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FLOW FORMING: A REVIEW OF RESEARCH METHODOLOGIES, PREDICTION MODELS AND THEIR APPLICATIONS

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ABSTRACT

After years of largely academic interest and niche applications, a new generation of high duty CNC machines is enabling the flow forming process find increasing application in aerospace, automotive and defense industries. The versatility of digital control has made it economically viable to deliver weight and cost savings for small to medium batch sizes while simultaneously improving quality and material proprieties.

To better understand the capabilities of flow forming this review surveys the reported research over last fifty years and summarizes both theoretical models and experimental investigations. Where possible the contributions of different researchers are described and assessed in terms of the accuracy of their predictive capabilities. In some cases practice has preceded the development of theory for example: the ratio of circumferential to axial contact is widely used as a defect prediction parameter, even if the process' failure mechanism is still not fully understood. In other areas, such as forming forces and powers, the literature provides a clear rational based on experimentally validated analytical models.

In addition to summarizing current knowledge the review also identifies gaps in currently literature where more research is required. For example: the evolution of stress/strain tensors during a flow forming process has not been reported due to the high computational cost and a lack of consensus on the most appropriate finite elements modeling approach to adopt. Similarly while the final microstructure of a formed part is often evaluated models of its development (during the series of plastic deformations created by a flow forming process) have not been reported. Likewise residual stress and final material proprieties, such as corrosion behaviour, have been not studied numerically or experimentally. It is also noted that the impact of tool paths (e.g. their geometry and topology) has not been deeply explored. Lastly the authors note, the surprising observation, that only a few researchers have reported the experimental optimization and characterization of flow forming process parameters using a 'Design of Experiments' methodology.

Key words: Flow forming, Review, Spinning, Design of Experiment, Process modeling

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1. INTRODUCTION

The flow forming process manufactures rotational components using deformation forces generated by rotating rollers that compress and stretch a blank (called a preform) though consecutive stages over a mandrel. Despite the limited commercial applications of the process a steady stream of research into its mechanics and characterization has been reported (mainly by German and Japanese researchers) since its introduction in the 1950s. (Figure 2). Today flow forming is of growing importance because it:

- Produces components with good tolerance control and geometrical accuracy.
- Allows precise control of a component’s wall thicknesses and so enables the manufacture of optimized designs.
- Supports a large range of workable materials (e.g. Steel, Alloy Steel, Titanium and Titanium Alloy, Brass, Copper, Aluminium, Nickel, Niobium).
- Improves the mechanical properties of formed materials (through working hardening).
- Generates components with excellent surface roughness (compared with other plastic deformation processes).
- Increases mechanical properties due to cold working (hardening) effects.
- Results in cost saving due to reduction in finish machining operations.
- Avoid material waste (compared with both classic forging or forming processes and machining).
- Costing savings due to heat treatment reduction.

The economic advantages arise from the processes ability to form material into a complicate shape that allows the elimination of subsequent manufacturing or finishing steps. Thus a reduction of cost can be achieved while simultaneously enabling lightweight designs with good mechanical properties.Any comprehensive literature review for flow-forming, must address both the physical mechanisms underlying the process and their application in the engineering of manufacturing procedures. To provide a framework for the review that effectively distinguished between these two interacting streams of work, the methodology proposed in Music et al.(2010) (for shear forming) has been adopted Figure 1). To identify where the emphasis of this framework will differ from that proposed for shear forming, reviews such as Sivanandini et al.(2012) and Wong et al.(2005) have been used to establish the appropriate scope. This process concluded that in order to apply the framework to flow forming it should be expanded to incorporate issues of microstructure (whose effect is fundamental to local yielding and deformation) in the knowledge section, as initialized in Marini et al.(2015). Likewise the ‘applications’ section should be extended to include the mechanical characteristics of the final product (because flow forming can frequently enhance these). The following sections populates the Figure 1 framework from left to right with Sections 2 and 3 presenting ‘knowledge’ (i.e. theory) and Section 4 detailing contributions related to applications .

The details, within this overall structure, are as follows: the Introduction concludes with three more sections that cover flow forming’s general features and distinguishes it from, the more common, shear and spinning processes. Section 2 reviews the research methodologies adopted by flow-forming researchers by dividing them in experimental and theoretical (i.e. analytical and numerical) with a sub-section dedicated to ‘Design of Experiments’ (DoE). Section 3 summarizes the outputs available to support the prediction of flow forming issues. Section 4 summarizes the reported applications of developed knowledge in areas ranging from the achievement of production targets to the process planning of the flow forming process. Section 5 concludes the review by highlighting current gaps in knowledge and identifying future research aims.

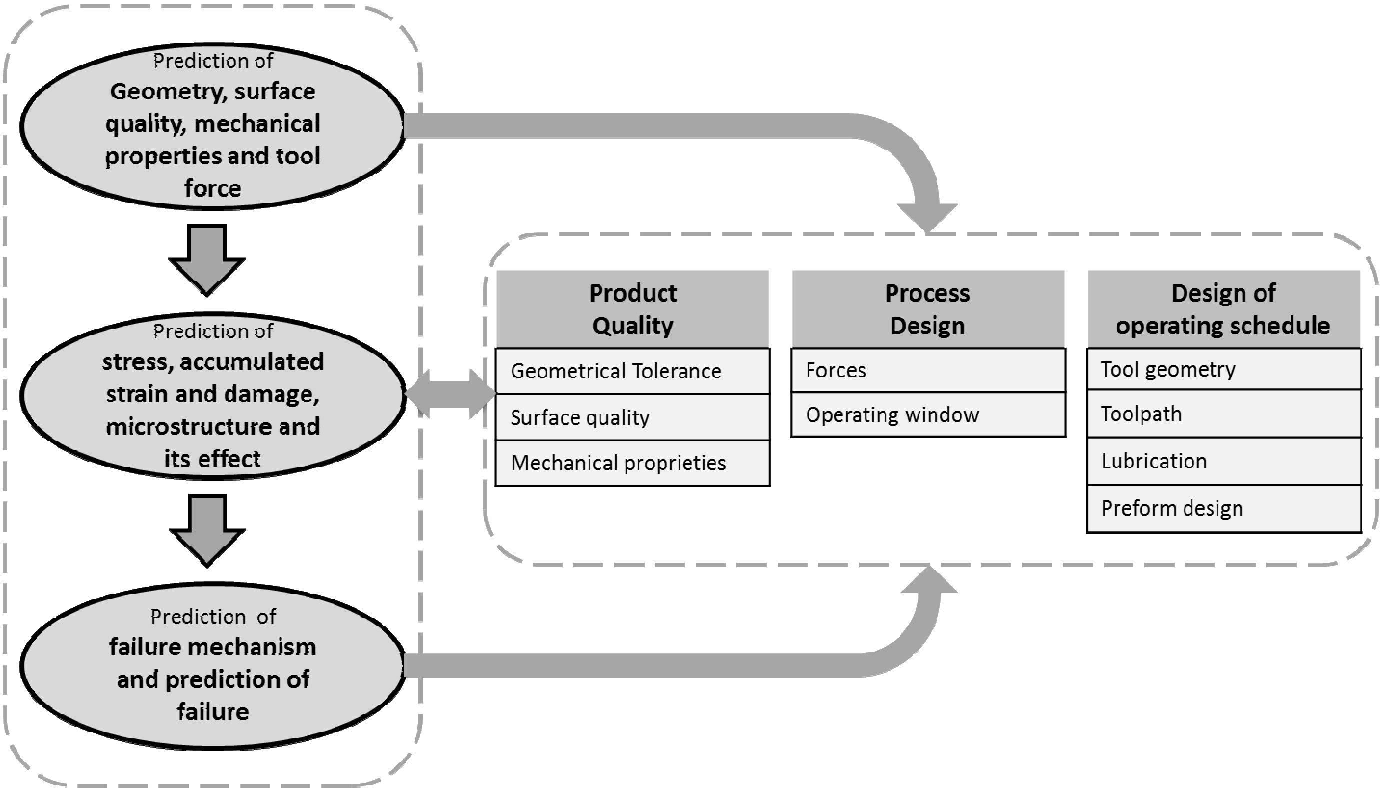

Figure 1 Review methodology developed from [Music et al.(2010)

1.1. Flow Forming Definitions and Terminology

Flow forming plastically deformation a hollow metal blank on a rotating mandrel by means of forces generated by a number of moving rollers (Figure 3).The blank's material is constrained to flow in an axial direction by the movement (i.e. feed) of a number of rollers. Large thickness reductions of over 50% can be achieved with multiple passes of the rollers (i.e. several repetitions of the forming process) while the internal diameter remains almost constant.

This distinctive capability of the process is characterized by the reduction ratio (R_0) parameter:

$$R_0 = \frac{t_0 - t}{t_0} \tag{1}$$

or

$$R_0 = \ln \frac{t_0}{t_0} \tag{2}$$

Where, t_0 is the initial thickness of the blank and t is the final thickness of the workpiece Hayama and Kudo(1979). In later sections of this review the limits of flow forming processes imposed by, say, material properties or machine power are frequently defined in terms of reduction ratio. For example tube "spinnability" is defined by Kalpakcioglu (1961a) as the maximum reduction achievable.

This large and controlled change in the thickness of the workpiece is often cited as the crucial difference between flow forming and conventional spinning (where the thickness remains essentially constant) Wong et al., (2003) The flow forming process has two main variants known as forward and reverse (or backward) flow forming. In forward flow forming, the blank is located (i.e. clamped) through the tailstock and mandrel (requiring the blank to have a suitable ‘flange’ geometry to enable this fixture) Wong et al., (2003). The arrangement constrains the workpiece material to “flow” in the same direction as the roller s axial movement. In other words it is pushed ahead of the rollers as progress down the mandrel. In backward flow forming, the workpiece is located against the headstock of the mandrel which forces the material to “flow” in the opposite direction to roller s motion (i.e. squeezed out from under the rollers themselves). Although this removes the need for the initial blank to have a locating flange Singhal et al.(1990) observe that it is easier for defects to occur (compared to forward processes). This is because the large axial deformations (material can be flowed along the length the mandrel) results in residual stress that can cause distortions and local weak-points. Consequently backward flow forming is also more susceptible in a loss of accuracy in the axial direction (Xu et al., 2001; Runge 1994).

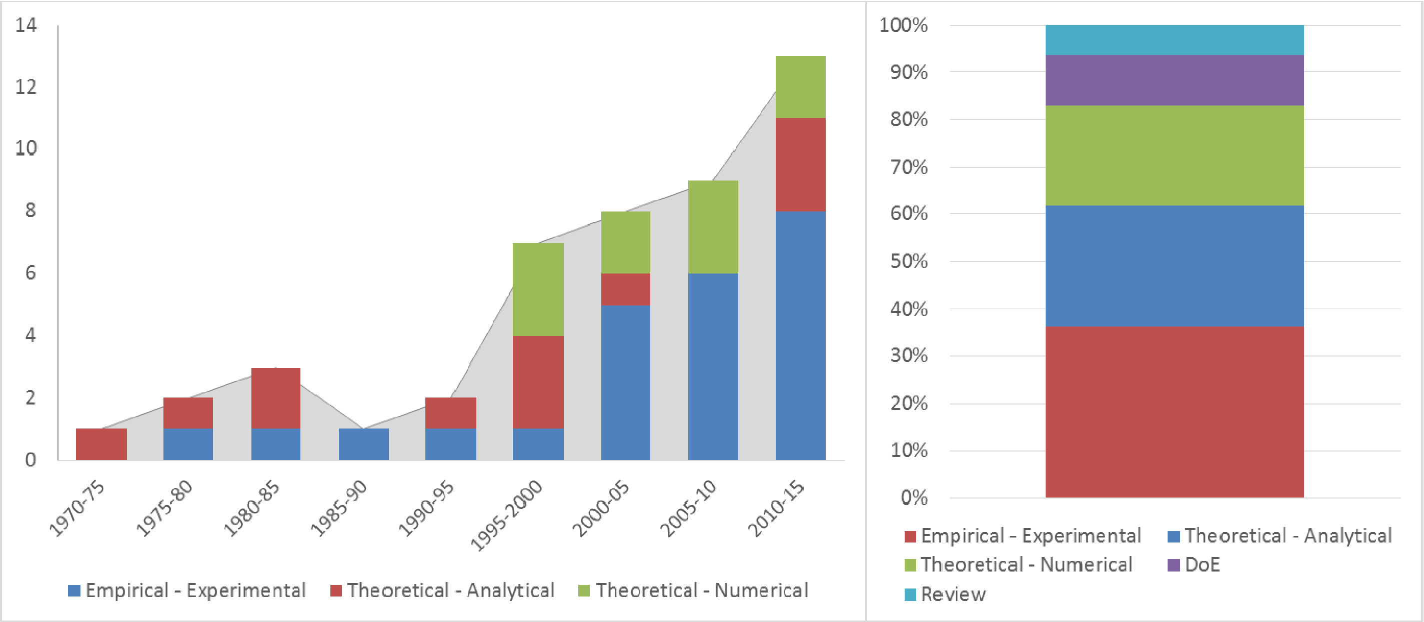

Figure 2 Timeline of articles about flow forming process.

