.

Since 1950, flow forming is being used in the aerospace industry producing rocket nose cones, dish antennas, rocket motors etc. Flow forming is also employed in making rocket casing, power train components in automobile industries. Recently, it has been used for manufacturing containers for storing radioactive materials[7].

Flow forming is gaining much importance due to the following advantages:

i. Products formed by flow forming have high good geometrical accuracy and have good control over tolerance.
ii. It permits a product with variable thickness by changing the distance between the mandrel and roller in a controlled manner.
iii. It can be performed over a large range of materials- such as pure metals (aluminium, ion, titanium, niobium, and nickel), alloys (eg Alloy steel, Al7075, brass, bronze, etc.), plastics, etc.
iv. It ensures superior mechanical properties such as tensile strength, hardness, etc rough work hardening. This is because it is a cold forming process.
v. Compared to other plastic deformation processes, the flow forming process can produce with superior surface finish by improving the surface finish of mandrel and roller and carefully choosing the process parameter.
vi. The products of flow formed process, in general, don’t require any further finishing operation. This is why the flow forming process is a step promoting a near net-shaped technology.
vii. A flow formed product doesn’t require further machining process and also since it avoids material waste as chips, hence, it results in huge cost saving in mass production.

1.5 **Components in Flow forming**

In a flow forming process, a hollow workpiece called preform is mounted over the rotating mandrel at one end while the other end is free. The material is deformed by the movement of a single roller or group of rollers which can move radially and axially and are free to rotate about its axis. The roller–mandrel gap can be controlled resulting in a product with variable thickness. When the roller moves in the longitudinal direction, it compresses the material, and at the same time, due to axial motion, it stretches the material in the material in the longitudinal direction. Thus the material gets deformed. According to the principle of the constancy of volume, the total volume remains constant in the metal deformation. Therefore, the material gets elongated as the thickness gets reduced. In principle, the flow forming process can be regarded as a modified spinning process.

So the main elements for designing a flow forming process are

(a) Material or preform

(b) Mandrel

(c) Roller Assembly – consisting of roller(s), their attachments

(d) Machine which can provide relative motion between roller and preform and also provide power for deformation. A typical flow forming machine is shown in figure 1.4.

(e) Lubrication.

All of the above components have been discussed later in the chapter. The design and fabrication of roller assembly have been discussed in chapter 3.

Figure 1.4: A typical flow forming machine [8]

1.6 Types of flow forming process

Based on material flow with respect to roller direction of movement, flow forming operation can be of two types:

(a) Forward Flow forming

(b) Backward flow forming

(a) **Forward Flow forming:** In the forward flow forming process, the material flow is parallel to direction of axial movement of roller as shown in Figure 1.5. The movement of roller exerts radial and axial force on the deforming zones.

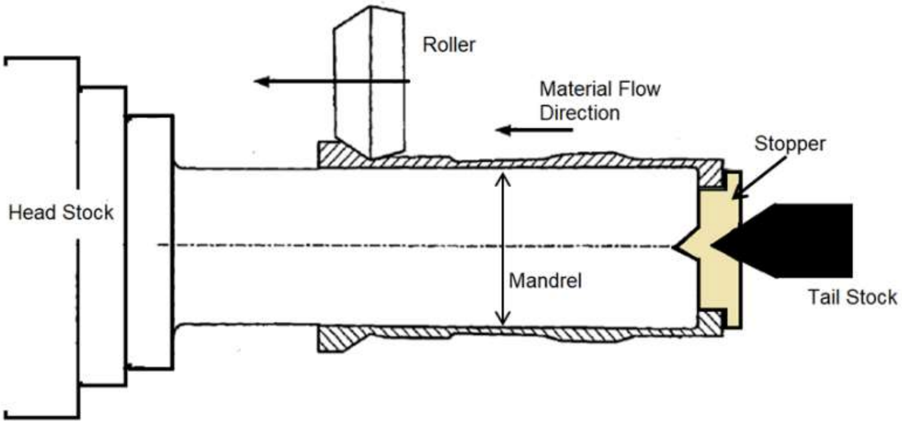

Figure 1.5: Schematic diagram of Forward flow forming process [9]

In forward flow forming, the length of mandrel determines the maximum length of preform. In general, the mandrel length is chosen according to the maximum dimension of the finished product.

(b) Backward flow forming: In backward flow forming, the deforming material flows in opposite direction to the axial movement of rollers as shown in Figure 1.6

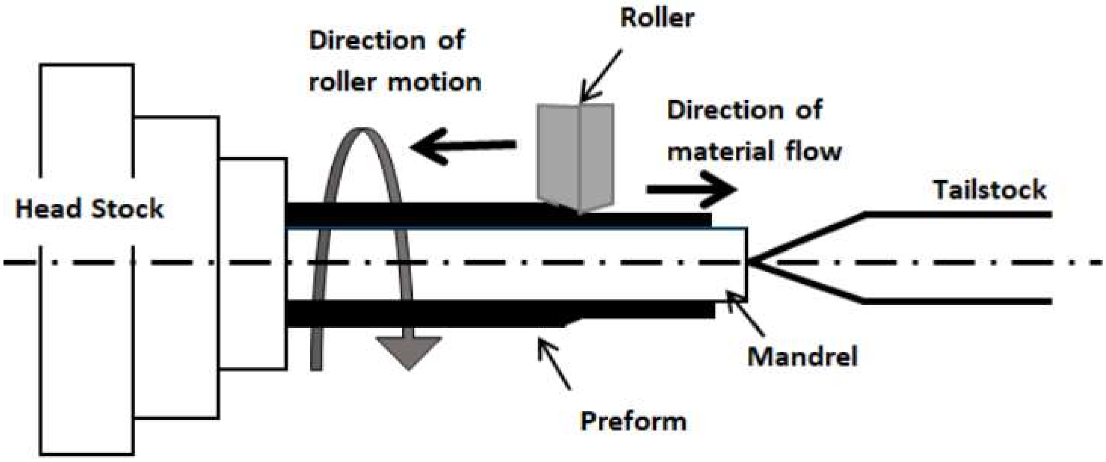

Figure 1.6: Schematic diagram of backward flow forming process. [9]

As seen from the Figure 1.6, the material flows in between the roller and the mandrel. The deformed material is supported over the mandrel or any tubular attachment that can be attached at the free end to support the mandrel that runs over the tailstock.

A comparative study of forward and backward flow forming shows that in forward flow forming, the material adheres to the mandrel resulting in high precision products. In backward flow forming, the formability of the material is improved due to triaxial compressive stress. Hence backward flow forming process is generally employed for deforming high strength preform.

Large thickness reduction in flow forming can be obtained in multipass however for soft metals such as aluminum, up to 90% thickness reduction has been reported in a single pass. However, the flow forming forces increases with increase in thickness reduction and hence the extent of thickness reduction per pass depends on the material undergoing deformation, the machine specifications.

One of the key aspects of the flow forming process is that it can be done on a simple lathe machine by slight modification. This flexibility of the process can make flow forming very cost-competitive in a small lot size production.

Table 1.5: Material Used in flow forming [10]

Flow formed at high temp	**Cold Flow formed**
	2024 Aluminum
7075 Aluminum	7075 Aluminum
	6061 Aluminum
Ti-6Al-4V CP2, Ti-15V-3Al-3Sn-3Cr	Ti-6Al-4V CP2, Ti-15V-3Al-3Sn-3Cr
	13-8 PH Steel, 15-5 PH Steel, 17-4 PH Steel, 17-7 PH Steel
Inconel 625	Inconel 625, Inconel 718
	Niobium(Columbium)
	4130,4140,4340 steel
	T-250, C300, C350 Maraging Steel

1.7 Factors affecting the Flow forming process

Flow forming parameters can be broadly classified into two categories viz. input parameters and output parameters. The input parameters can be further classified into:

a) Geometrical parameters such as roller radius, tool geometry parameters such as tool nose, attack angle, roller land, mandrel diameter

b) Operating process parameters such as roller feed, mandrel speed, and effect of lubrication.

c) Material-related parameters such as yield strength, crystal structure, heat treatment, defects, etc.

The output parameters are generally grouped as mechanical parameters such as flow-forming forces, power, hardness, formability, surface roughness, and metallurgical parameters such as residual stresses, product microstructure, grain size, grain structure, etc. The research methodologies that the various researchers have been followed are grouped into experimental methodologies and theoretical methodologies.

