Flow Forming Of Tubes-A Review

M.Sivanandini, S.S.Dhami, B.S.Pabla

Abstract— Flow forming technology has emerged as the most advanced metal forming technique due to its manifold advantages over conventional metal forming techniques such as extrusion and tube drawing. It offers remarkable utilization of metal, high strength high precision rotationally symmetric components with very high specific strength, excellent surface finish and close dimensional tolerances within the envelope of reasonable economics. With the introduction of heavy-duty CNC flow forming machines hard to work materials can be formed easily and deformation above 95% has become possible even for metals like maraging steel. In the last three decades flow-forming technique has undergone several remarkable advancements. The process is quite versatile in view of the fact that a great variety of tubular parts, flexibility provided for complicated parts nearer to net shape, can be manufactured with basically the same tooling, enabling customers to optimise designs and reduce weight and cost, all of which are vital. The ever-increasing strength demands of automotive industries, defense and aerospace sectors have given considerable impetus to research work in this area. In this paper, process details of flow forming, the major experimental studies reported in literature have been reviewed. The study brings out the potential and the ever increasing applications of this manufacturing technique in defense, automotive and aerospace sectors.

Index Terms—Preform ,CNC Flow forming machine, Flow Forming, Forward Flow forming, Shear Spinning,Tube Spinning,Reverse Flow forming,

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1 INTRODUCTION

The Flow forming is a modernized, improved advanced version of metal spinning, which is one of the oldest methods of chipless forming. Flow forming has spread widely since 1950. The metal spinning method used a pivoted pointer to manually push a metal sheet mounted at one end of a spinning mandrel. This method was used to fabricate axisymmetric, thin-walled, light-weight domestic products such as saucepans and cooking pots. Although the method used a lathe-like machine, the repeatability of a finished product largely depends on the operator's skills. However, due to the inherent advantages and flexibilities of the metal spinning method such as simple tooling and light forming loads, and the modern trend towards near net shape manufacturing of thin-section light-weight parts, the method found new popularity in the aerospace industry. The Initially thick based sauce pans were produced to be used on electric cookers. For some time it had been kept in the background due to the difficulties in recruiting labor. Since more power is needed to carry out the process it was confined for long time to the processing of soft materials, such as non ferrous metals. However, it soon developed again with the introduction of hydraulic machine with copying attachments which can be operated by unskilled labor. Mechanization of the spinning process has led to the evaluation of flow turning and flow forming. As a result, the modernized version of metal spinning, i.e., flow forming evolved. The experience gathered showed that this technique could also be applied for different branches throughout the industry. 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 larger diameter starting blank than the largest diameter of the finished part very similar to deep drawing. No reduction of the wall thickness is contemplated, is very difficult to control. Flow forming, on the other hand, is based upon a predetermined reduction of the thickness of the starting blank or preform, reduction, which is very accurately controlled. Instead of using a pivoted pointer, the flow forming method uses rollers with automated controlled movements. The rollers force specimen material to flow in the axial and radial directions of the mandrel. Thus, flow forming has significantly improved flexibility and accuracy in forming parts with large thickness variation.Since 1950, flow forming has been used to produce rocket nose cones, rocket motor cases, gas turbine components, and dish antennas in the aerospace industry. It has also produced power train components and wheels in the automobile industry, and gas bottles and containers for storage applications. Modern spinning machines provide high forming forces. Flow forming machines are much more robust in construction than spinning machines and therefore can generate much higher forces required to extrude the metal through its entire thickness. These machines helped in processing of stronger materials such as steels, light, medium, and even heavy gauge material and cast, forged or machined performs. This chipless metal forming technique has gained increasing importance especially over the past two decades, to meet further demands of originals equipment manufacturing (OEM) industries.

Flow forming is a cold metal forming process for the manufacture of rotationally symmetrical, hollow components.