Flow forming, shear forming and conventional spinning have several common traits that can make it difficult for new comers to clearly distinguish between different members of the family of rotational forming processes. As explained in Runge (1994), the term ‘spinning’ refers to all process for the production of rotating, symmetrical, hollow components. Spinning is generally defined by workpiece rotation through a mandrel where the component is clamped usually by tailstocks and is deformed into the required shape by spinning tools.

The essential difference between flow forming and spinning is that, metal spinning utilizes a relatively thinner piece of starting material than flow forming and produces the shape of the finished part from a starting blank whose diameter is bigger than the largest diameter of the finished part. This is similar to deep drawing, in which no reduction of the wall thickness occurs. Flow forming, on the other hand, is based upon an precise, pre-determined reduction of the thickness of the starting blank, or preform. reduction Sivanandini et al.(2012).

A form of spinning that both forms sheets on to a mandrel and creates changes in material thickness is known as shear forming. Essentially flow forming and shear forming vary in the degree of the deformation mechanisms employed (e.g. reduction ratio) and the geometry of the billet (i.e. sheet for shear or tube for flow). Gur and Tirosh (1982) differentiate between these two processes by describing flow forming as being a combination of extrusion and rolling processes. Kalpakcioglu (1961b) developed a ‘sine law’ for shear forming, which define the angle of available deformation of the piece through the mandrel inclination without defects. This determines the spinnability of the metal undergoing these working conditions. With this hypothesis, Kalpakcioglu (1961a) defines the metal flow conditions for shear forming and conclude that it is distinctly different from the flow forming process. As in Gur and Tirosh (1982), Kalpakcioglu (1964) defines the deformation mode of flow forming as being similar to extrusion.

These observations suggest that although similar, shear forming and flow forming are based on different deformation mechanism and should be treated separately Music et al.(2010). It is also interesting to note that considerable effort was expended by researchers in the investigation of shear spinning of cones during early 60s, which achieved both practical and theoretical success. However as Nagarajan et al.(1981) points out, these models are not able to predict flow forming process behavior correctly.

Given the similarities, and difference, of the various rotational forming processes it is not surprising that there have been a number of proposals for criteria to produce an unambiguous classification.

The only standard classification of spinning processes is the DIN 8582 standard which classifies processes by means of the stresses generated during spinning operation. Using this criterion DIN 8584 classifies conventional spinning as processes where plastic deformations are caused by application of tri-axial compressive and tensile stresses. Similarly flow and shear forming are defined (DIN 8583) as processes that applies only compressive stresses. Using this classification DIN 8583 makes no distinction between flow and shear forming. However is clear that while similar in the deformation force applied, flow and shear forming differ in the nature of preforms and mandrels used.

But the DIN standard does not represent a consensus view, Lange(1985), for example, groups flow forming and conventional forming with other sheet forming processes (such as deep drawing), and classifies them as tensile-compressive. Shear forming process are grouped with bulk-forming processes such as rolling, due to the compressive stresses applied to the workpiece. Similarly Kalpakjian and Schimd(2009) develops a wide classification of these manufacturing processes and divide them in to bulk and sheet forming, placing all the spinning processes in the latter. Slightly different is the definition of Music et al.(2010). They associate metal spinning with a group of forming processes, where the common mechanism is a plastic deformation on mandrel through single or multiple rollers in one or more stages.

In 1989, Wang, Z.R., Lu (1989) proposed a standard nomenclature for all spinning process, but as Music et al.(2010) pointed out in 2010, it has not been widely adopted in industrial or research environment.

In summary there is no universally accepted definition, or taxonomy, for rotational manufacturing processes. Manufacturer and researcher use different terminology for similar equipment and working technique, especially for the ones which involve reduction of thickness. For example the process of tube spinning, flow forming, shear forming and power spinning are all simply classified as tube forming process. Table 1 summarizes flow forming terminology and nomenclature found in the literature.

Table 1 Flow forming terminology and nomenclature

Term	***Alternatives***	***Description***
Conventional Spinning	Multi-pass spinning, deep-drawing spinning, spinning, simple spinning (spinning in a single pass)	Spinning process where a sheet blank is formed into a desired axisymmetric shape without a change in the wall thickness and with a deliberate reduction in diameter either over the whole length or in specific areas.
Shear spinning	Shear forming, flow forming, shear/flow turning, power spinning, hydrodynamic spinning	Spinning process where a sheet blank is formed by a roller into an axisymmetric part with a desired shape and thickness distribution. The thickness is deliberately reduced to obtain a desired distribution while the diameter of the part remains constant.

Term	***Alternatives***	***Description***
Flow Forming	Flow turning, Tube spinning	Spinning process where a blank is formed into a desired axisymmetric shape with possibility of changing in wall thickness and with a constant or variable reduction in diameter in whole length or in specific areas.
Roller(s)	-	Rigid roller that forms the sheet over a mandrel.
Tailstock	-	Circular disk clamping the sheet to the mandrel. May be flat or curved to fit over the mandrel and further support the sheet while it is being formed.
Preform	Blank, cup, disk	Initial workpiece with different possible shapes, dependent on the final required shape of product.
Initial thickness (t_0)	-	Original thickness of the part.
Final thickness (t)	-	Final thickness or thicknesses if variable along the component.
Mandrel	Chuck	Rigid axisymmetric tool with the profile of the final component. Supports the workpiece during deformation.
Roller feed rate	Feed rate	Linear speed of the rollers in axial direction (mm/s).
Mandrel speed	Rotational Speed	Rotational speed of the mandrel (rpm).
Feed ratio	Feed per rotation, feed per revolution	Stoke of the roller for every rotation (mm/rev).
Tangential force	-	Three mutually perpendicular components of the
Axial force	-	roller force.
Radial force	-	
Roller nose radius	Nose radius	Blending radius between the two flat surfaces on the outer surface of the roller.
Roller attack angle	Attack angle, leading angle, approach angle	Angle lying between mandrel axis and inclined surfaces of the roller.
Roller diameter	-	Roller main dimension (mm).
Reduction ratio (R_0)	Degree of thinning, thickness reduction ratio, spinning ration, forming ratio, maximum reduction	Proportionality between initial thickness and final thickness.

Term	*Alternatives*	*Description*
Thickness reduction	Diameter reduction, depth of cut	Reduction in thickness and diameter imposed by the rollers
Limit degree of thinning	Limit thickness reduction, spinnability, critical reduction ratio	Limit reduction ratio before failure occurring.
Circumferential Flow (S)	-	Length of circumferential contact between workpiece and roller, proportional to the material beneath the roller flowing in a circumferential direction.
Axial Flow (L)	-	Length of axial contact between workpiece and roller, proportional to the material beneath the roller flowing in an axial direction.

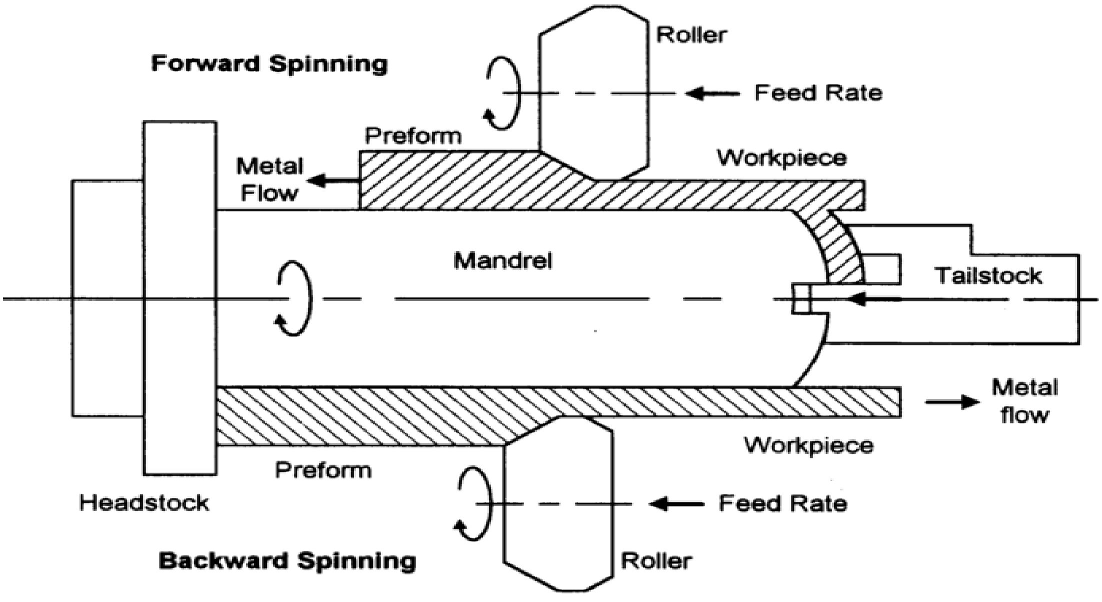

Figure 3 Flow forming parameters and geometry description Chang et al.(1998)

2. RESEARCH METHODOLOGIES

This section reviews the experimental and analytical methodologies adopted by flow forming researchers. Some conventional spinning articles are presented when their findings, or theories, have also been shown to be valid for flow forming.

2.1. Experimental Methodologies

In flow forming, empirical studies have been used to seek to correlations between inputs (e.g. the workpiece material's properties and process parameters such as the radial, tangential and axial forces on the rollers) and outputs (e.g. surface roughness, mechanical properties or dimensional accuracy). A notable example of this approach are Hayama and Kudo(1979b) who report an experimental investigation in to backward and forward tube-spinning (effectively flow forming with two rollers) through different reduction ratios and parameters setting (feed rate and rollers angle) on mild steel. First, they evaluate the impact of process variables on the product s dimensional accuracy. They explicitly distinguish between different material flow conditions using the concept of a plastic wave (created in the upper zone of contact between the roller and the workpiece) of material displaced along the workpiece. A coefficient that defines the size of the plastic wave is defined and used to evaluate the stability of the process. Not surprisingly larger wave sizes are associated with an unstable process.

The experimental validation of an analytical model of flow forming is reported in Hayama and Kudo(1979a) that represents the volume of material that flows in axial direction, (which is a fraction of the volume of material involved in the deformation process). These parameters give a numerical explanation of the physical phenomena of deformation. The results confirm the influence of thickness reduction ratio, feed rate and roller geometry on process stability and accuracy. Figure 4 shows the reference system used and the material flow model for backward flow forming.

Experimental work by [Jahazi and Ebrahimi(2000) also demonstrates that the axial flow must overcome the circumferential flow in order to avoid friction phenomena and avoid defects in the final product (e.g. waves on the external surface and thickness inhomogeneity).

Singhal et al.(1987) test these theories on hardest and low deformable materials by conducting experiments on various alloys 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.

Chang et al.(1998) also investigated the forming limits of Aluminium alloys for forward and backward flow forming, adopting different process parameters and rollers configurations. The tested materials are two different alloys (2024 and 7075) and two different heat treatments (full-annealed and solution-treated), giving a total of four combinations. Micro-spinnability and macro-spinnability are evaluated for these four combinations of materials and heat treatments. The latter is evaluated by varying the thickness reduction until failure (destructive testing) or until reaching the desired reduction ratio (non-destructive methods). Micro-spinnability is evaluated with non-destructive methods such as microscopic techniques (TEM, SEM, OM) and Vickers hardness measurement for detecting the presence of microcracks and microvoids on the surface.