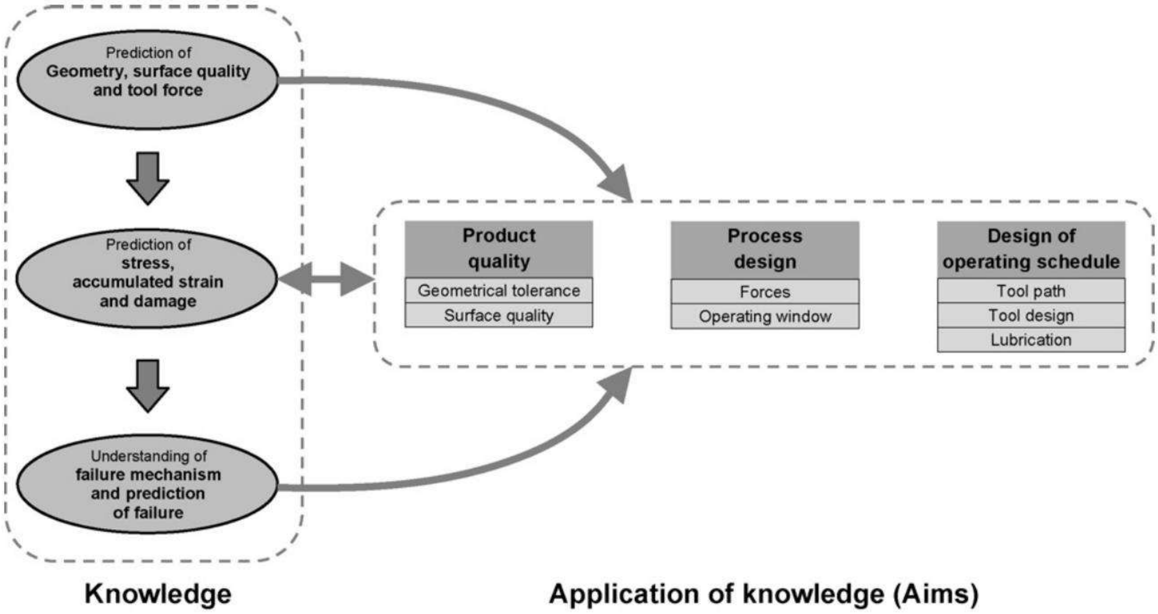

Figure 1.7: Flowchart showing the interdependence of research aim and knowledge available [1]

As flow forming and metal spinning processes are similar, most of the earlier investigations tend to consider flow forming investigation similar to the metal spinning process.

The following section discusses the various research methodologies adopted by various researchers.

1.8 Researches based on Experimental investigation

Experimental investigations carried out by various researchers tried to correlate various input parameters with output parameters listed above. Hayama and Kudo [11], Shirizly and Dolev [12] studied the forward and backward flow forming of preform using 2 rollers. The authors [12] studied the effect of changing reduction ratios, feed rate, and roller angle on the dimensional accuracy of the flow-formed product. The authors[12] also studied the behaviour of plastic flow during flow forming by considering the material flow as a plastic wave that is produced in the upper part of the deformed region. To differentiate the waves associated, a constant was defined to take care of changes in parameters. The authors[12] tried to establish the stability of the process with the size of the wave. The higher the plastic wave, the lesser would be the stability of the process. Hayama and Kudo [11] showed that process stability and accuracy depend on thickness reduction ratio roller feed rate and roller geometry.

Jahazi and Ebrahimi[13] conducted experiments with 3 rollers and studied the effect of geometrical parameters (such as roller attack angle, the shape of the contact line) and the percentage thickness reduction on the quality of the product. The authors[13] tried to find the optimum conditions of the input parameters which can result in the elimination of defects such as microcracks etc. The authors [13] also studied the influence of preheat temperature, holding time, and cooling time in producing desirable microstructures which can result in the best strength- toughness combination. The authors' [13]investigation showed that defects can be correlated with the S/L ratio where S is flow in circumferential direction and L is flow in axial direction a methodology developed by Gur and Tirosh[14]

Jahazi and Ebrahimi[13] also investigated Vickers and Rockwell hardness tests of flow formed steel. The authors [13] tried to estimate the fracture resilience of material using yield strength and final true strain.

Singhal et al.[15] experimentally investigated the power consumption in flow forming of hard to deform materials such as pure Titanium, Titanium alloys (Incoloy 825), Ni-Cr steel (Inconel 600), and stainless steel (AISI-304). Different reduction ratios were tested to evaluate the final material proprieties and dimensional accuracy, as well as a microscopic investigation for evaluating the final product hardness. Maj et. al[16],[17] studied the mechanical properties and microstructure of Inconel 625 flow formed workpieces which were subjected to laser and other heat treatments.

Chang et al.[18] investigated the microspinnability of aluminium alloys under different heat treatment conditions. Al2024 and Al7075 were flow formed under two heat treatment conditions – full annealed or solution treated. Microstructural analysis using OM, SEM, and TEM, and hardness measurement, were carried out to access the microspinnability. Macrospinnability was studied by deforming material till desired thickness reduction and deforming till failure. The presence of surface microcracks was analyzed.

Rajan and Narasimhan [19] studied the defects that arise during the flow forming of steel tubes AISI 4130. The authors[19] studied the common defects such as diametral growth, fish scaling, premature bursting of tubes, build up, and bell mouthing and tried to correlate with the metallurgical and process parameters that can be probable causes for the above defects. The authors[19] used 4 axis CNC flow forming machine. 3 roller reverse flow forming operations were carried out on AISI 4030 that were not electro slag melted and contained 22 ppm dissolved oxygen, 110 ppm dissolved nitrogen, and 3 ppm hydrogen. The authors performed non-destructive and destructive testing such as a proof pressure test followed by a burst pressure test. Metallurgical investigations and optical microscopy were then performed to study the properties of final flow formed products. Rajan et al. [20] studied the effect of heat treatments of the preform (such as annealing, normalizing, quenching, and tempering) on the mechanical properties of AISI 4130 tubes. The methodology used inspection of the preform, performing multipass flow forming, and final inspection. The overall process steps used by the authors is given in Figure 1.8.

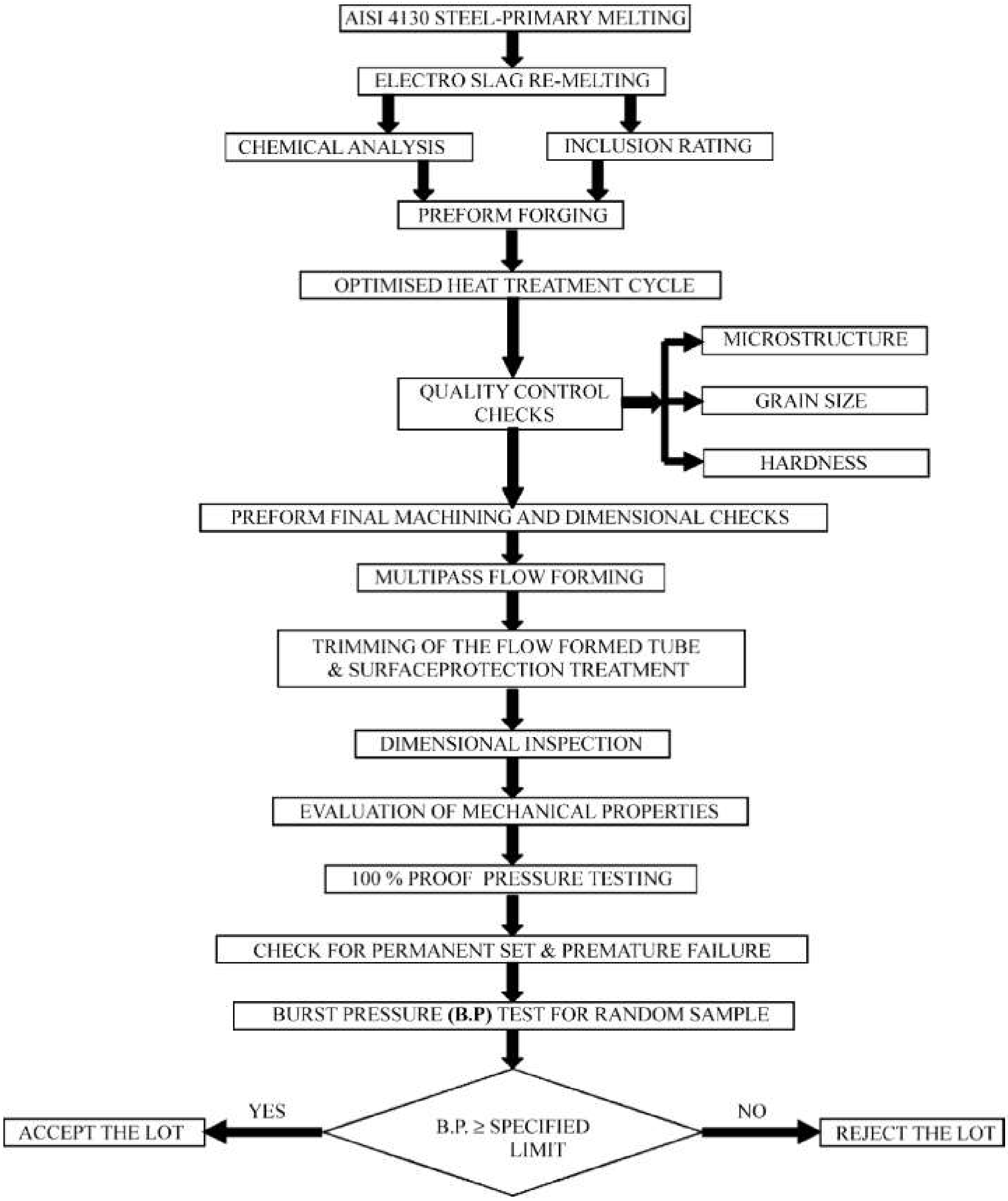

Figure 1.8: Flow chart depicting the process used for flow forming of the preform and Testing [20]

Rajan et. al.[21] also studied the suitability of different theoretical models of failure such as the Svensson model in predicting the burst pressure. The authors produced different flow formed pressure vessels and then applied high pressure till it failed to evaluate the burst pressure. The microstructure of the failed tube was investigated to determine the grain elongation, in comparison with thickness reduction.

Groche and Fritsche[22] experimentally investigated the production of internal gear teeth using flow forming operation. The authors used an externally geared mandrel which was fitted in a cup-like preform. Using three rolls and multiple rolls, the preform was flow formed and the product characteristics such as defect, forming forces.

Gupta et al.[23] investigate the cracks generated during the flow forming of Columbium Alloys Nb-Hf-Ti using a conical mandrel. The authors flow formed a conical divergent. Intermittent annealing was employed to delay the onset of work hardening. Analyzing the microstructure, hardness, and fractography of the samples around the cracked region, the authors tried to correlate the formation of cracks with the process parameters.

Davidson et al.[24] investigated the flow forming of AA6061 alloy using the Taguchi approach. The author used a 4 axis CNC flow forming machine and multi-pass flow forming was done with a single roller. Based on the L9 orthogonal array, the author investigated the effect of mandrel speed S(rpm), depth of cut Dc (mm), and feed F mm/min on the percentage elongation of the workpiece.

Notarigiacomo et al.[25] investigated the influence of process parameters on the fatigue behavior of different steels used in the automotive industry. The authors investigated four materials DD11 (European Normative: EN 10111), FB600 9 commercial code), HSLA 420 (S420MC; numeric code: 1.0980; European Normative: EN 10149-2) and M800 (commercial codes) and developed a relation between flow forming conditions and variables high strength steel material properties. The authors [25] proposed a relation predicting the fatigue performance of flow forming workpiece. The authors [25] also developed and validated a FEM-based fatigue model to predict the increasing fatigue life based on thickness variation. The authors[25] performed the chemical tests, tensile test, FLD test microhardness, and microstructure test to validate their experimental findings.

Plewinski and Drenger[26] studied the quality of flow forming of aluminium Al7075 in semi-finished conditions in combination with heat treatment. The authors[26] investigated the surface cracks, surface roughness, and metallurgical characteristics such as grain growth.

Roy et al.[27] experimentally investigated the evolution of equivalent plastic strain during the flow forming of AISI 1020 steel. The authors [27] performed single roller flow forming using a smooth mandrel but roller having an outer profile. Three passes of the roller were used to deform a flat circular blank. The authors[27] try to correlate the Berkovich hardness value to the equivalent strain at a different level of plastic strains during the forward flow forming process. The author[27] measured Berkovic microhardness at different locations of a section of tensile specimen cut out of flow formed specimen. The measured value of Berkovich hardness gives the measurement of true hardness and true strain. The evolution of strain is characterized by roller/mandrel contact and thickness reduction ratio. The authors[27] develop two expressions due to the mandrel effect and the effect of the rollers. The sum of these two strains gives the total deformation in the axial direction. A local frame is defined in the contact zone, where functions determine its angular limit and allow an analytical expression of the contact surface to be developed.

Molladavoudi and Djavanroodi[28] experimentally studied the effect of thickness on mechanical properties and spinning accuracy during flow forming of aluminium Al 7075-O. The authors investigated the mechanical properties, surface roughness, diameter growth, geometrical accuracies, and crystal refining during backward flow forming. The forming operation was performed on an NC lathe modified to perform the activity. The authors performed optical microscopy, tensile test, performed hardness test.

1.8.1 Design of Experiments (DOE)

Design of experiments (DOE) is defined as a branch of applied statistics that are used in planning and conducting an experimental trial. DOE provides an important data collection and analysis tool that can be used for analyzing and interpreting test results. DOE becomes an important tool when more than one factor affects an output.

Davidson et al.[24] use Taguchi Orthogonal Arrays (OAs) to investigate to evaluate the critical factors such as depth of cut, speed of mandrel, and feed on percentage elongation. The authors used called analysis of variance (ANOVA) to select the optimum level of process parameters. Nahrekhalaji[29] applied classical fractional factorial design to characterize the flow formed diameter and proposed a polynomial regression equation.

Srinivasulu et al.[30] used Box- Behnken design which is a response surface methodology (RSM) to model the mean diameter of flow formed tube. The authors applied ANOVA to take into optimizing the process parameters. Their RSM model was able to predict the internal diameter in the selected range with an error < 0.08%. The author developed a regression model to predict the mean diameter

Aghchai et al.[31] [32]investigated forming of steel. The authors applied fractional factorial DoE and graphical methods (i.e. RSM) and ANOVA to determine the influential parameters other than roller geometry and axial speed. The authors reported that ANOVA analysis suggests that the reduction ratio has more influence than other parameters such as roller geometry and axial speed. The authors propose an optimized values of variables which was validated by simulation.

Kemin et al.[33][34] analyzed the staggered roller forming and developed a multi objective algorithm. The authors used FORTRAN language to evaluate a three roller (in staggered configuration) in forward flow forming operation. The setup configuration proposed by the authors replaced a multipass process by a single step.

Lee and Lu [35] suggested a formula for calculation of calculating tensile forces during 6 roll flow forming. The authors used power sensors to monitor force continuously. The deformation force and the frictional component of the force in plastic and non- plastic zone are evaluated, without taking total energy into account.

1.8.2 **Numerical Analysis**

Finite Element Analysis is one of the most important numerical analysis technique to analyse flow forming operation. ABAQUS has been most commonly used software. Many researchers used explicit approach to understand the process and to predict the forces and stress in the flow forming process. Explicit based approach, as reported by several researchers, though is very accurate in comparison to implicit analysis, but it saves lots of computational time. However, implicit analysis is done by very few researchers such as Wang et. al [36], Song et. al.[37], Kim et.al [38], etc used.

Both linear and non-linear models have been proposed by different researchers. Lexian and Dariani [39] proposed a nonlinear model to simulate roller workpiece contact surface without considering friction. 3D shell elements were used to model the surface. Kemin et. al [33][34] used 3D brick elements to simulate the flow forming process using three staggered rollers. Xu et.al[40] used a numerical method using a differential equation to calculate the contact zone stress and strain rates for forward as well as backward flow forming. The author associated these stresses and strain rates to different states of tensile stresses in contact zone. Li and Lu [41] applied a three-dimensional non-symmetric model and proposed a rotational matrix in order to formulate the problem as a system of simple hinges in the contact surface in polar coordinates. Both explicit and implicit methods have been used by various authors and it has been reported that the implicit method gives better results than the explicit method. [42][43]. However, implicit methods require large computational time and explicit methods of analysis provides fast results and have been reported by various authors. Further explicit analysis is expected to maintain the interaction among the nodes and therefore would results in more coherent transfer of forces.[44]

The problem of convergence in case of highly non-linear geometries and, high computational time and thus high computational cost associated with the implicit analysis have forced most researchers to adopt explicit analysis. Explicit analysis provides higher robustness, lesser computational cost, and faster result. Explicit analysis is said to produce a quasi-static response

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1.9 THE PREDICTIVE MODELS: THE MECHANICS OF FLOW FORMING

The present section of the dissertation reviews the prediction models and strategies used by different researchers while understanding the flow forming process. The main emphasis in prediction strategy was to predict the

(i) product characteristics- such as product dimensional accuracy, product surface characteristics, expected mechanical properties and product microstructure and its effects, Stress and strain , defect models

(ii) Process parameters – prediction of flow forming forces, power,

Both the theoretical and experimental approaches have been reviewed in this section. As flow forming is considered as variant of metal spinning process, so some relevant work of the authors have also been considered.

In the plastics deformation process, the choice of flow stress function is considered an important step while modelling the process. The flow stress function (σ) can be assumed to be a function of different variables such as current strain (ε), strain rate ($\dot{\varepsilon}$), temperature (T), initial state of the material (σ_w). Another variation can be when time (t) and strain rate and temperature (T) are independent functions. In general, for cold working process like flow forming process, most of the researchers assume flow stress as function of current strain only. [45]

1.9.1 Models for predicting product geometry

Product dimensional accuracy has been a key area which have been taken by many researchers. Theoretically the final diameter of the product depends on mandrel – roller distance, but practically many other factors affect the final diameter of the preform such as springback, properties such as tensile state has also been found to affect the final diameter. Product final diameter and other dimensional tolerance depends on process parameters and configuration of machine, so researchers have tried to find their influence over the final dimension. Diametral growth, spring back, ovality (roundness) had been investigated in detail.

Diametral growth had been taken by most of the researchers such as Srinivasulu et al. [30], song et. al. [37], Xue et. al.[33], Aghchai et. al. [31], Podder et.al. [46], Rajan et.al[19] , D'Annibale [47], Jolly and Bedi [48] , Singhal et. al. [49], Ma et. al[50], Molladavoudi[28], Davidson et.al.[24] etc. All these authors have either used numerical and/or experimental techniques to establish the factors the affect the diametral growth. As diametral growth mainly affects soft metals [11], [49], hence generally these investigations were made on softer metals like aluminum, copper, low and medium carbon steels.

Song et al.[37] presented elasto plastic model and experimental validation for their model and proposed an empirical formula for diametral growth behavior as non-linear function of distance from origin as

$$y = A(1 - \exp(-Kx^n)) \tag{1.1}$$

Where A, K and n are material properties, and x is normalized distances (against initial preform diameter) from mandrel surface and y is normalized diametral growth (against initial preform diameter).