Jahazi and Ebrahimi(2000) investigates the effect of flow forming on steel using Vickers and Rockwell hardness tests. By assessing yield strength and final true strain of the material, they are able to measure the fracture resilience of the material. The trials are conducted for different rollers geometry and reduction ratios. They also map the relationship between axial contact and circumferential contact, which are evaluated using the S/L (equation 7 to 12) methodology Gur and Tirosh (1982). Rajan and Narasimhan(2001) investigate the occurrence of defects in flow forming process for steel tubes. The authors use a sequence of non-destructive and destructive investigations that consist of a proof pressure test followed by a burst pressure test, in order to evaluate the final product proprieties. Rajan et al.(2002a) perform different tests on flow formed pressure vessels in AISI 4130 steel in order to evaluate the effect of the heat treatments (annealing, normalizing, quenching and tempering). Rajan et al.(2002b) also investigate on the production of flow formed pressure vessels, applying high pressure until material failure (Svensonn model). The microstructure is investigated in order to detect the grade of grain elongation, in comparison with thickness reduction. The authors described a number of distinct phases of the forming process using a flowchart and apply analytical method to determine the preform dimensions and the expected ultimate strength.

Groche and Fritsche(2006) apply flow forming to the production of a wheel with internal gears teeth. Their description of the development of three dedicated mandrels and rollers configuration is a significant contribution. Gupta et al.(2007) investigate flow formed crack propagation mechanism for Niobium alloys. Material proprieties are evaluated through SEM investigation and hardness tests with visual inspection to locate defects. Davidson et al.(2008) investigates the causes of roundness errors and variability in other measures of flow forming quality.

Roy et al.(2009) test surface micro hardness (Berkovic) of a workpiece to map true stress and strain resulting from forward flow forming operation. Evolution of strain is characterized by roller/mandrel contact and thickness reduction ratio. The authors develop two expressions in order to evaluate the strain due to the mandrel effect and the rollers effect. 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. Interaction zone extension is measured iteratively for the whole process. Haghshenas et al.(2011) relate the indentation hardness (Berkovich) and the Von-Mises true strain for flow forming of splined steel wheels. In this way, equivalent stress can be deduced for the critical point of the workpiece. The measurements of hardness were performed at different points on the wheels, particularly around the ribs where the deformation is largest. The authors map the strain on the mandrel s external surface, for different reduction ratios. The same approach is used later in Haghshenas et al.(2012) for evaluating hardening in wheels with internal splines.

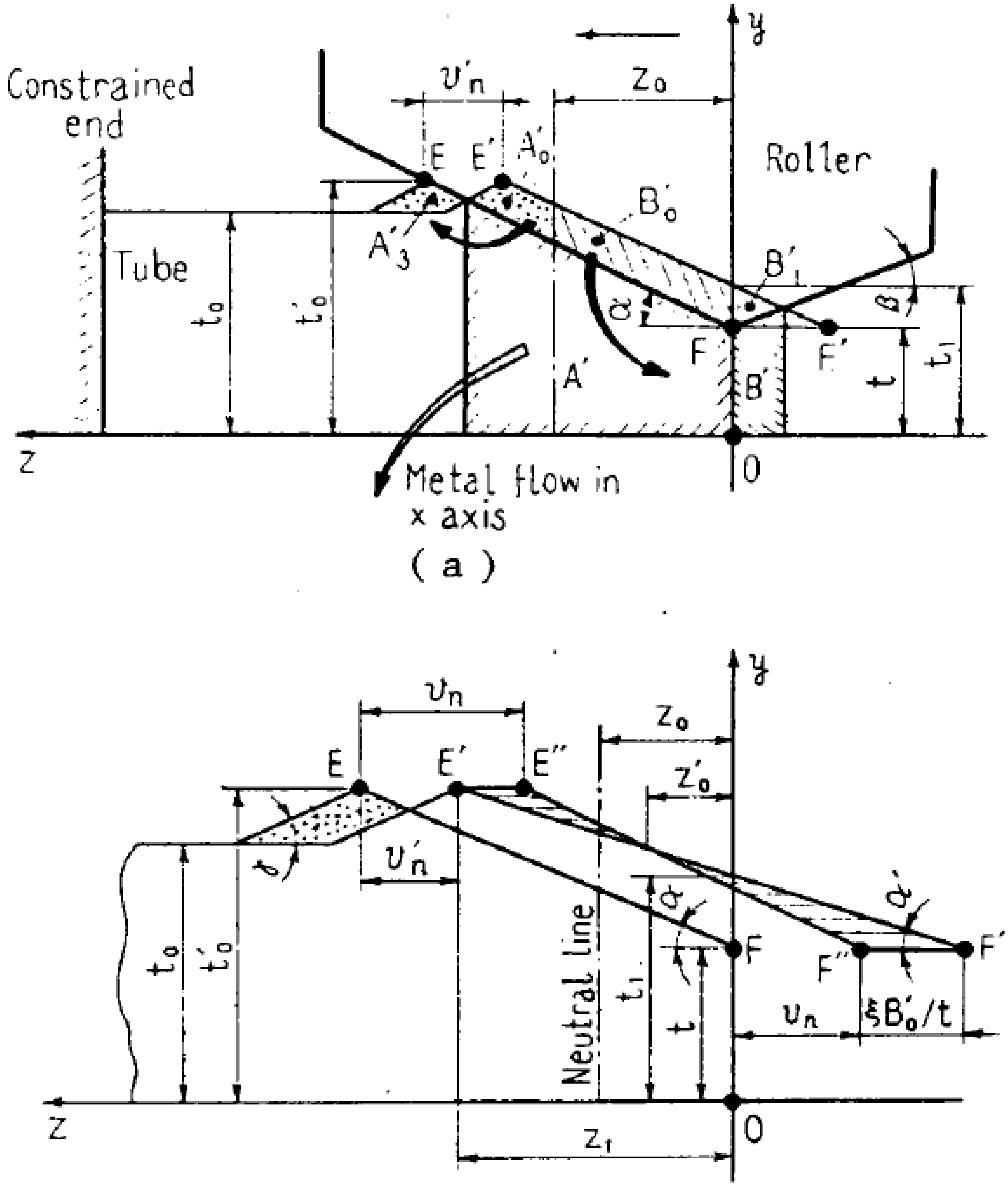

Figure 4 Mechanism of plastic flow in backward flow forming

Podder et al.(2012) discuss the influence of preform heat treatment on the reduction ratio and its influence on final strength for backward flow forming. To do this they map the true stress and strain for different heat treatments (e.g. spheroidizing, hardening and tempering, annealing). Notarigiacomo et al.(2009) investigate the influence of process parameters on fatigue behavior of flow formed wheels for automotive industry. The authors develop an experimental correlation between strength and surface proprieties of wheels. They develop and validate a FEM fatigue model which is able to predict the increasing fatigue life associated with thickness variation.

2.1.1. Design of Experiments (DoE)

Design of experiments (DOE) is a methodology for designing programs of experiments to determine the relationship between factors affecting processes and their output. By identifying cause-and-effect relationships process inputs can be managed to optimize outputs.

Davidson et al.(2008) use Taguchi Orthogonal Arrays (OAs) in order to evaluate the critical factors and their influence on the mean value of reduction ratio for an aluminum alloy. The authors also use another statistical method, called analysis of variance (ANOVA), with the aim of quantifying the relative influence of each parameter. Using this, a general optimization based on the selection of parameter levels is developed. In another investigation on aluminum alloys, Nahrekhalaji(2010) use classic DoE with fractional factorial design in order to characterize the flow formed diameter thorough a polynomial regression equation. Although the number of variables is probably too high (related to the number of trails) to give a robust statistical significance to the results (i.e. the error's degree of freedom in ANOVA analysis would be too low).

Srinivasulu et al.(2012a) develop a characterization of the process through the use of a particular classic DoE design (Box-Behnken), which is related with RSM (response surface methodology) evaluation of the results. Their ANOVA takes into consideration the importance of the degree of freedom. The RSM is able to predict the internal diameter in the selected range of variables with good approximation (i.e. the error is less than 0.08%). Jalali Aghchai et al.(2012) use fractional factorial DoE and graphical methods (i.e. RSM) in order to characterize the variables of their model for steel. They report that Analysis of Variance determines the reduction ratio has more influence on process than roller geometry and axial speed. The authors propose and optimized set of the variables built by simulation trials for validation. Wang et al. use only an interaction plot and analysis of means without producing optimization of output.

Table 2 summarizes characteristics of the reported application of DoE to investigation of flow forming process.

2.2. Theoretical Methodologies

Theoretical methodologies are able to investigate the tension and displacement states and their evolution in the deformed blank during the flow forming process. A combination of this knowledge with failure, or deformation, models and criteria can predict the failure (i.e. damage accumulation) and final characteristics of the worked piece.

2.2.1. Analytical

The main focus of analytical research is to develop a model of the flow of the metal during the flow forming process. This would provide the means to quantify the working energies and the forces required to form a specific geometry from a given billet. This can also give general feasibility boundaries for the process (e.g. the maximum reduction ratio achievable in one pass for a certain kind of process and metals). All the models start with the assumption of conservation of volume and consequently evaluate its distribution between axial growing and radial reduction.

Mohan and Misra (1970), use a grid-lines model in order to evaluate the tri-axial state of strain during flow forming process. Their energy based calculations of plastic work are grounded in an assumption of linear deformation. Calculations of the displacement and knowledge of the material proprieties make it possible to evaluate the strain tensor. The main problem of this theory is the need for point-to-point calculation of all displacements values during the process. Using their own metal flow schematization and volume exchanging parameters, Hayama and Kudo (1979a) develop an energy model in order to predict the working forces and their relation with the reduction ratio. They divide the energy exchange in the process into four main parts: plastic deformation energy (under the roller), velocity discontinuity energy (due to the metal flow velocity discontinuities in the various worked zone), frictional energy (contacts between mandrel/piece and piece/rollers)and blocking energy (mandrel constrains). They are able to make a unified theory for backward and forward spinning by identifying the position of the neutral line of plastic flow. This zone identifies the volume of material that passes from the front of the roller to the growing zone of the worked piece. For the backward process, this zone is located at a certain distance from the roller on the feed axis. In contrast, the forward has this point exactly under the contact point between roller/piece. Singhal et al.(1990) simplify Hayama and Kudo (1979a) approach for stainless steels, excluding diametral growth, which is negligible for hard materials. They evaluate power absorbance by friction and velocity, and make the conclusion that the first (i.e. friction) has no influence. Jolly and Bedi (2010) apply same model but with a different reference system. They use a polar coordinates system and a circumferential force. The authors define the contact zone between rotating tools and workpiece as a circular sector of the roller (14°), which is consider infinitely rigid. Regarding aluminum alloys, another application of the Hayama s model is described by Molladavoudi and Djavanroodi (2010), including diametral growth and plasticity parameters. The authors include microstructural analysis and defects correlation with process parameters, and reach conclusions similar to other experimental evaluations.

Gur and Tirosh (1982) use an upper-bound method for analysing the contact between roller and workpiece during flow forming process. Material may flow beneath the roller in an axial direction (L) or circumferential direction (S). If the length of circumferential contact is much longer than the axial contact length, then the axial plastic flow dominates the circumferential one. Axial flow must overcome the circumferential in order to avoid huge friction phenomena and avoid defects in the final product (waves on the external surface and thickness inhomogeneity). The authors develop simple formulas for S and L. In this way, it is possible to evaluate S/L (equation 7 to 12:) ratio for establishing dominant flow and defect insurgence. This methodology has been tested and validated for different conditions and materials by several papers, through experimental and numerical method Jahazi and Ebrahimi (2000), Rajan and Narasimhan (2001), Roy et al.(2010) Parsa et al.(2008) Jalali Aghchai et al.(2012), Podder et al.(2012) Podder. Mathematical expressions of circumferential and axial contact are described in the ppendix.

Roy et al.(2010) extend this work in order to obtain a detailed analytical expression of contact zone. Division of contact in various sectors allows the authors to identify different contribution of process parameters in the contact surface area. Experimental results confirm the validity of the model and the approximation obtained by the S/L ratio. The mathematical model has a complex geometrical approach even if it does not include a correlation between the material and superficial proprieties.

Park et al.(1997) develop an upper-bound method built in comparison with traditional tubes ironing. Stream functions are developed in order to evaluate the changing speed in the material during backward and forward flow forming processes using the same approach. Plastic stream stress and working forces are calculated taking into consideration three different type of velocity fields in the material (one trapezoidal and two spherical).

Nagarajan et al.(1981) adopt previous models for shear forming and spinning (such as Mohan and Misra Mohan and Misra (1970) and report a systematic evaluation of them through experiments and empirical data to establish the effectiveness of the models. Rotarescu (1995) applies a similar approach for the flow forming of tubes using spherical tools. Obviously, the author develops a different contact zone model in order to evaluate the multi-balls deformation mechanism.

Table 2 Summary of experimental DoE approaches to flow forming.

	Davidson et al. (2007)	*Nahrekhalaji et al (2009)*	*Srinivasulu et al (2012)*	*Wang et al. (2013)*	*JalaliAghchai et al. (2012)*
DoE methods	**Taguchi OAs (L9)**	**Classic DoE (Fractional Factorial)**	**Classic DoE (Box-Benknen design)**	**Taguchi OAs (L4)**	**Classic DoE (Box-Benknen design)**
Experiments' aim	Optimization	Characterization, Modeling	Characterization, Modeling, Optimization	Screening, Robustization	Optimization
Repetitions	-	-	-	2	-
Number of trials	9	3	17	4	17
Variables number	3	5	3	3	3
Selected variables	Depth of cut, Spindle speed, Feed rate	Thickness reduction ratio, Spindle speed, Feed rate, Initial thickness, solution time, aging time	Roller Radius, Spindle speed, Feed rate	Feed rate, Spindle speed, Material (mild steel, aluminum)	Thickness reduction ratio, Feed rate, Roller nose radius
Variables levels	3 (max,med,min)	2 (max,min)	2 (max,min)	2 (max,min)	3 (max,med,min)
Responses number	1	1	1	3	1
Selected responses	Thickness reduction ratio	Final external diameter	Final internal diameter	Final internal diameter, minimum wall thickness, final depth	Diametral growth
Evaluation method	ANOVA, Non standards plot	ANOVA, Polynomial Regression, Normal Plot	ANOVA, RSM, Polynomial Regression, Normal Plot	Interaction plot, ANOM	ANOVA, RSM

Kemin et al.(1997) develop a multi-objective optimizing algorithm (using the Fortran language) in order to evaluate a staggered configuration of the rollers (i.e. three roller in a row) in forward flow forming. This design of flow forming machine permits what would traditionally be a multi-pass processes to be implemented in only one step. Lee and Lu (Lee Lu 2001) develop a simple formula for the calculation of the tension during a six rollers flow forming process through monitoring continuously the forces with power sensors. The total force of deformation and its frictional contributions (in plasticization zone and non-plasticization zone) are evaluated but without considering the energy consumption.

2.2.2. Numerical

Finite Element Models (FEM) allow aspects of the flow forming process to be evaluated that are impossible to assess analytically (e.g. roller deformation). Numerical simulation avoids the expense of experiments and allows precise understandings of process trade-offs to be developed. However the implicit necessity of 3-dimensional modeling and complexity of contact surfaces create difficulties in this kind of approach. Despite this, eleven papers have reported numerical models for flow forming. Three papers use an implicit approach Xu et al.(2001), Kemin et al.(1997b,c) meanwhile six use an explicit approach Wong et al.(2005), Lexian and Dariani(2008), Parsa et al.(2008), Jalali Aghchai et al.(2012), Li et al.(1998), Mohebbi and Akbarzadeh(2010)Wong et al.(2004compare both approaches. Only two papers Xu et al.(2001), Li et al.(1998) Li, Hao, Lu and Xue model numerically the friction between roller and workpiece, (while other authors neglects friction contributes to displacement). Most use commercial software (e.g. ABAQUS) which has been modified to incorporate appropriate solution codes.

Wong et al.(2005) combine two different roller path and different rollers geometry (flat and with nose) in order to evaluate their effect. The two different types of roller identified are radial and axial. These are determined by the approach direction. Both radial and axial path are possible depending on the approach direction taken towards the blank. In a radial approach the axis is perpendicular to the spindle axis, in an axial paths it is parallel. The influence of these two methods on the final proprieties, working force and defects are combined with influence of roller geometry.

Lexian and Dariani (2008) develop a non-linear model that simulates the contact surface between roller and workpiece, excluding the friction among the parts. Surfaces are modeled with 3D-shell elements. Kemin et al.(1997b) use 3D-bricks element in order to evaluate working forces in a three, staggered, rollers deformation process. In contrast to all other researchers, they use the ADINA FEA software. This attempt extends the authors previous work on 2-dimensional modeling of the flow forming process Kemin et al.(1997c) in order to evaluate the linearity/non-linearity of the contacts in a two roller flow forming system. The symmetry of the contact point makes it possible to model the rotating surface during the process.

Li et al.(1998) developed a rotational transformation matrix in order to reformulate the simple hinges model on the contact surface in polar coordinates. This coordinates transformation is applicable in both the flow forming variants, if 3D elements are applied and allow easy definition of the constraints associated with mandrel and rollers.

In Xu et al.(2001) the application of the differential equation to the numerical model follow a particular methodology (Markov). The stress and strain states are evaluated and associated to different states of tension around the contact zone for reverse and forward flow forming. Although the model is complex, the results agree with Hayama and Kudo (1979a)'s approach (giving further validity to this model). Explicit and implicit solutions for FEA are proposed by Wong et al. (2004) for the flow forming of lead. The results of the analysis suggest that the implicit method gives the best correlation with the experimental results.

However, Parsa et al. (2008) report an explicit solution, justifying this choice with the possibility of maintain the interaction between nodes and the consequent transfer of forces with better coherency. Mohebbi and Akbarzadeh (2010) also use an implicit solver for simulating the flow forming process. In order to evaluate the local deformation, pins are mounted on the worjpiece to allow experimental validation of the model. Jalali Aghchai et al.(2012) use DoE for evaluating most important factors effecting diametral growth. The S/L (equation 7 to 12) ratio is used to validate their model s results. This is a good example of use of a DoE methodology to structure the analysis produced by FEM investigations. In this way only statistical relevant parameters for the selected responses are evaluated during numerical modeling.

The above suggest that implicit code is more directly related to nature of the problem than explicit one. The difficulty of converging solutions for the highly nonlinear process and the high computational cost of implicit approaches have pushed researchers to select explicit methods. Overall the explicit approach seems to be the best alternative because of its robustness, computational efficiency, and its ability to produce a largely quasi-static response. Explicit code is also conditionally stable although it is affected by challenges inherent in implementing sufficient time steps due to the process long computational cycle time. One proposal for overcoming this computational problem is to reduce the number of increments by increasing material density or loading speed, as expressed in Wong et al.(2004). Although, this approach may increase computational speed effects, it will decrease solution accuracy (i.e. impacting on inertial effects).

3. PREDICTION MODELS: THE MECHANICS OF FLOW FORMING

An overview of theoretical and experimental approaches is given in this section where the flow forming mechanism is analyzed through the models used by various authors. Papers about conventional spinning, judged relevant to flow forming applications, are also presented in this chapter.

3.1. Prediction of Product Final Geometry

Relating the final product geometry to specific process parameters is one of the main aims of researchers working flow forming. However the task is far from simple; For example although the final diameter is imposed by roller distance several effects, such as springback, material proprieties and tension state also influence the final shape of the flow formed product. Accuracy of product diameter and dimensional tolerance are related to both process parameters and machine configuration, so researchers have investigated how these interact to determine the final geometry. The diametral growth of formed parts is studied analytically and numerically, but experimental approaches are mainly used for spring back and roundness/ovality evaluation:

Diametral growth affects mainly soft material like aluminium or copper alloys Hayama and Kudo(1979a), Singhal et al.(1990). In this case, it increases with feed rate and thickness reduction. Only in case of highest thickness reduction and thickness reductions ratio, is it found to decrease. In case of low and medium carbon steel, problem of diametral growth appear with high thickness reduction and also in backward flow forming. In other words a large reduction of thickness (i.e. analogous to depth of cut in machining terminology) combined with lower feed rates can also produce diametral growth Davidson et al.(2008). Management of the contact ratio between circumferential and axial length (equation 7 to 12) is primary technique for minimizing this factor Rajan and Narasimhan(2001).

There are no theoretical models available to accurately predict springback. However it is known to be strongly effected by the amount of reduction, the strain hardening exponent of the material, the geometry of the roller and the feed rate Rajan and Narasimhan(2001).

Roundness error is influenced by thickness reduction and feed rate. Increasing the amount of reduction decreases workpiece roundness error, due to most uniform deformation under the roller. On the other hand, this deformation causes other defects (e.g. waviness). So, Joseph Davidson et al.(2008) propose 2mm of thickness reduction as optimal solution. Increasing feed rate is proportional to roundness; while defect are only slightly correlated with variations in mandrel speed. So feed rate, thickness reduction, material properties and roller geometry impact significantly a on product s geometrical proprieties.

However, geometrical inaccuracies evolve into defects when they overcome certain levels (e.g. out-of-roundness). Table 4 summarizes the main effect of process parameters on the appearance of defects.

In this area, it is clear that improved FEM models, including material characterization, and experimental models would have a great impact on accuracy of geometrical prediction. Better connection needs to be established between analytical models, FEM and experimental validation. However for now, the S/L (equation 7 to 12) ratio remains a good measure of the impact of process parameters on flow forming process accuracy.

3.2. Prediction of Surface Properties

Although typical ranges of surface roughness values for different materials have been established the precise relationship between process parameters and surface roughness is an open question in flow forming research. Singhalet al. (1987), suggest that surface finish is independent from reduction ratio and always less than 0.9 µm (Ra values) for stainless steel and hard to deform alloy, such as Titanium or Inconel. Lubricant selection has impact on surface finishing of flow formed materials. For steel, surfaces are between 0.5 and 0.8 µm and although different lubricants and reduction ratios change these values, surface roughness never moves beyond the cited range Prakash and Singhal (1995). Increasing feed rate impacts negatively on surface roughness, due to the associated increase in radial force. With a constant roller radius value, Rajan and Narasimhan (2001) notice an increase in roughness (from 0.8 µm to 1.6 µm) as the feed ratio increasing (from 50 mm/rev to 100 mm/rev). The same authors develop an empirical relationship (3) for calculating height of the feed marks on the workpiece surface. The relationship shows that for decreasing feed rate and increasing roller radius, superior surface roughness tends to be achieved.

$$h = R - \frac{1}{2}\sqrt{4R^2 - f^2} \tag{3}$$

Where, h is the height of the mark on the workpiece (mm), f is the feed ratio (mm/rev) and R is the roller radius (mm).

Although researchers have shown that material microstructure, feed rate and roller dimensions are parameters with most impact on surface roughness there is still a need for further investigations into the influence of other process characteristics on final surfaces roughness. In the future, it is likely that FEM models will be able to use material grains as element and consequently predict surface roughness but such a capability still needs modeling refinement and experimental validation.

3.3. Prediction of Mechanical Proprieties

In addition to the process parameters (i.e. speeds and feeds) the material properties of the formed parts depend on the microstructure and heat treatment of the workpiece. The following investigations have attempted to quantify these interactions. For example the, tensile strength of flow formed parts changes between longitudinal and radial directions due to the grain structure created by cold forming. For instance, radial ultimate tensile stress is measured as 0.93% the hoop tensile strength in Rajan et al.(2002b). Singhal et al.(1987) register an increasing tensile strength with reduction up to 0.75 (obtainable as in (1)), for all tested materials (steel, Titanium and Inconel). For reduction ratios beyond 0.8, however, the tensile strength was found to decrease. In Prakash and Singhal(1995) for a blank thickness of 4mm, the tensile strength of the stainless steel AISI-304 increased from 637 MPa to about 1421 MPa at about 0.8 reduction and the yield strength (0.2% proof stress) form 431 MPa to about 1324 MPa. The ductility decreased to below 0.1% and the mechanical proprieties exhibit negligible correlation with feed rate and mandrel speed Notarigiacomo et al.(2009).