Srinivasulu et. al [30] proposed a complex formula ,equation (1.2) , for mean diameter as a function of speed, feed rate and radius of workpiece.

$$\text{Mean diameter(D)} = +56.33 - 0.25315\,F - 0.024075\,V - 0.295R - 1.620e\text{-}04\,(FV) + 3.15e\text{-}03(FR) + 8.0e\text{-}04(VR) + 1.77e\text{-}03\,F^2 + 7.45e\text{-}05\,V^2 - 4.453e\text{-}03\,R^2 \tag{1.2}$$

Where F- feed rate; V – Speed of mandrel; R – radius of workpiece.

Shinde et. al. (2016)[51] also proposed a complex expression for maraging steel. Other researchers produce experimental investigations. These numerical models are mostly material dependent and no model seems to work generally for the wide range of metals. The different factors that affect diametral growth have been discussed in section 1.12.1. For springback, there are no such theoretical models proposed. However, Rajan and Narasimhan(2001)[19] proposed that spring back were found to be strongly affected by percentage thickness reduction, strain hardening exponent of preform, roller geometry, and feed rate.

There is only one mathematical model in literature, proposed by Shinde et. al (2016)[51], that tried to directly calculate the ovality or roundness error. The model was developed based on response surface methodology and correlates ovality as a function of feed rate, thickness reduction ratio, and attack angle and nose radius. However, the model contains several complex interactions which make it difficult to use. Roundness error is most affected by the amount of thickness reduction. Larger thickness reduction decreases roundness error due to more uniform flow under the roller however it leads to other defects such as waviness. So, Davidson et.al. [24] proposed optimal thickness reduction to be 2 mm. The factors affecting ovality is discussed in section 1.12.2.

Though improved FEA models have a great impact on the prediction of geometrical accuracy of finished products, yet better robust FEA models are still lacking that can correlate with experimental results. The ratio S/L has been still the better measure of the impact of process parameters.

1.9.2 **Model for Prediction model for Surface Properties**

Surface roughness of product have been taken by many researchers and there are no precise relationship in literature which can correlate surface roughness with process parameters. Singhal et. al. (1987)[15] proposed that surface finish is hardly affected by reduction ratio and reported that the product surface finish to have surface ratio less than $0.9\mu m$ (Ra values) for statinless steel, titanium or Inconel.

Another important factor that affects surface roughness is lubrication. Prakash and Singhal [15] reported surface roughness between 0.5 to 0.8 μm although these values depends on other factors such as selection of lubricant, roller and mandrel surface roughness may affect the values. Increasing feed rate increases radial force and is found to decrease surface finish. Rajan and Narasimhan [19] reported that surface finish found to decrease with increasing feed ratio. The authors presented an empirical relationship relating height of feed rates as function of roller radius and feed rate as

$$h = R - \frac{1}{2}\sqrt{4R^2 - f^2} \qquad (1.3)$$

h= height of feed mark (mm)

f= feed rate (mm/rev)

R= roller diameter

Based on the empirical relationship, the authors deduced that superior surface finish can be optimized by decreasing feed and increasing roller diameter.

The above models/ observations can be used as a reference. Till now, as per the reviewed literature, no mathematical model is present that can predict surface finish for wide range of metals. Experimental investigation for each metal has been the most favoured technique to determine the surface finish.

1.9.3 **Model for prediction of mechanical proprieties**

Mechanical properties of the flow formed product are the most important aspects that have been taken by researchers. The key mechanical properties of the product are tensile strength, hardness, ductility etc. As the flow forming is in general a cold forming process, the product characteristics of a flow formed product would resemble a product from other cold forming process- such as increase in yield strength, UTS, decrease in ductility, increase in hardness etc. The main aim of the researchers was to quantify the change in mechanical properties of flow formed product with respect to reactants. The input parameters being process parameter such as feed and speed, the microstructure of the preform and heat treatment of the workpiece. However, experimental results are always an important basis to validate a mathematical model.

To predict the bursting pressure of a flow-formed tube, the Svensson model can be used. Rajan et al [20] modified the Svensson model and proposed their model which the authors[20] claimed to be more accurate than the Svensson model for thin pressure vessels. The authors[20] also experimentally showed that in the case of steel, the ultimate tensile strength in the radial direction was around 0.93 times the UTS in hoop direction in the case of AISI 4130. Lee et al. [52] reported that lower mandrel and feed rate, greater tangential speed resulted in increased hoop strength of the flow formed tube.

Singhal et. al. [15] reported that in flow forming of steel AISI-304, commercially pure titanium and Inconel 825 and Inconel 600, the tensile strength first increases, reaches maximum at percentage thickness reduction at around 75% and then reduces as % thickness reduction increases beyond 80% due to formation of micro cracks. The tensile strength of AISI-304 was found to be doubled at 80% reduction while the yield strength was reported to be tripled. Ductility was found to be decreased to below 0.1%. For aluminium, Chang et. al. [18] reported the increase in UTS with amount of thickness reduction in Al2024 and Al7075 in annealed and solution heat treated. Figure 1.9 shows the variation of tensile strength in axial direction in different heat treated 7075 and 2024.

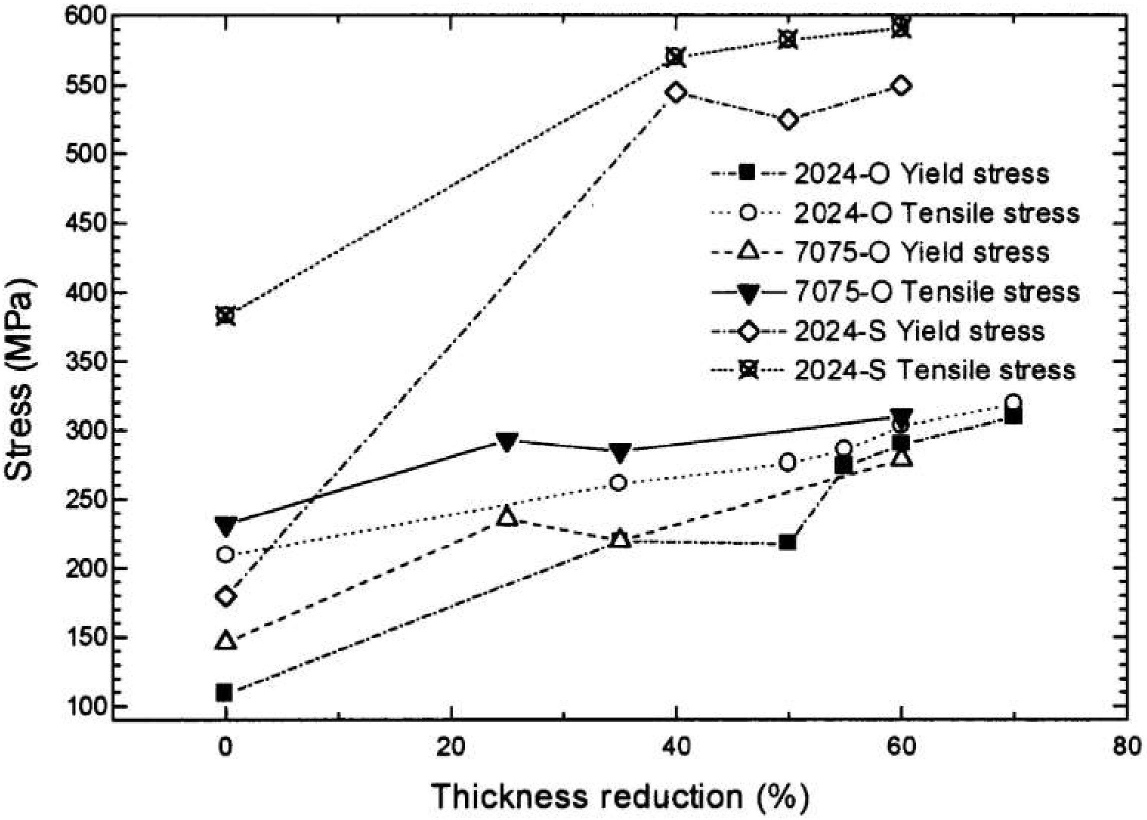


Figure 1.9: Tensile Strength in axial direction in 7075-O,2024-O and Al2024-S [18]

Various authors have tried to propose mathematical model for determining ultimate tensile strength of flow formed product. Most of the authors had based their model on Hollomon's power law given by equation (1.4)

$$\text{UTS} = K\varepsilon_U{}^n \qquad (1.4)$$

Where UTS= Ultimate Tensile strength MPa, ε_U = plastic strain when stress equals UTS and n = strain hardening coefficient and K = Strength in MPa.

For example, Podder et. al. [53] reported that the true stress true strain obtained in AISI 4340 closely follows Hollomon's law. Similarly, Rajan et. al. [21](2002) proposed a model (equation (1.5) based on Erasmus law which is modified form of Hollomon's law.

$$UTS = K[n + \left[\frac{1}{1-\Delta A}\right]^{n} \tag{1.5}$$

Where ΔA variation in cross sectional area.