Similarly for Aluminum, Chang et al.(1998) determine that the ultimate tensile strength has a relationship with the amount of thickness reduction (Figure 5). Hollomon’s power law (4) is deployed by some authors Podder et al.(2012), Jalali Aghchai et al.(2012) for predicting the ultimate strength of formed components and shows good agreement with experimental data.

$$S_u = K(\varepsilon_u)^n \tag{4}$$

Where: S_u, ultimate tensile strength (MPa); ε_u , total plastic strain; n, strain hardening exponent; K, strength coefficient, or strength index (MPa). In [Podder et al.(2012), true stresstrue strain curves for steel are seen to conform closely to Hollomon s relationship.

After every deformation, variations in hardening exponent and the strength index modification make it diffcult to predict accurately final strength values. Erasmus law (5), used in Rajan et al.(2002), is derived from Hollomon s one. This formula, which considers section variation (A_r) and accuracy in its prediction, is tested by the authors.

$$S_u = K\left[n + \frac{1}{1 - A_r}\right]^n \tag{5}$$

Notarigiacomo et al.(2009) investigate the fatigue strength of flow formed components and ultimate tensile strength of flow formed parts (Figure 5). Experimental investigations suggest a partial correlation between fatigue strength and surface roughness. A closer correlation is found between fatigue strength and microcracks on surfaces generated by flow forming processes. For a reduction ratio of 0.4, a general improvement in fatigue life is estimated for all tested steels (from 20% to 40% of fatigue strength increasing).

The desire to avoid further machining operations and heat treatments motivates researchers to continue to improve proprieties prediction. In other words defining a product s final proprieties correctly ensures proper process design and so minimizes the need for further operations to reach acceptable levels of product quality.

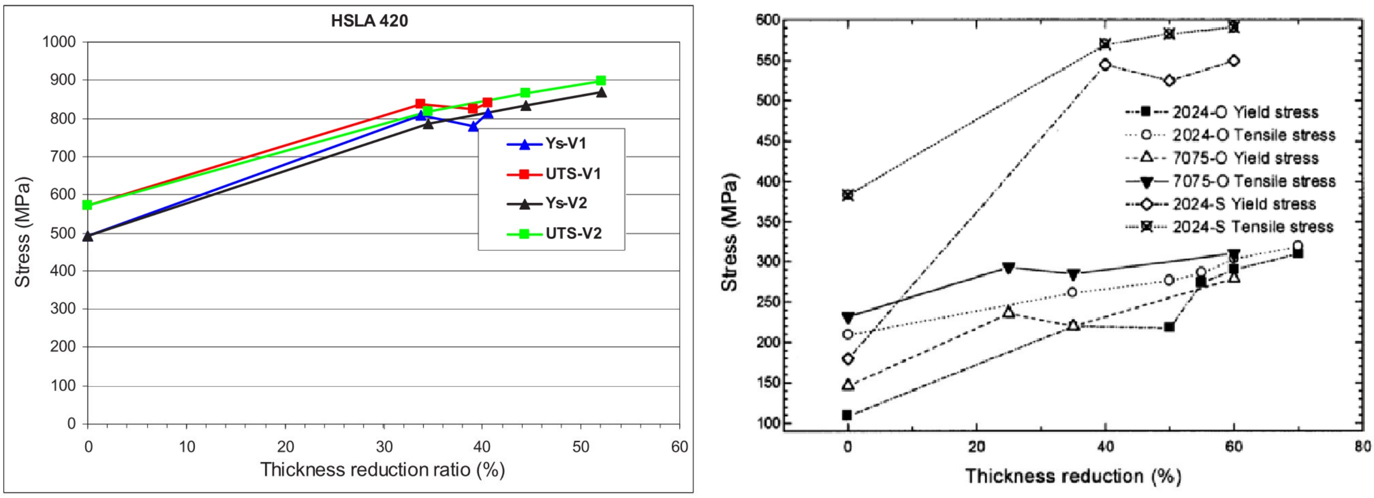

Figure 5 *Left*: yield stress and ultimate tensile stress for HSLA 420 for different reduction ratios and forming speed Notarigiacomo et al.(2009); *Right*: axial tensile properties of 7075-O, 2024-O and 2024 aluminum tubes for different reduction ratios Chang et al.(1998)

3.4. Prediction of Product Microstructure and its Effects

The ability of the flow forming process to modify and influence microstructure is an extremely important part of the process. Material behavior plays a fundamental role in severe cold plastic forming processes, so a preform s microstructure and heat treatments can be significant factors in the results. Evolution of microstructure for different process configuration has been investigated by several authors.

The anisotropy of the final flow formed structured is investigated in Rajan et al.(2002a). The grains are stretched along the flow forming axis and, as a consequence, the catastrophic cracks created by burst tests happen in the hoop direction instead of the axial. As observed in Haghshenas et al.(2011) for steel, elongation of the worked material grains along the feed axes is noticeable as well as the stretch of ferrite grains in zones of large plastic deformation. These zones are usually located to the mandrel contact zone.

Generally, increasing carbon content and increasing amount of alloying elements decrease spinnability as well as inclusion and precipitates. The literature suggests that generally, alloy steel with more than 4% of carbon should not be used Rajan et al.(2002a). For hard to deform material (Titanium, Incoloy and Inconel), Singhal et al.(1987) notice no significant changes in micro-hardness for various reductions ratio. At the beginning of the operation, there is increase in hardness, although at about 0.6 reduction ratio it becomes almost constant. Microscopic examination of a 0.85 reduction sample was carried out and it was found that the tube had developed microcracks. In Gupta et al.(2007), a niobium alloy is worked successfully with a good reduction rate (0.2-0.25). This kind of alloy exhibits significant hardening with only one pass, which can compromise the structure integrity in sequent forming steps. Consequently the authors recommend annealing treatment between the passes. Chang et al.(1998) also note that aluminum alloys may reach a spinnability of 0.7, which is limited only for solution-treated alloys. Figure 6 shows alloys' microstructures for different thickness reductions. The micro-hardness investigation shows a clear inhomogeneity of hardness due to the anisotropy of the final structure, due to the elongated grains in axial direction. This behavior increases exponentially with the magnitude of thickness reduction. Indeed surface hardness demonstrate also same the relationship with thickness reduction Chang et al.(1998), Nagarajan et al.(1981), Molladavoudi and Djavanroodi(2010).

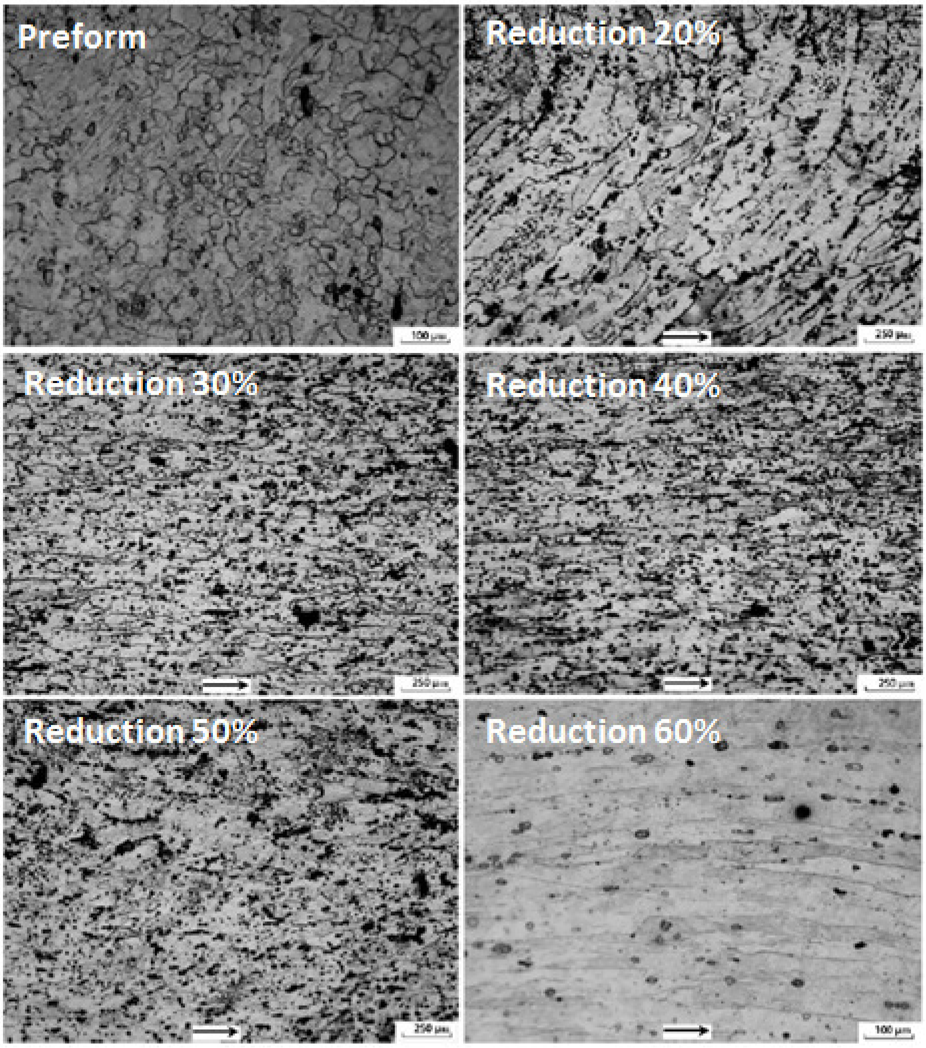

Figure 6 Microstructure of full annealed 7075 aluminum alloy, 0.2 thickness reduction, 0.3 thickness reduction, 0.4 thickness reduction, 0.5 thickness reduction, 0.6 thickness reduction (adapted from Molladavoudi and Djavanroodi(2010).

Different heat treatments (e.g. quenching, tempering, annealing) are evaluated in Jahazi and Ebrahimi(2000) to establish the influence of the parameter on the final microstructure of the flow formed parts. Annealing does not give resilience to crack propagation, less strength and hardness. But tempering and quenching have the opposite effect although impurities and inclusions limit their usage. The authors propose an optimum heat treatment cycle, based on an ideal combination of resulting strength and toughness. Rajan et al.(2002) agree with the previous statement, and normalize the tested heat treatments for steels. The annealing improves steel formability and decrease working stresses and forces but do not provide enough tensile strength to make the final part, distinctive from the other hardening treatments.

Numerical modeling is still not able to reliably predict grain dimension after forming process. Heat treatments are tested by several authors but not for the complete range of available materials and process parameters, consequently even empirical models are unavailable.

3.5. Prediction of Power and Tool Forces

One of the early objectives of academic research was the analytical prediction of forces in flow forming process. A total of twenty papers have reported different approaches to force prediction in flow forming and conventional spinning (fourteen analytical, four numerical and two experimental). The forming force is composed of three mutually orthogonal components: radial, axial and tangential (or circumferential, if a polar reference system is adopted). In the literature the reference system always indicated axial axes as mandrel one.

For soft materials, Hayama and Kudo(1979) develop a connection between the thickness reduction rate and process instability by an evaluation of the wave of material by considering the variation of the measured radial forces. Usually, the radial force is constant with the stroke of the roller. Indeed if it begins to increase, the process is considered instable. With these criteria, it is possible to evaluate the critical reduction ratio (called the limit degree of thinning) and feed ratio in order to obtain a steady plastic flow. The authors assert that the forward spinning has a bigger set of stable conditions than backward. A linear relationship is also denoted between the reduction ratio and the inverse of the feed rate. Hayama and Kudo(1979a) also present an analytical evaluation of the working forces and how they change as a function of the reduction ratio. The effect of the increasing of roller s attack angle is investigated in Singhal et al.(1990) for hard materials.

Radial force in tubes spinning is bigger than axial force, that in turn is bigger than the tangential component for every configuration and process parameters Hayama and Kudo(1979), Park et al.(1997), Prakash and Singhal(1995), Wong et al.(2004), Parsa et al.(2008), Roy et al.(2009), Xu et al.(2001). All three components of forming force increase with the reduction ratio and feed rate Hayama and Kudo(1979), Singhal et al.(1990). Increasing the roller diameter increases both with radial and axial components Singhal et al.(1987), Jolly and Bedi, (2010), with only negligible effect on tangential component Singhal et al.(1990). Axial force recorded is higher with reducing feed rate because of the higher real reduction achieved. Friction factor impacts on radial, axial and tangential forces but it does not have a significant effect on power consumption Park et al.(1997) Table 3 summarizes effect of process parameters, roller geometry and preform. Exactly how material microstructure, hardness and ductility impacts on tool forces is still not clear and severely case dependent.

3.6. Prediction of Stresses and Strains Evolution

Prediction of instantaneous stress and accumulated strain is a necessary step in the process of forces prediction. The same approach allows damage evolution to be assessed in the workpiece during forming operation. Interestingly none of the authors surveyed are concerned about residual stress insurgence and their impact on stress/strain behavior and proprieties of worked product. Material microstructure evolution is also not studied in comparison with strain behavior during a forming process.

Roy et al.(2009) determine the maximum equivalent plastic strain from experimental measures of surface hardness. A map of true strain is developed for all contact regions. Functions, which correlate experimental values and maximum equivalent strain, are developed for different thickness reduction (while keeping constant other parameters). The authors Roy et al.(2009) also get a maximum admissible strain which allows them to map available thickness reductions for AISI 1020 steel. [Haghshenas et al.(2012) use similar procedure for mapping equivalent strain of two aluminum alloys (6061 and 5052-O). The alloy with greatest point-to-point difference in equivalent plastic strain on a formed workpiece has the highest final yield stress propriety. The authors associate strain behavior only with high variability in alloy grains, and associate yield stress increases with hardening behavior. Front tension increases with the deformation ratio but also decreases with frictional forces increase (between workpiece and mandrel, as described by Lee and Lu(2001) through sensor measurement during flow forming of tubes.

Table 3 Effect of process parameters on forming forces (components) and forming power.

Process parameters	**Force components**			**Total forming**
	Axial	**Tangential**	**Radial**	**Power**
Increasing feed ratio	+	+	+	+
Increasing mandrel speed	negligible	Negligible	negligible	negligible
Increasing working depth	not available	not available	not available	not available
Increasing thickness reduction ratio	+	+	+	+
Increasing preform diameter	+	Negligible	+	+
Increasing roller attack angle	+	+	-	optimum exists
Increasing roller nose radius	not available	not available	not available	not available
increasing roller diameter	+	Negligible	+	+
increasing friction factor	+	+	not clear	optimum exists
Increasing preform hardness	+	not clear	not clear	not clear
Increasing preform yield strength	+	+	+	+
Increasing preform ductility	not clear	not clear	not clear	not clear

Xu et al.(2001) identify complex tensional and strain states in the contact zone. They divide contact in three zones: metal before and behind axial direction of roller (zone A), tangential regions (zone B) and contact zone (zone C), called radial. First one has a tri-axial compressive tensional state, which produces compression in axial direction and tension in tangential and radial. When compression in zone B overcomes the tension in contact zone C, it results in compression in the axial direction produces tube reduction meanwhile tension in radial direction leads to material piling.Results of the numerical model agree with consideration made by Hayama and Kudo(1979a).

Figure 7 shows schematically the stress and strain in the various regions of the workpiece (top) and deformation distribution in axial, radial and tangential directions (bottom).

3.7. Prediction of Failure

Prediction of instant stresses, accumulated strains and damage evolution should lead to an understanding of failure mechanisms and the prediction of failure Music et al.(2010) Interestingly experimental, numerical and analytical studies all have slight different definitions of failure. Due to absence of general connection between strain/stresses and modes of failure, later researchers have assumed that it is associated with the manifestations of fracture and defects. For example some of the authors in this section identify fracture as a phenomenon caused by tension in forward flow forming and buckling in backward. Chang et al.(1998) indentified the critical reduction ratios for *microcracks* propagation. Exceeding this values, the fractures become visible with a microscope. Main reason for generating of this phenomenon is the nucleation of microvoids (due to inclusions and incoherent particles). This propagation is registered both on surface and within the material matrix. Also if material appears to have good macro-spinnability proprieties, microcracks eventually extend to form cracks both in axial and circumferential direction. These defects generated on the surface will degrade the surface finish and eventually reduce the feasible thickness reduction, even if the visual appearance of a part results defectless. Although these deformations have little effects on ultimate tensile strength, they affect fatigue life and result in extended *macrocracks* for higher reduction ratio. Microcracks and macrocracks are strictly connected with flow stability Rajan et al.(2002a).

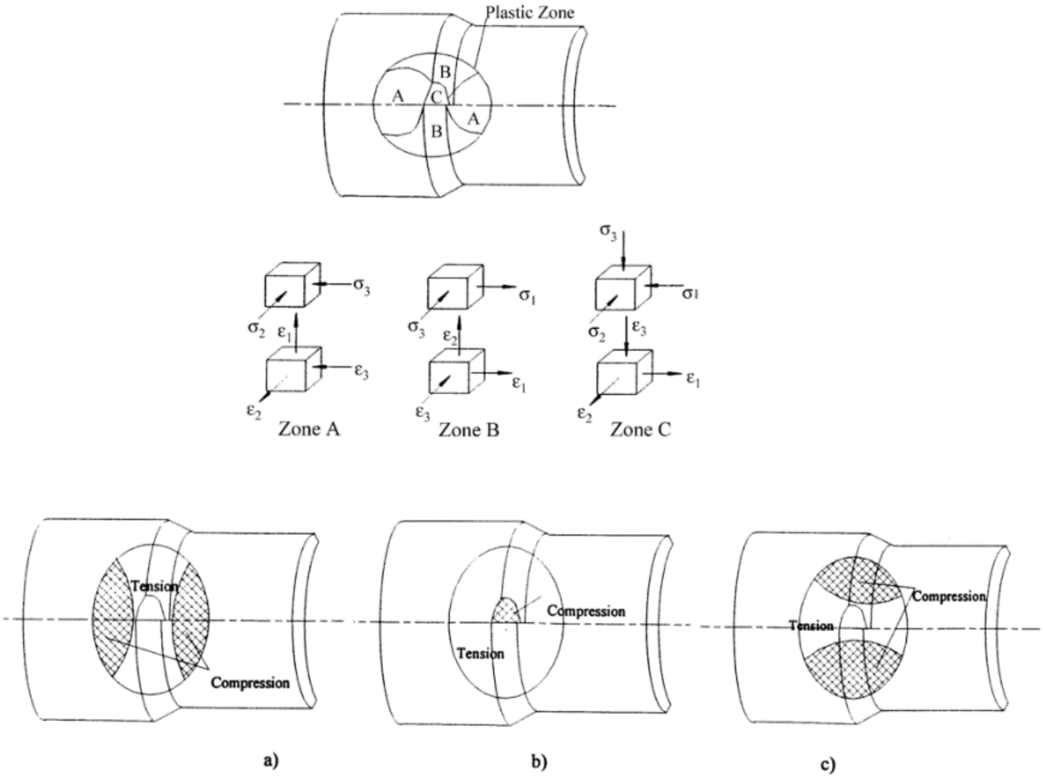

Figure 7 Microstructure of full annealed 7075 aluminum alloy, 0.2 thickness reduction, 0.3 thickness reduction, 0.4 thickness reduction, 0.5 thickness reduction, 0.6 thickness reduction Xu et al., (2001)

Excessive diametral growth (thickness variation), ovality (out-of-roundness), fish scaling (or bulging or waviness), wrinkling and springback are the main forms of *defects*, which may occur during flow forming process. Table 4 summarizes defects types and the effects of process issues on their insurgence.

Ovality (*out-of-roundness*) is influenced by feed rate and roller radius, but the defect can be minimized through correct selection of these two parameters, as demonstrated in [Srinivasulu et al.(2012b) Srinivasulu, Komaraiah and Rao]. Decreasing feed rate produces deformation in the radial direction, which in turn causes an increase of ovality. The highest values of feed rate combined with low reduction rate produce largest ovality. Podder et al.(2012) also assert the influence of heat treatments and microstructure on ovality. *Wrinkling* are caused by lack of proper mandrel support and excessive feed rate, as investigate in Gupta et al.(2007) for Niobium alloys. High and complex tensional states are the main causes of these defects. As results at tip of the wrinkles, microcrackings are generated due to combined bending and buckling.

Fish scaling (*bulging* or *waviness*) is mainly due to a non-uniform grain size, particle inclusion and residual stresses. A low roller attack angles and feed rates may develop defects that lead to cracking Rajan and Narasimhan(2001). Essentially a high fee rate produce wave-like surfaces, even more if in combination with elevate depth of cut Davidson et al.(2008). Large attack angle in combination with high feed rate are responsible of this defects in backward and forward tube spinning Hayama and Kudo(1979b).

As mentioned, the relationship between defects and the ratio of circumferential and axial contact length is used by several authors. *S/L ratio* (Appendix) expresses plastic flow quality for given of process parameters; therefore it represents a simple and effective instrument for obtaining indications about defects insurgence.

Table 4 Influences of process parameters on defects and geometrical inaccuracies (*H, high; L, low; n/a, not available; n/c not clear*).

Defects types	**Possible Influences**										
	-Feed rate	**-Mandrel speed**	**-Depth of cut**	**-Reduction Ratio**	**-Preform initial thickness**	**Roller Dimension**	**-Roller attack angle**	**Preform microstructure**	**-Preform Hardness**	**-Lubricant**	**Heat treatments**
Diametral growth	Hi	Lo	n/c	Hi	Lo	Hi	Hi	Lo	Lo	n/a	Lo
Ovality	Hi	Lo	Hi	Hi	n/c	Hi	n/c	Hi	Hi	n/a	Lo
Fish Scaling	Hi	Lo	Lo	Hi	Hi	n/c	Hi	Hi	n/a	n/a	Hi
Wrinkling	Hi	Lo	n/a	Hi	Hi	n/c	Hi	n/a	n/a	n/c	Hi
Springback	Hi	n/a	n/a	Hi	Hi	Hi	n/a	Hi	Hi	n/a	Hi
Cracking	Hi	Lo	Hi	Hi	Hi	n/c	Hi	Hi	n/c	n/c	Hi
Microcrackings	n/c	n/a	n/a	n/c	n/c	n/a	n/a	Hi	n/c	n/a	n/c

If the axial contact length (*L*) is greater than the circumferential length (*S*), circumferential plastic flow dominates ($S/L<1$). Consequently geometrical inaccuracies and defects emerge in this case. Increasing the *S/L* ratio causes interfacial friction that enhances the axial flow. In this case ($S/L>1$) and most of the material flows in axial direction and defects tend to disappear. Although, if the contact ratio becomes too large ($S/L>>1$), friction coefficient become close to unity and the material flows under the roller along a direction angle, which is smaller than attack angle. In this case, wave-like surfaces and thickness variation in workpiece occur. Initial thickness, feed rate, roller attack angle and reduction ratio need to be balance in order to obtain a defect less part. Using Gur and Tirosh(1982)] formula (Appendix) is possible to correctly evaluate the influence of these parameters. Material failure is connected with tension and stress tensors, crack propagation mechanism and process instability.

4. APPLICATIONS OF FLOW FORMING MECHANICS KNOWLEDGE

Applications of knowledge associated with flow forming applications can be classified into three categories

- Achieving given product quality characteristics;
- Designing a flow forming process;
- Operating a flow forming process.
- The following section discuss each of these in turn.

4.1. Achieving Quality Targets

In order to achieve quality targets (i.e. dimensional accuracy, surface roughness etc.) and avoid defects, optimum process parameters must be selected. This selection is strictly material dependent, although *several researchers report general methodologies and optimization process for different alloy and configurations.*

For example Hayama and Kudo Formatting Citation evaluate the accuracy of a workpieces internal diameter. Internal diameter accuracy depends on feed rate, thickness reduction ratio and modality of deformation. Generally, diametral growth decrease with feed ratio increasing, for forward and backward spinning.

Feed rate selection is connected with preform diameter and thickness.