Fatigue strength of flow formed components is also an important parameter which will decide the applicability of Notarigiacomo et. al. [25] investigated the fatigue strength and ultimate tensile strength of flow formed components and suggested a partial correlation between fatigue strength and surface roughness where presence of micro cracks the surface affects the fatigue strength strongly. Under the experimental conditions, the authors Notarigiacomo et. al. [25], reported that with moderate thickness reduction of 40%, the fatigue strength was found to improve from 20% to 40%. Lai and Lee [44] studied fracture and creep properties of flow formed tube . Hong et al [45] studied the necking in progress during the flow forming operation.

The absence of any rigid mathematical models to predict the mechanical properties has led to dependence on experimental investigations. FEA analysis results are important data which can save experimental time and resources but experimental validation is required. The experimental technique is more important in understanding the product microstructure. The next section tries to present the available literature on product microstructure.

1.9.4 **Model for Prediction of Product Microstructure and its Effects:**

One of the key factors that affects the product’s properties is its microstructure. Preform microstructure and heat treatment are important considerations while designing a flow forming process. Understanding the microstructure in different process configurations has been taken by many researchers. The main tests performed for microstructure analysis by different researchers are OM, SEM, TEM, XRD, and EBSD.

Flow forming products are anisotropic in nature. This was investigated by Rajan et al. [21] who found that elongation of grains along the direction of roller movement direction. The authors proposed that the catastrophic failure in the burst test are due to cracks generated in hoop direction instead of axial direction. This was the consequence of grain elongation in the axial direction. Due to anisotropic behaviour, non-uniform variation in microhardness would be expected.[18] The non –uniformity in microhardness would increase with increase with percentage thickness reduction. [18],[28], [56].

Haghsena et. al.[57] studied the preform mandrel contact zone and found the elongation of preform along feed axis contains stretch in ferrite grains, especially in zone of large plastic deformation.

In steels, flow formability decreases as the percentage carbon and the other alloying elements increases. Presence of inclusions and precipitates also reduces the flow formability of the preform. Rajan et. al.[21][20]. Haghsenas and Klassen [58][59] investigated the flow forming of FCC alloys such as 70/30 Brass, pure copper, Al5052, and Al6061. The author reported that the equiaxed grains of the preform had been converted to an elongated grain structure. The author also reported annealing twins to a larger extent in 70/30 brass and to a smaller extent in pure copper. In all cases, severe flow forming produces grain refinement, grain orientation, and grain elongation along the mandrel axis. The authors [58] also reported that in these alloys strain hardening leads to limited uniform elongation in true stress- trues strain curve which also suggests that no dynamic recovery took place due to suppression of dislocation climb or cross slip. The authors[59] also reported that some serration phenomenon occurred in Al5052 probably due to Portevin – Le Chatelier(PLC) effect. The serrations were attributed to an interaction between fast diffusing solute atoms (example Mg) with dislocations, leading to pinning of dislocations.

Severe deformation can also lead to dynamic recrystallization in which the grains after deformation become equiaxed instead of elongated grains. [60],[61].

Gupta el. al [23] recommended intermittent annealing between the passes for hard to deform alloys such as niobium, as significant hardening can take in each pass which can result in high deforming forces and defects. For niobium, a percentage thickness reduction of around 20-25% generally produces good results. Annealed preform would not provide resilience to crack propagation, found to produce strength and hardness but quenched and tempering was found to produce an opposite effect as expected from the annealed preform.[13][21]. However, the action of tempering and hardness were limited by the presence of inclusions and impurities [13]. To obtain the optimum condition of mechanical properties, the authors[13] proposed a modified cycle of heat treatment.

Reliable numerical model predicting the microstructure and grain size and distribution is still not available in literature till now. The experimental results are available for some materials only.

1.9.5 **Model for Prediction of Power and Tool Forces**

One of the most important objectives of academic research was the prediction of forces in flow forming process. The flow forming force have three components radial, axial and the tangential direction (circumferential direction). In all literatures, the axial direction has been taken along the mandrel axis.

Hayama and Kudo [11] considered the formation of the wave of material just ahead of the roller and developed a connection between the thickness reduction ratio (degree of thinning) with the radial force. According to the authors, the radial force always remains constant for a small degree of thinning. However, the radial force increases as the degree of thinning increases indicating the process becomes unstable. The authors quantified the wave by the relationship

$$\frac{1}{\zeta} = a - b\,R \qquad (1.6)$$

where ζ is the size of the wave, R is reduction ratio, a and b are constants that depends on feed of roller. The authors also provided the values of a and b in tabular form. The result of the authors (Figure 1.10) shows a linear relationship between radial force and $\sqrt{feed}$

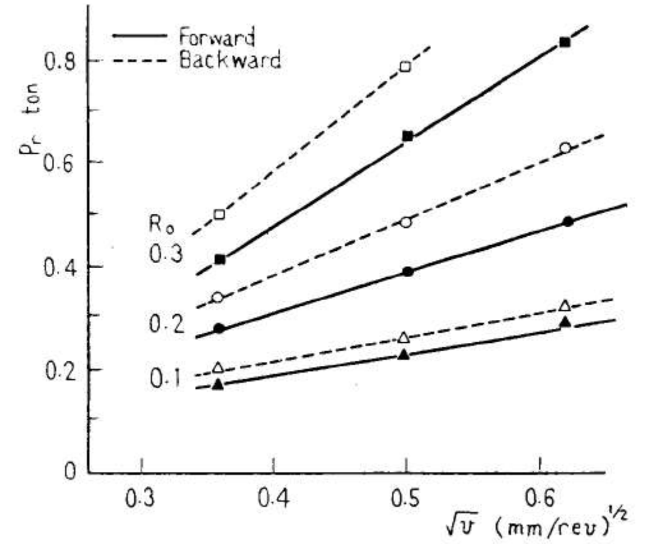


Figure 1.10: Radial force variation with $\sqrt{\boldsymbol{v}}$ ($\boldsymbol{v}$ is feed in mm/rev).[11]

The authors [11] concluded that forward flow forming provides more selectability than backward flow forming due to a larger critical degree of thinning. The authors also concluded that the attack angle of 20-25° provides lower working forces for a feed of 0.249 mm/rev. The authors [11][62] also presented an analytical model for evaluating working forces and their interdependence on reduction ratio.

Chang et al [63]Singhal et al [49]investigated the power required and forces in hard to deform materials by assuming no flow in the tangential direction (x-direction) and no build up in diameter. The authors analytically investigated the forces involved using an upper bound method and validated it experimentally. The authors showed that roller diameter had no significant effect on power consumption. The power consumption was reported to increase with increase in thickness reduction but changing feed don't have significant effect on power consumption but a higher feed spoils the surface finish of the job. Radial forces in tubes was found to be bigger than axial force in tube spinning which in turn was bigger than circumferential force. [11][64][15][44][27][42][40]. Various mathematical models have been proposed to predict the forces in flow forming. The expressions for the radial force, axial force and circumferential force as given by some researchers are listed below.

1.9.5.1 Existing mathematical equations relating flow forming forces

The different mathematical expressions relating the flow forming forces are given below

Radial Force [65][66]:

$$F_r \approx \frac{\sigma_m \Delta t \sqrt{Rf cot\,\gamma}}{K_f} \tag{1.7}$$

$$F_r \approx K_r \sigma_m{}' t_i \sqrt{2Rf cot\,\gamma} \tag{1.8}$$

The various expressions for axial force are given as [65][66]

$$F_a \approx \frac{\sigma_m \Delta t \sqrt{Rf tan\,\gamma}}{K_f} \tag{1.9}$$

$$F_a \approx K_a \sigma_m{}' t_i \sqrt{2Rf tan\,\gamma} \tag{1.10}$$

The various expressions for tangential component of flow forming forces are given as: [65][66]

$$F_t \approx \frac{\sigma_m \Delta t\, f}{K_f} \tag{1.11}$$

$$F_t \approx K_t \sigma_m{}' t_i f \tag{1.12}$$

where σ_m is average effective material strength,

Δt = depth of material processed = $t_i - t_f$

K_r, K_a, K_t= derived constants always <1; K_f= process efficiency

f= feed in mm/rev

γ = roller attack angle

R= Roller effective radius

R' = Roller radius

$$\sigma_{m'} = \frac{2\sigma_m}{\sqrt{3}} \tag{1.13}$$

Nagarajan et al. [56] however commented that the forces calculated from the mathematical models given by Equations (1.7) and (1.12) were about 1.5 to 5 times the experimental results. The authors attributed to the large difference to the complex nature of the material flow at the contact zone. Kalpakcioglu [67] suggested the large differences in calculated and experimental forces could be attributed to the choice of average yield stress especially in cases involving higher strain rate and higher temperatures.

Singhal et. al [49] proposed expression for estimating power and force in cone spinning of long tubes using energy method.

1.9.5.2 Radial force :

The mathematical expression relating radial forces are given by equations (1.7) [66] and (1.8) [65]. It was reported by various researchers that radial forces were highest among all the three components of the forces. [11] [15] [27] [40] [42] [44] [64]. The radial force was found to increase with the increase in feed rate. Radial force was also found to increase with increasing roller diameter [15],[48]. According to Park et al.[64] friction factor increases the radial force. Radial force was found to increase with increase in yield strength of the preform and the hardness of the preform.