For forward flow forming, low feed rate develops a too low material flow in axial direction, producing good surface finish and characteristics (i.e. especially combined with high rotational speed Srinivasulu et al.(2012a). Increasing in internal diameter is consequence of this selection, as theoretically stated by Singhal et al.(1990) and Hayama and Kudo (1979a) and experimentally tested by Jahazi and Ebrahimi(2000). Values of internal diametral growth increase with thickness reduction for low feed ratio (0.124, 0.249 mm/rev). A smaller feed rate produced more constant diameter reduction but machine and tool deflection needs to be compensated in order to achieve a higher accuracy in diameter reduction Wong et al.(2004). The surface roughness of the tube was found to be increased with feed.

For high feed rate, the surface roughness of the tube has been found to be increased with feed. High feed rate gives enough axial flow but can be associated defects such as unevenness in thickness, diametral variability and poor surface roughness, because, as the roller transverses the mandrel very quickly, the plastic deformation is slowed. In high feed rate conditions (0.349 mm/rev), minimum growth has been obtained for a reduction of 0.2. As explained in Gur and Tirosh(1982), material tends to escape from the roller with high feed rate. Highest feed rates (more than 90 mm/min) formed the tubes with roller marks on the surface, as deployed by Sivanandini et al.(2012) and Singhal et al.(1987). Feed rate has an optimum value for minimizing diametral growth, which varies for material, process configuration and interaction with other parameters.

Backward spinning presents a similar trend but with lower values than forward.

Reduction ratio's dimensioning impacts dramatically on final product quality. Increase of thickness reduction amplifies diametral growth Hayama and Kudo (1979a) Kemin et al.(1997b), also if too small reductions may cause thickness variation Kemin et al.(1997b). Generally, geometrical accuracy decreases with reduction ratio increasing. Surface roughness increases also with an increasing in thickness reduction, on the other hand it increases product.

Respecting S/L(equation 7 to 12) ratio relationship is still most applicable rule for generating a defect less process.

The experimental application of a Design of Experiment methodology is established as an effective procedure for experimentally optimizing the accuracy of a flow forming process. Table 1 summarizes the results of Jalali Aghchai et al.(2012) for minimizing diametral growth in a steel alloy case (AISI 321). Main problem of this procedure is the case-by-case evaluation, which is necessary in this highly parameter and material sensitive process.

Table 5 Process parameters optimization for diametral growth reduction Jalali Aghchai et al.(2012)

Process Parameters	**Feed rate (mm/min)**	**Thickness reduction**	**Roller Nose Radius (mm)**
Initial range	45-75	20-46	3-7
Optimum	65	20	3
Initial Preform Geometry: 45.5 mm - internal diameter, 1.5 mm - thickness, 65mm - initial length			
Roller Geometry: 50 mm - diameter, 25- attack angle			

4.2. Designing a Flow Forming Process

The parameters that influence the maximum thickness reduction before failure can be divided into two major categories. One category consists of process parameters like feed rate, roller tip radius, and roller attack angle. The other category includes the mechanical properties of material and metallurgical factors such as, cleanness of the alloy, chemical composition Jahazi and Ebrahimi (2000) and average grain size Parsa et al.(2008).

Give this complexity the choice of feed and reduction rates often require a trade-off choice between competing process variables. Generally, low flow stress, high ultimate tensile strength to yield strength ratio, high elongation and thickness limit reduction are decisive in order to obtain good formability in spinning processes.

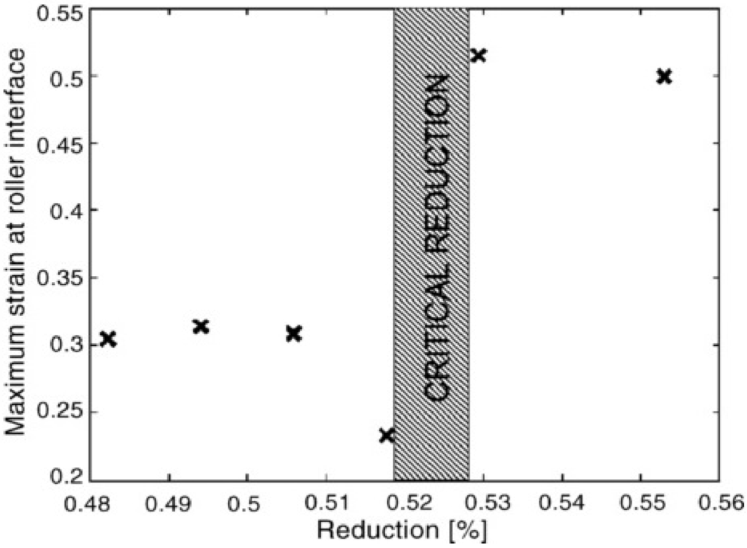

Figure 8 Maximum equivalent plastic strain incurred at the roller interface found from fitted relationships versus thickness reduction level Roy et al.(2009)

Maximization of reduction ratio minimizes number of passes but its dimensioning needs to take into consideration different contributions. Spinnability predictions should be taken into considerations for avoiding defects and failure. Larger reduction and higher accuracy can be obtained through several passes of the roller. Attention should be paid to reduction ratio dimensioning. As stated in Hayama and Kudo(1979b), a first pass can have a reduction ratio similar to acceptable limit of the material, but the second pass can require a large radial force to operate the process. In Prakash and Singhal (1995) A total reduction of 0.8 can be achieved without intermediate annealing. The reduction is, however, achieved in several passes for steel.passes for steel. Chang et al.(1998) determine limit reduction ratios for four Aluminium alloys (7075-O, 7075-S, 2024-O and 2024-s). The feasible reduction ratio is limited by the appearance of surface and matrix defects, which can be evaluated only by microscopic investigations. From 0.74, 0.5, 0.8 and 0.7 (i.e. values calculated as in equation (1)) respectively, limit reduction ratios decade to 0.4, 0.4, 0.5 and 0.4 respectively if the part is to have a good visual appearance. This concept could be applied to a range of materials for defining the operational windows of reduction ratios values. In recent numerical investigations, ranges of thickness reduction and critical reduction ratios have been used to assess the feasibility of operations. Thickness reduction is limited by equivalent plastic flow on workpiece. This defines critical reduction ratios, which should be avoided in order to not incur damage, as in Figure 8.

Process parameters that minimize tool forces and forming power are investigated by several authors. Roller geometry has a significant impact on forces and consequently optimization of its geometry is the subject of several papers.

The power consumption and forces increases as the initial preform thickness and reduction rate increase Singhal et al.(1987). A decreasing feed rate implies a reduction in working forces, changes to mandrel speed however have negligible impact. Feed rate decision need to be balanced between forces minimization, contact surface and desired production rate. Figure 9 shows the impact of feed rate on the S/L ratio(equation 7 to 12), which define the appearance of defects, and on axial and radial forces.

4.3. Operating a Flow Forming Process

For each application the engineer must select tool geometry, preform dimension and heat treatments as well as lubricants. The selection of tool geometry and path has an impact on defects rates, forming forces and other operating parameters. The preforms microstructure, and heat treatments, influence the final product s quality and forces. Lubricant selection is also important mainly for friction and surface roughness.

Vibration of equipment limit reduction for certain type of materials Notarigiacomo et al.(2009). Interestingly studies of the natural vibration of flow forming machine structures do not appear to have be reported literature.

4.3.1. Tool Geometry

Roller diameter has no significant effect on the power consumption. However, a choice of the diameter of the roller has to be based on contact surface (i.e. S/L ratio) and on the final diameter of the product. Roller diameter also impacts also on surface roughness.

Although the impact of *roller nose radius* is understood in conventional spinning, its significance is not clear in flow forming. In spinning, nose radius degradation influence errors in tool movement compensation by CNC machine, because it defines the contact point of roller which generates the path. Increasing roller nose radius results in high tool forces, small thickness reduction and high surface finish for spinning Wang and Long(2013). Varying the nose radius has a small effect on the contact surfaces between roller and workpiece in flow forming Roy et al.(2010). In analysing steel forming, a value of 3 mm was found as optimum for reducing diametral growth Jalali Aghchai et al.(2012).

For spinning rollers, Singhal et al.(1987) discuss the influence of the *roller's land* (external zone of the roller between attack (front) and relief (back) zone, with same inclination but lower in angle than the attack zone)on process performances, particularly on feed rate and surface finish. An increasing of the roller s land can increase admissible feed rate but it decreases surface finish. They notice that with a certain roller s land dimension (2 mm), it is possible to increase the speed of the process without affecting dimensional proprieties.

Roller attack angle has impact on working forces, accuracy of parts and limit degree of thinning. For soft materials, Hayama and Kudo[Hayama and Kudo (1979a,b) demonstrate, experimentally and analytically, that the attack roller angle must be kept between 20 and 25 degrees in order to minimize axial forces. Generally for a given reduction, the attack angle must be selected in order to have no instability in plastic flow Jahazi and Ebrahimi(2000). When the attack angle increases, the S/L ratio become higher due to increasing friction between roller and workpiece. Various authors deploy different attack angles in order to maximize the S/L ratio and minimize defects. A 30 roller produces a defect-free process Jahazi and Ebrahimi(2000) but impacts negatively on working forces by significantly increasing the radial component. So increasing the attack angle requires more power and decreases the efficiency of the forming process. Therefore, an optimum balance between the percentage reduction and attack angle is necessary Gur and Tirosh(1982). Figure 10 shows impact of attack angle on process stability and S/L ratio. As a compromise, the roller attack angle is usually chosen to lie in a range between 20° and 25°.

4.3.2. Tool Path Design

Tool path is determined by feed rate and mandrel speed. The workpiece approach zone has impact on final quality of the part. As determined in Wong et al.(2005), axial and radial rollers create different kinds of problems, on the free surface during the initial contact phase. Radial path creates thin hollows on the opposite side of the workpiece; axial path creates cup-form deformation on the part s free face.

4.3.3. Lubrication

Lubricant is essential for reducing the working forces. Lubricant also has a fundamental role in decreasing working temperature and improving the surface proprieties of the material. Prakash and Singhal (1995) assert that different lubricants do not influence significantly the forming power and forces. A blend of grease and fine copper is use in Singhal et al.(1987) in order to avoid cold-pressure welding phenomena between workpiece and mandrel. It plays an important role in high surface finish quality creation. The authors assert that the kind of lubricants do not influence other process performances.

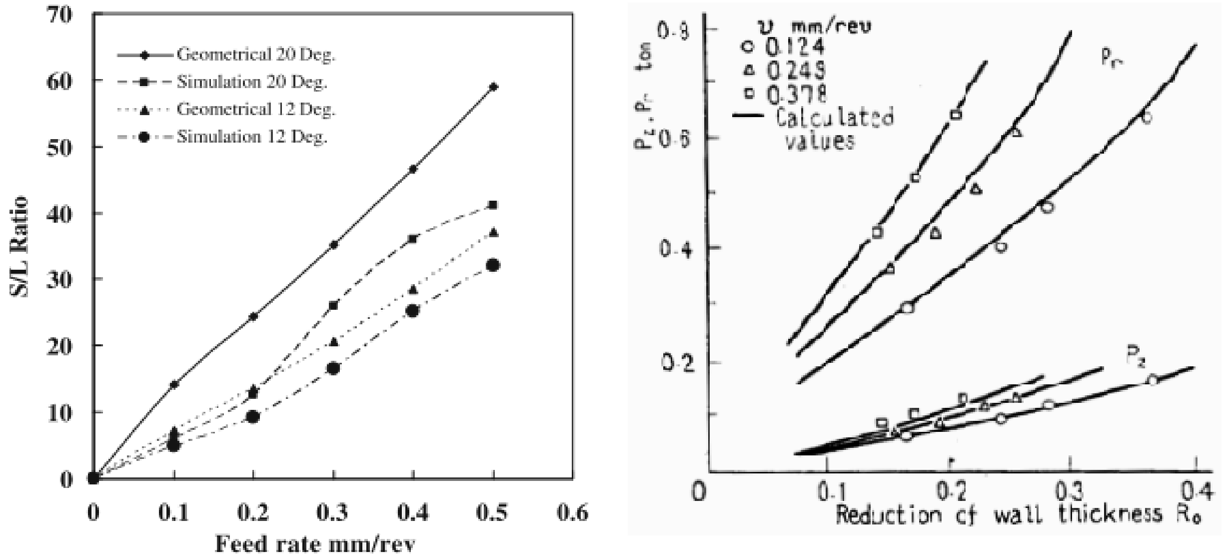

Figure 9 Impact of feed rate on S/L ratio, with constant roller attack angle for experiment and FEM simulation *(left)* Parsa et al.(2008). Impact of thickness reduction ratio on radial and axial forces for different feed rate *(right)* Hayama and Kudo(1979).

4. 4. Preform Design

Dimensional and geometric accuracy of the preform influences both the flow forming process and the final product properties.

After deciding reduction ratio, the principle of volume constancy helps in determining the initial dimensioning of blank hollow parts. The initial hollow tube should be fairly concentric and straight, otherwise uneven material flow occurs which bends the spun tube, making spinning difficult Singhal et al.(1987). Variation in microstructural features and mechanical properties of the pre- forms by heat treatments significantly affects the flow formability and the deformation homogeneity of the resultant flow formed parts Podder et al.(2012)

4.4.1. Heat Treatments

Grain size control is important because fine grain sizes are not desirable for cold forming, and large grain sizes lead to fish scaling and cracking. Soft preform (annealing) has good formability but develops poor strength after flow forming. On the other hand, hard preforms (resulting from normalizing and tempering) may compromise the accuracy and final shape as well as develop cracks and defect. However, a hardened preform usually achieves the requirements for ultimate strength after flow forming operation for alloy steel Rajan and Narasimhan(2001), Rajan et al.(2002a). For steel, Podder et al.(2012) Podder, Mondal, Ramesh Kumar and Yadav express superiority of spheroidizing treatment for obtaining the best final product mechanical proprieties of steel. Compared with annealing and hardening/tempering, this heat treatment shows ultimate tensile strength and hardness similar to latter one but with superior elongation properties, as showed in Figure 11. For Niobium and other low formable alloys, increasing of hardness near microcracks, which generate fracture during flow forming, suggest there could be benefits in annealing treatment between each deformation step Gupta et al.(2007).

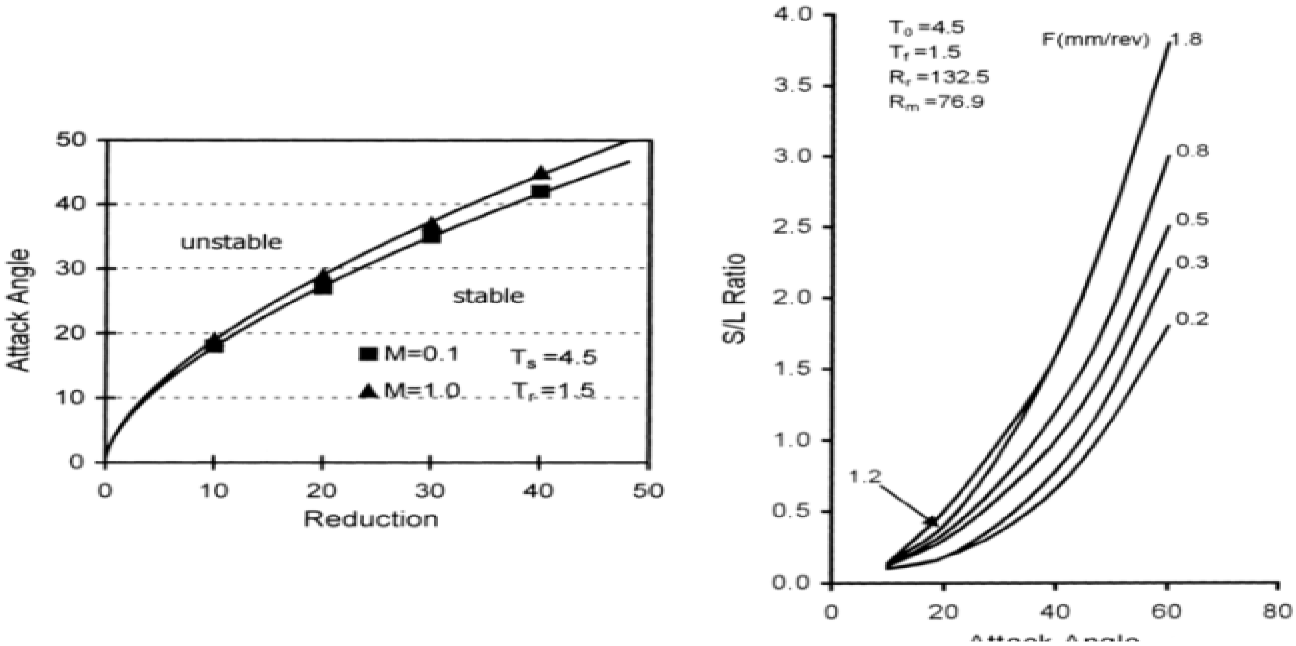

Figure 10 Influence of attack angle and thickness reduction on process stability (*left*). Influence of attack angle on S/L ratio for different feed rate (*right*) Jahazi and Ebrahimi(2000).

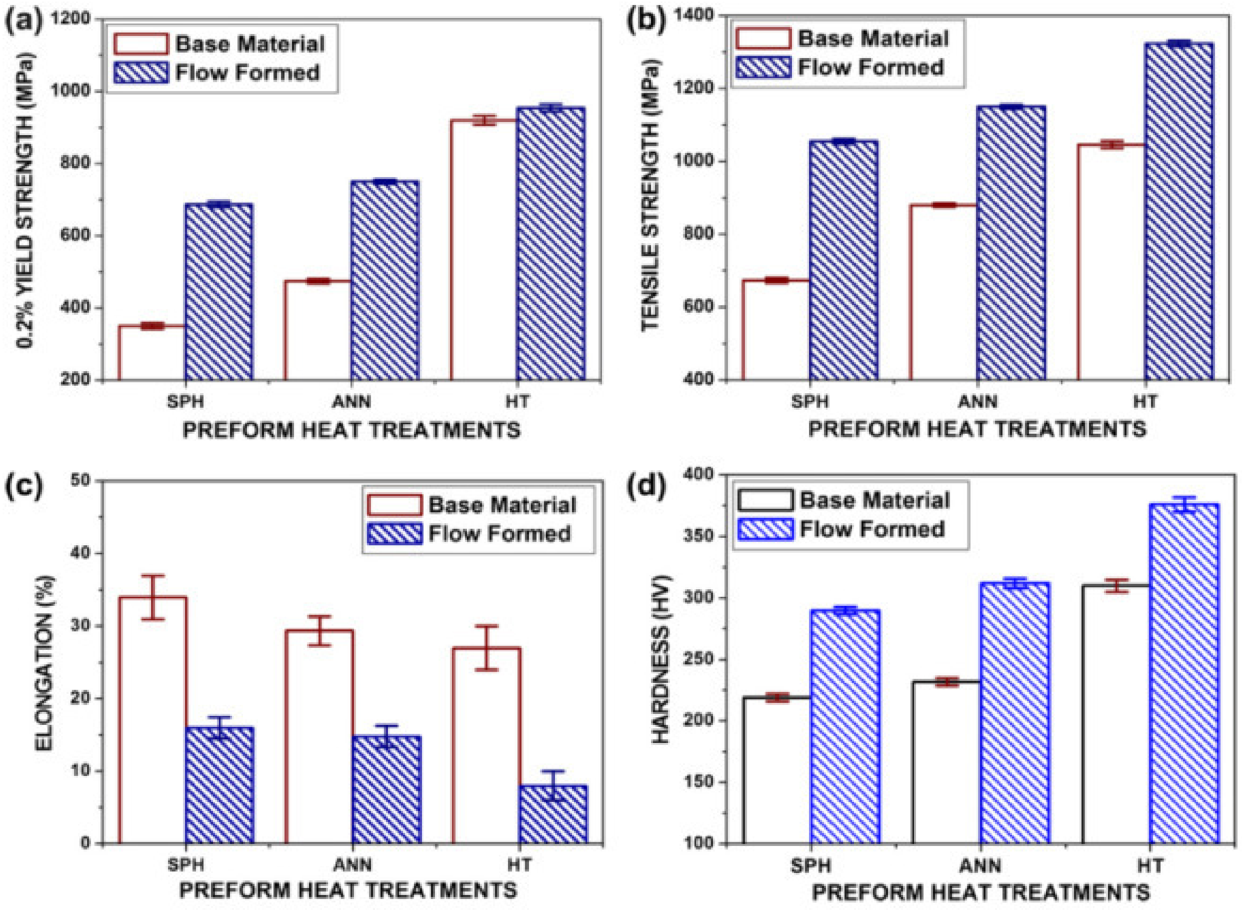

Figure 11 Comparison of mechanical properties between the preforms with different heat treatments (SPH-spheroidizing, ANN-annealing, HT-hardening & tempering) and corresponding flow formed tubes: (a) yield strength, (b) ultimate tensile strength, (c) elongation, and (d) hardness Rajan et al.(2002a).

4.4.2. Initial Dimensioning

A preform thickness and length must be decided based on final component dimensions, percentage of thickens reduction required and required final mechanical properties. In defining the final piece length and thickness reduction required for achieving strength properties, it is possible to estimate initial thickness though reduction ratio (1). Likewise by considering internal diameter constant (i.e. equal to the mandrel diameter) and defining final part diameter, it is possible to use volume constancy to determine the initial preform length. Equation (6) can be used for simple tube preforms, although this needs to be changed for complicated shape.

$$L_1 = L_0 \frac{D_0^2 - D_i^2}{D_1^2 - D_i^2} \tag{6}$$

Where: D_0, initial external diameter (mm); D_1, final external diameter; D_i, internal diameter; L_1, final length; L_0, intial length.

5. CONCLUSION

The sensitivity of the flow forming process to material properties affects the prediction accuracy and, so the impact, of theoretical models. This study has identified several knowledge gaps.

- Stress and strain tensors evolutions are not fully determined for a workpiece, due to the high computational cost and the difficulty in identify the best finite elements approach.
- The ratio of circumferential to axial contact (S/L ratio) is widely used as a defects prediction parameter, although the process failure mechanism is still not fully understood.
- Forming forces and powers can be analytically, and numerically, defined in correlation with process parameters.
- None of the authors surveyed in this review connects microstructural evolution with instant stresses and accumulated strains in order to obtain a general model of failure. Although final microstructure is often evaluated for specific cases, its evolution during plastic deformation is not widely studied or understood.
- Residual stress, springback and some final material proprieties, such as corrosion behavior, have not been studied numerically or experimentally.
- Tool path impact and alternative geometries are not deeply explored. Similarly, microcracks investigation and causes are not well investigated.
- Process experimental optimization and characterization through Design of Experiment is still limited to a few papers and usually not well developed.
- Lack of accurate numerical models makes it difficult to do process optimization through algorithms.

Many attempts have been made in order to predict failure and defects. The roles of material microstructure and properties are still not well understood. Relationships between microstructure and failure are implicit and usually misdirect researchers. As a result researchers should target the development of new theoretical and numerical methods for prediction of stresses and strains. This would allow accurate definition of a flow forming process window and so also combinations that will lead to failure. Consequently an empirical approach needs to be adopted so heat treatment experiments and flow forming operation can be systematically performed in order to achieve required properties for final component. In this regard the DoE approach has unrealized potential for optimization of geometrical inaccuracy and final properties in many flow forming processes.

6. APPENDIX

Expression of circumferential contact (S) and axial contact (L), from Gur and Tirosh(1982).

$$S = R_R \beta \tag{7}$$

$$L \cong \frac{T_0 - T_f + 2}{f + \tan\alpha} \tag{8}$$

Where,

$$\beta = \cos^{-1}\frac{a^2 + c^2 - b^2}{2ac} \tag{9}$$

$$a = R_R + T_f + R_M \tag{10}$$

$$b = R_M + T_f + f \tan\alpha \tag{11}$$

$$c = R_R \tag{12}$$

With, R_R, roller radius (mm); R_M, mandrel radius (mm); α, roller attack angle; T_0, initial thickness (mm); T_f, final thickness (mm).

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