1.9.5.3 Axial Force :

The mathematical expression relating axial forces are given by equations (1.9) [66] and (1.10) [65]. Wong et al. [42] reported that the axial force reduced with increasing feed rate . According to the authors [42] , this was due to higher real reduction that was observed in case of lead. The axial force was also found to increase with increase roller diameter and hardness of the preform.[15][48].

1.9.5.4 Tangential Force:

The mathematical expression relating cirumferential forces are given by equations (1.11) [66] and (1.12) [65]. Tangential force increases with increase in feed rate [42]. However the magnitude of tangential force was found to increase with increasing friction factor and increasing thickness reduction per pass. Increasing mandrel speed, preform diameter and roller diameter has found to be negligible effect on tangential force.

The effect of nose radius on flow forming forces was studied by Elkhabeery et. al. [68], Ma [50]. Elkhabeery et. al. [68] used theoretical model and concluded that flat roller nose would result higher flow forming forces as compared to roller with nose radius. Ma[50] concluded that though the nose radius affect the flow forming forces, the effect of feed rate was found to be most dominant among nose radius, roller angle and feed.

The flow forming forces was also found to be affected by roller attack angle. Ma[50] concluded that too high attack angle would increase the flow forming forces. Similar too low attack angle would also increase the flow forming forces. Hence, an optimal attack angle was proposed at which the resultant spinning force was found to minimum. However, Ma[50] reported that the optimal angle depend on many other factors such as roller diameter, friction factor, feed rate, thickness reduction etc. The optimal angle was found to increase with increase in increase in feed rate and thickness reduction but decreases with larger roller diameter and friction factor.

Effect of other factors such as preform microstructure, preform ductility etc also affect the flow forming forces but the dependency was found to be case dependent.

Lee and Lu [35] considered the flow forming as drawing process and studied the effect of front tension and back tension on the total force and roll pressure. The authors reported that the total force was found to increase with increasing deformation and increasing friction force. The front tension was found to increase with increase in thickness reduction but decreases with increase in the frictional force between preform and the mandrel.

1.10 Stress and Strain in Flow forming

Flow forming being a cold forming process is associated with the accumulated stress and strain. Prediction of instantaneous stress and strain in flow forming process had been taken up by many researchers. Very few authors have researched about the residual stress and their impact over the defect and stress / strain behavior of deformed product.

Hayama and Murato [69] experimentally measured the strains in conventional spinning process and reported that strain distribution was largely depended on the feed rate but the variation of strain rate strongly dependent on working condition.

Roy et. al. [27] used the measure of surface hardness and correlated with the maximum equivalent plastic strain using Tabor [70] work. The authors [27] used the correlation between Berkovich Hardness and surface hardness as

$$H(\epsilon) = A(\epsilon + \epsilon_{ind})^n \tag{1.14}$$

Where H is Berkovich micro hardness (kgf/mm2), and n are material constants and ϵ_{ind} is the average equivalent plastic strain. The author mapped the true stain developed at the contact regions in AISI 1020 steel. The experimental values and the maximum equivalent strain were correlated for different thickness reduction.

Haghshenas et. al.[71] used the similar technique and measured Berkovich hardness and used the data to correlate the maximum equivalent strain. The author used Tabor (1951) work and used the experimental data proposed the mathematical expression correlating Berkovich hardness and maximum equivalent strain for two aluminium alloys 5052-O and 6061-O as

$$\varepsilon_p(H)_{5052-O} = \left(\frac{H}{1.402}\right)^{7.1} - 0.08 \tag{1.15}$$

$$\varepsilon_p(H)_{6061-O} = \left(\frac{H}{1.113}\right)^{4.4} - 0.08 \tag{1.16}$$

Where H was Berkovich Hardness in GPa.

The authors reported that the across the thickness of the flow formed product of different material, the average von Mises equivalent plastic strain was found to be same but the local equivalent plastic strain, local maximum equivalent strain was found to vary for two alloys 5052-O and 6061-O under consideration, probably due to different stain hardening characteristic of the workpiece. The variation was also attributed to different grain size as the author reported that the size of microhardness indentations were smaller than grain size.

The authors also reported that the von Mises equivalent plastic strain increases with increasing thickness reduction. Haghsena et al. [57] reported similar result in splined mandrel flow forming of AISI 1020 where maximum equivalent von Mises plastic strain was found in ribbed region of spline. However, the extent and sensitivity of increase was depend on the geometry of splined mandrel.

1.11 STATE OF STRESS

Xu et al. [40] reported the complex state of strain in the contact zone. The authors divided the deformation zone in three different zones as shown in Figure 1.11

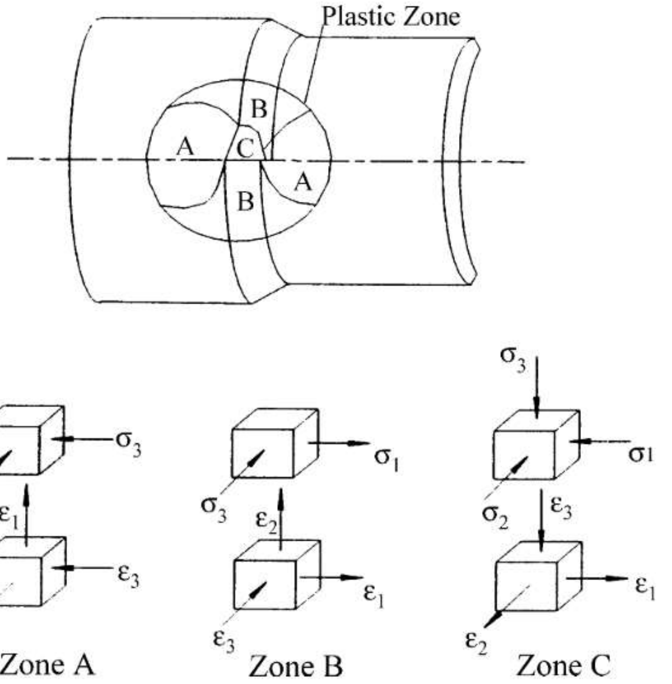


Figure 1.11: Deformation zone in flow forming[40]

The author reported a 3D compressive triaxial state of stress in Zone of Contact (Zone C). The roller compresses the material in contact region which induces compressive stress in nature in radial direction and tensile in radial and axial direction due to outward flow. The tensile stress induced in the contact zone produces deformation in the axial and tangential direction. In zone B that is the zone of deformation in tangential direction of the contact region, the authors reported biaxial state of stress – tensile in axial direction and compressive in tangential direction. In zone A which represents the deformation zone in the axial direction of roller, a state of 3D compressive stress exist with compression in axial while a tensile stress was reported in the radial and tangential direction. The state of stress in the deformation zone as reported by the author is given in Figure 1.12

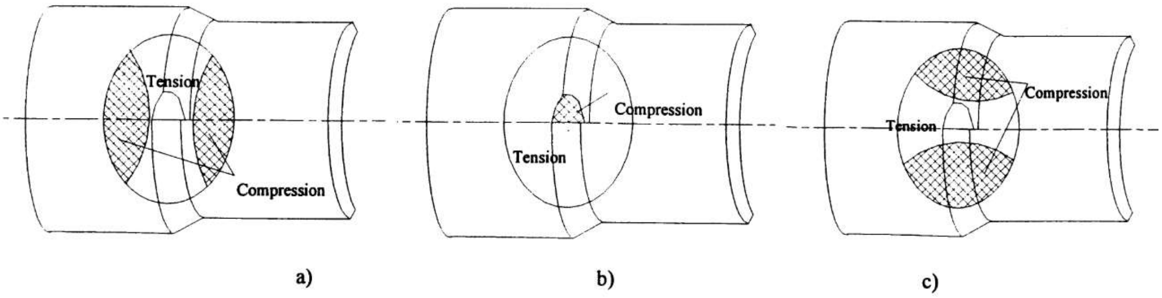


Figure 1.12: Deformation zone and the state of stress (a) axial direction (b) radial direction and tangential direction [40]

Bylya et al.[72][73] investigated the mechanics of flow forming and proposed that stress-strain rate in flow forming are non-uniaxial and non-uniform and might involve high gradients of stress and strain.

1.12 Defect and failure of flow formed samples

Like all manufacturing processes, defects are common in flow forming process. The main defects that are associated with the flow forming process are diametral growth, ovality, fish scaling, springback, micro cracks, and wrinkling. This section tries to correlate the different defects with the possible factors affecting it.

Many authors reported that the many flow forming defects can be related to the material flow that would be taking place in circumferential and axial direction. S/L ratio relates to the quality of material flow and would be correlated to defect prediction. Gur and Tirosh [14] had analyzed the material flow in metal spinning. The authors suggested that if the axial contact length L exceeds circumferential contact length (S) that is S/L<1 then circumferential plastic flow dominates. This results in geometrical inaccuracies and give rise to related defects. If S/L >1 , then axial flow dominates due to interfacial friction. Higher the flow in axial direction would result in lesser chance of defects. However, if S/L is too high ie. S/L >>1, then friction coefficient increases close to unity. As a result, more material would flow under the roller along some direction at an angle smaller than the attack angle. This would result in wave like appearance and unevenness in thickness would occur. The defects can be minimized by proper selection of initial thickness, feed rate, and reduction ratio and roller attack angle. Micro crack and material failure can be related to stresses and process instability. The relation between the defects and the probable causing factors has been presented in Table 1.6. The relationship have been grouped as high suggesting high order of relationship, low for low order of correction and NA for almost no correlation and no specific relationship data reported.

Table 1.6: Summary of defects and their probable influencing factors. Table adapted from Marini et. al.[74]

Defect Type	Factors influencing the Defects									
	Geometrical parameters		Preform Characteristics			Process Parameters				
	Roller Dimension	Roller Attack angle	Preform initial Thickness	Preform microstructure	Preform Hardness	Feed rate	Mandrel Speed	Depth of cut (in- feed)	Lubrication	Reduction Ratio
Diametral growth	High	High	Low	Low	Low	High	Low	NA	NA	High
Ovality	High	NA	NA	High	High	High	Low	High	NA	High
Fish Scaling	NA	High	Low	High	NA	High	Low	Low	NA	High
Wrinkling	NA	High	NA	NA	NA	High	Low	NA	NA	High
Springback	High	NA	High	High	High	High	NA	NA	NA	High
Cracking	NA	High	High	High	NA	High	Low	Low	NA	High
Microcrackings	NA	NA	NA	High	NA	NA	NA	NA	NA	NA

High- Strong influence, Low – Weak influence, NA- not available

The following section discusses some of the important defects that are seen in flow forming operations.

1.12.1 **Diametral growth:**

Diametral growth measures the dimensional accuracy of the internal diameter formed by the flow forming process. This is important as this defect would result in deviation from the near net shape that is expected from the flow forming process. The generally accepted root cause for diametral growth is the presence of circumferential residual stresses. Xue et al [33] were one of the first few researchers who had tried to address the issue of diametral growth using a numerical method by performing an elasto plastic finite element analysis. Xu et al. [40] analyzed the stress and strain distribution in forward and backward tube spinning using a rigid-plastic finite element model. Wang and Long [75] investigated the effect of roller path design and tool compensation technique to avoid wrinkling and reduce diametral growth. Hua et al. [76] performed FEA analysis to study the Diametral growth. Mohebbi and Akbarzadeh [43] used explicit FE code to study redundant strain distribution and correlated with diametral growth phenomenon. Until now, none of the FEA models had been successfully predicted the extent of residual stress and diametral growth for a given material. This can be accounted due to:

(i) Complex deformation nature of the flow forming process

(ii) Most of the model were based on rigid – plastic material which did not involve residual stresses. Therefore, diametral growth was accounted in the analysis.

(iii) Non conformity of experimental and numerical method can also be due to wrong or oversimplified assumptions. Mass scaling and explicit integration assumptions can induce large numerical errors especially while simulating dimensional accuracy, especially diametral growth. Static implicit code though better than explicit code but due to high computation cost and difficulty in obtaining convergence in the solution, this was not frequently used.[37] [77]

Diametral growth was found to be increased by increasing thickness reduction ratio and roller attack angle but was less affected by preform hardness or mandrel speed.[74]. Rajan and Narsimhan [19] found that the diametral growth increases with increasing percentage thickness reduction in AISS 4130 but it was hardly affected by roller feed rate. The authors related the diametral growth to the ratio of S/L; where S= circumferential contact length and L represents axial contact length. Lower S/L will lead to higher diametral growth and vice versa. Controlling S/L ratio would be therefore a better strategy to minimize the diametral growth. To minimize diametral growth, dimension of mandrel should be modified to have negative clearance for the expected growth.[19], [78].

1.12.2 **Ovality or out of roundness:**

This is another common problem encountered in flow formed components. Ovality was reported to highly influence by feed rate and depth of cut and reduction ratio strongly affect the ovality of the finished product. Ovality also depends on the preform microstructure and preform hardness. Srinivasulu et al. [30] showed that the correct combination of feed rate and depth of cut can reduce the problem of ovality. The authors [30] also reported that ovality first increases reaches a maximum, and then decreases with an increase in feed rate. The authors also reported that ovality increases with a decrease in feed rate as in that case the deformation in radial direction increases. On the other hand, ovality also increases if the feed rate is too high combined with a low reduction rate. Srinivasulu et al.[30] reported that ovality of the flow-formed tube increases with increasing roller nose radius due to lower forces induced by small nose radius. Podder et al. [46] reported the preform microstructure a preform hardness affect the extent of ovality.

1.12.3 **Wrinkling:**

Gupta et. al.[23] Suggested that the problem of wrinkling arises is caused due to inappropriate mandrel support or very high feed rates. Figure 1.13 reveals the problem of wrinkles. The main cause of wrinkles was attributed to the high complex tensile stress in the localized deformation zones. Wrinkle tip would lead to micro cracking if the stress generated by combined bending and buckling exceeds the limiting strength. [23][69] **.**

Figure 1.13: Wrinkling defect Gupta et al. [23]

1.12.4 **Fish Scaling :**

Fish scaling or waviness is a surface related problem that is formed during flow forming operation. Figure 1.14 shows the example of fish scale

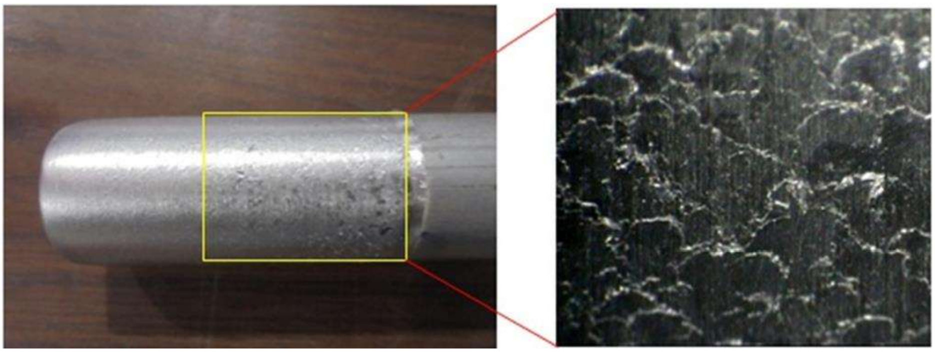


Figure 1.14: Fish Scales on flow formed component. [79]

Davidson wt. al. [24] , Bhatt and Raval [79]suggested that high feed rate, high speed and low percentage thickness reduction are ideal conditions for fish scales. The authors Bhatt and Raval [79] explained that under the said conditions, the material mainly flows in the circumferential direction due to large cold work in a small region (thin region). This would increase strain hardening and hence results in fish scales.

Rajan and Narasimhan [19] studied flow forming of SAE4130 steel and reported that fish scaling appeared generally in second or third pass of multi pass flow forming. The authors suggested that fish scale are related to non-uniform grain size that would result due to non-uniform heat treatment. The presence of inclusions also affect the fish scales behavior by introducing non- uniform deformations and residual stresses. Preform containing large sized grains are more prone to fish scaling. Large attack angle when combined with high feed rate would this kind of defect .[11]

1.13 **Flow forming Roller geometry**

Roller geometry in flow forming is an important consideration in designing the flow forming process. The main elements of roller design are roller diameter, roller attack angle, relief angle, and nose radius and roller surface finish.

Roller diameter is an important design parameter that affects the S/L ratio. The choice of Roller diameter are based on its effect on S/L ratio and final diameter of the flow formed job. Roller diameter is not found to affect the power requirement fir the process however it affects the surface roughness of the product.

The effect of nose radius had been studied by some of the researchers. Though the effect of nose radius was quite significant in conventional spinning process, its effect in flow forming is not very clear. In conventional spinning, degradation in nose radius is found to induce error in tool compensation in CNC machine as it defines the toll reference point for defining tool path.

Wang and Long [75] reported that an increase in nose radius results in high deforming forces, smaller percentage reduction and results in higher surface finish. Roy et. al[80] found that the change in nose radius had small effect over S/L ratio. Aghchai et al [31] tried to obtain an optimized value of nose radius in flow forming process where the output parameter was diametral growth. The author reported that the nose radius of 5 mm with attack angle of 25^{0}C was optimum value for controlling diametral growth.

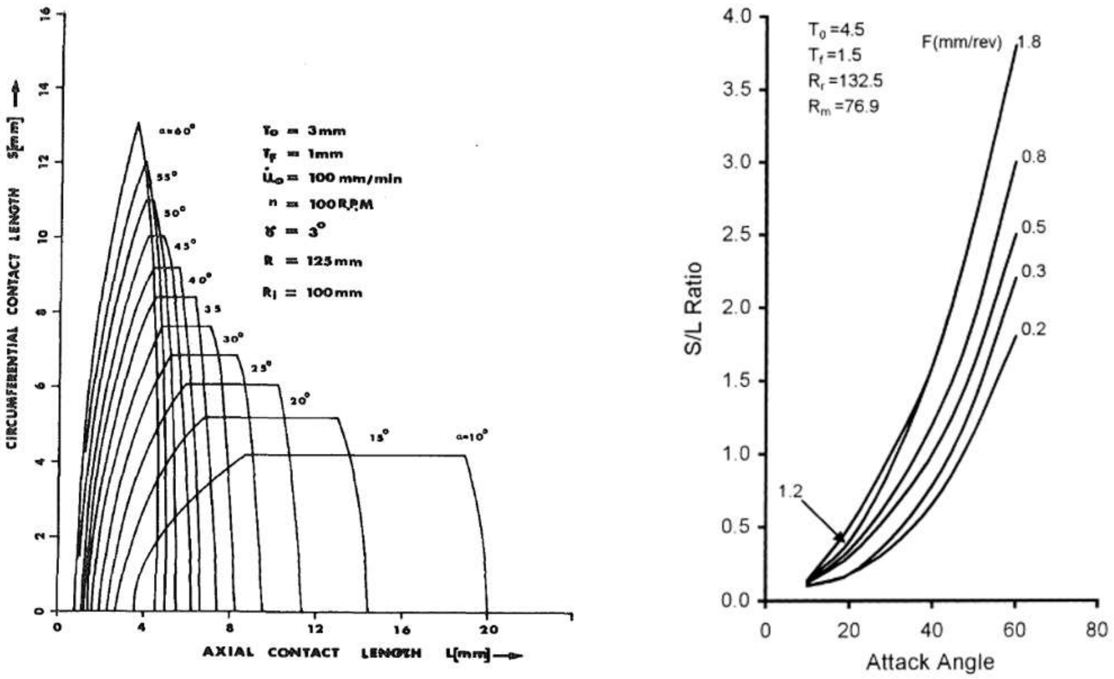
Singhal et al. [15] studied the effect of roller land – the region between the roller attack angle and roller relief angle on parameters such as feed rate and the product surface finish. The authors found that increasing roller land would permit higher feed rate but it surface finish was found to be poorer. The authors proposed that roller land of about 2 mm would allow higher permissible speed without having much effect on dimensional accuracy.

One if the most important parameter of roller design is roller attack angle. Roller attack angle has strong effect over flow forming forces, power requirement, and dimensional accuracy and limiting degree of thinning. The effect of roller attack angle has been studied both experimentally and analytically. Hayama and Kudo [11] found that for soft metals an attack angle of around 20-25 degree would minimize axial force requirement. Jahazi and Ebrahimi [13] suggested that the choice of attack angle for a given thickness reduction, should be made such that it should not result in plastic flow instability. The authors [13] also stated that choice of roller attack angle also affects S/L ratio.

A higher attack angle would result in higher S/L ratio due to higher friction between the preform and the roller. To maximize S/L ratio, some researchers had used different attack angles. Jahazi and Ebrahimi[13] has suggested that a 30 degree attack angle had produced a defect free process but had resulted in increased the radial force. Hence, increasing attack angle increases the total power consumption and thereby decreases the process efficiency but at the same increases S/L ratio and would results in defect free product. Gur and Tirosh

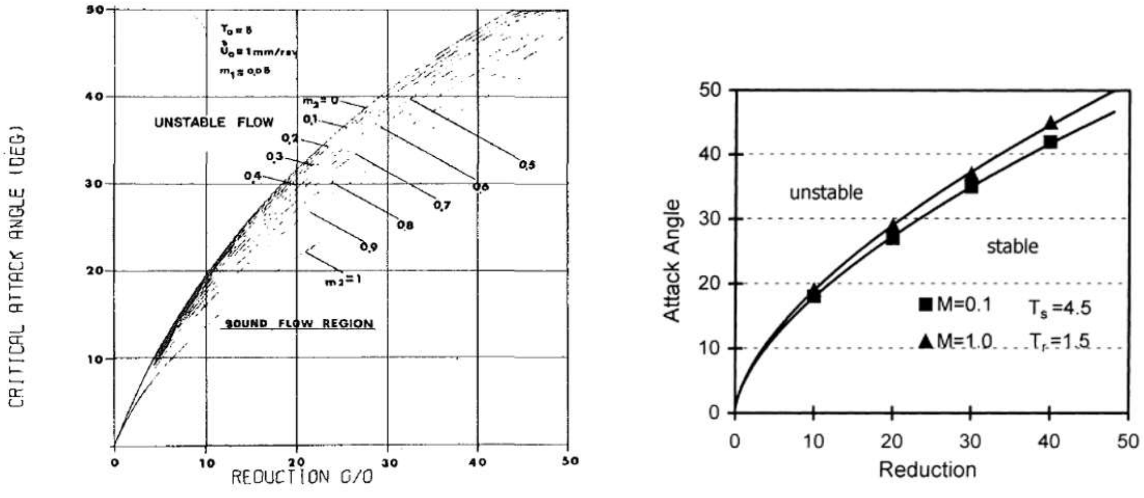
[14] investigated the role of attack angle on different process parameters such S/L ratio, suggested that an optimum value of roller attack angle should be around 20-25º. Figure 1.15 shows the effect of attack angle on circumferential and axial contact length.

From the work of Gur and Tirosh[14] and later by Parsa et.al.[44] and Jahazi and Ebrahami[13] , a more comprehensive insight on S/L can be obtained as a function of attack angle. Quantitative correlation between the stability and critical attack angle, shown in Figure 1.16 by the authors provide some insight in choosing the attack angle while planning for the process



(a) (b)

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]



(a) (b)

Figure 1.16: (a) Correlation between critical attack angle and thickness reduction. [14] (b) Correlation of attack angle and thickness reduction [13]

1.13.1 Tool Path Design:

In flow forming the path traced of the tool relative to the workpiece is called tool path. The tool path can be controlled by two parameters- mandrel speed and feed rate. This parameter has strong effect on surface finish of the flow formed product.

Wong et al.[81] investigated the effect of tool path on flow forming of solid lead workpiece. The author investigated two paths- radial path and axial path. Radial path was found to reduce the workpiece diameter creating a thin walled cup shape on the free end of the workpiece while axial tool movement pushed the material in opposite direction forming a shallow crater.

1.14 Effect of Lubrication

Lubrication affects the friction condition between the mandrel and the tube and also between the roller and the workpiece. Lubrications also reduces the working temperature.

Singhal et al. applied blend of grease and fine copper between the mandrel and workpiece to avoid the chances of cold welding. The author asserted that the lubrication affects the higher surface finish but it had almost no significance over other process parameters.

1.15 Preform designing

Many researches have been done on different types of material. Most of the researches were earlier based on soft metal such as aluminium, lead, copper, low carbon steels but lately plastics, hard to deform alloys such as stainless steel. [49]. Plewinski and Drenger [26] investigated flow forming of Al7075 high strength steels such as 0H18N9T and 00H17N14M2 , Inconel 625 alloy. Rajan and Narasimhan [19] investigated AISI 4130.
Preform dimension and geometrical accuracy has large effect on process and the final product properties. Singhal et. al. [15] found that the uneven , non-concentric preform generally lead to bending of formed tube.
The preform should be free of defects such as hydrogen embrittlement to eliminate the defects due to inherent defects in the material stage. The microstructure of preform severely affects the flow formability of the preform [53]. Materials with higher impurities and inclusion rating are more prone to defects like microcracks. Presence of deformed MnS in AISI 4130 acts as a stress raiser and would lead to microcracks [82].

1.16 Heat Treatments

As flow forming is a cold forming process, fine grained preform is not desirable as it would lead to higher deforming forces. However, large grains would lead to fish scales or even cracking. Annealed samples have high formability but would result in a lower strength products. However, a normalized and/or tempered preform has higher strength and thus require higher force and also may result in cracking and other defects but the flow formed product obtained would much higher strength. [21][82]. For steel, spheroidizing treatment would result in superior mechanical properties of the final product Podder et. al. [53], as the above treatment produces a product with comparable UTS and hardness like annealing and hardening/tempering, but with better elongation properties

Gupta et. al. [23] reported that intermittent annealing would reduce the chances of microcracks in flow forming of the low formable alloys and niobium based alloys.

Flow forming is a versatile forming process, it mechanics is complex. This makes the applicability of existing numerical models which are applicable to some materials only. Mostly, the experimental analysis becomes the only mode to give accurate data. FEA analysis are also fast emerging but again the analysis has to be backed by experimental data. Even the results changes with change in preform temper condition and changing the alloy composition. This has given me the motivation to try flow forming of three Aluminium materials -– Al7075, Al6101 and Al2014. As per current knowledge, no flow forming condition is available for Al6101 and Al2014. Very few data is available for Al7075.

1.17 Scope and Aim of the Thesis:

The aim of the thesis is to investigate the gaps that exist in understanding the flow forming process. Flow forming is a versatile process but till now its acceptance in industries is very less. In India, very few companies are using the flow forming process. So the present investigation tries to look into the feasibility of converting an existing facility in machining workshops to perform the forming operation. Once the setup is developed, then flow forming characteristics would be studied by performing flow forming on three different alloys of aluminium. The materials that had been chosen for investigation are Al6101 T6, Al2014, and Al7075. These materials are chosen because very little research work on these materials. There are few pieces of research on the flow forming of Al7075 is available in the literature. There is almost no research work on Al2014 and Al6101 is available till now. The investigation would try to measure in situ forces and power. To predict the forces, a mathematical model would be developed that has to be validated by experimental results. Further, the product characteristics have to be studied such as their microhardness, microstructure, etc. Residual stresses would also be measured.

In summary, the aim of the thesis is achieved by satisfying the following objectives:

(i) Fabrication of setup for performing flow forming operation using the in-house facility.

(ii) Developing a mathematical model based on upper bound to determine the flow forming forces and validating the same with experimental results.

(iii) Study the characteristics of flow forming on three aluminium alloys – Al6101, Al2014 and Al7075.