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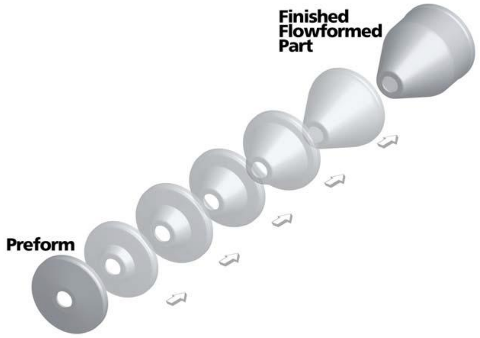

Fig.1

This forming technique offers significant advantages in comparison with conventional production techniques such as spinning, deep drawing, rounding circular bodies with subsequent welding etc. These advantages are particularly pronounced when components are to be produced in small or medium size batches due to relatively lower tooling costs than other process such as deep drawing. The other advantages are:

1. Low production cost.
2. Very little wastage of material.
3. Excellent surface finishes.
4. Accurate components.
5. Improved strength properties.
6. Easy cold forming of high tensile strength alloys.
7. Production of high precision, thin walled seamless components.

The development of this technique has increased the flexibility of incremental forming technology and provides manufacturers with an alternative to conventional forging and deep drawing, where size or complexity of shape of a component is beyond the capacity of conventional presses. Flow forming techniques are being applied for the production of many key components, especially for the automotive industry. The ability to enable metal to flow in complicated paths using simple tools not only eliminates multi-production stages on presses, thus reducing costs, but also offers the potential for the production of lightweight, net shape parts.

This paper begins by classifying and describing process flow forming and follows by outlining developments in machine tools. In addition, research carried out in this area is reviewed. Finally based on the current trends, future directions of research in this area are discussed**.**

2 FLOW FORMING

Flow forming is an advanced, often net-shape, hot and cold metal-working process for manufacturing seamless, dimensionally precise tubular and other rotationally symmetric products. The process involves applying compression to the outside diameter of a cylindrical preform, attached to a rotating mandrel. Compression is applied by a combination of axial and radial forces using a set of three or four rollers that are simultaneously moved along the length of the rotating preform, the material flows plastically in both radial and axial directions. The result is a dimensionally accurate, high-quality cylindrical or shaped tubular product [1] having increased mechanical properties and fine surface finish. The starting blank can be in the form of a sleeve or cup. Blanks can be produced by spinning, deep drawing or forging plus machining to improve the dimensional accuracy. Advantages such as an increase in hardness due to an ability to cold work and better surface finish couples with simple tool design and tooling cost make flow forming a particularly attractive technique for the production of hydraulic cylinders, and cylindrical hollow parts with different stepped sections as in Fig. 2.

Fig.2

A wide range of flow-formed open- and close-ended shapes are currently available in a variety of difficult-to-form materials, including titanium alloys and nickel-base super alloys. The flow-forming process has been used for several years to produce high-quality seamless, thin, and variable walled tubular components for aircraft-aerospace systems, nuclear, chemical, and petrochemical facilities, and many other major industries. Other names for this process include Roll Flo (LeFiell Manufacturing Co. Santa Fe Springs, CA) and Flow Turning (Lodge & Shipley Co.); similar processes include shear forming, spin forging and tube spinning. One important benefit of the flow-forming process is the use of preforms for stock material, where preforms are significantly shorter than the dimensional requirements of the final part. The smaller configuration of preform stock simplifies handling and inventory and preforms can be designed to improve utilization of stock material. Preforms are configured from dimensional specifications required in the final piece, and they are generally supplier specific and proprietary in nature. Flow forming also offers flexibility for product designers who are seeking more unitized designs with such features as: Tubes with integral end fittings Ducts with integral flanges Thin-walled tubes with heavy walled ends Tubes with both thick and thin wall sections, etc. Flow forming can help tubular-product designers meet critical targets for weight and affordability with monolithic/unitized structure and, in most cases, improved materials properties (which allows thinner walls). Other important advantages may include reduced need for welding fabrication (and the nondestructive evaluation of weld integrity), reduced length of starting stock, and inventory reduction. Of course, detailed capability is supplier-process specific, and tighter design tolerances may be achievable at higher cost. As with any process, a balance must be struck between fit, form, functionality, weight, and cost.

2.1 AFlow forming Methods

Tube Spinning:

One method of flow forming is tube spinning, in which a tubular or cylindrical shape is generated. A tubular preform with a wall thickness, length and inside and outside diameter precisely calculated to produce the required final dimensions is placed on a cylindrical mandrel made of hardenable steel. Forming rollers with specific profiles are set at precise distances from each other and the mandrel. When the machine is activated, depending on the configuration of the machine, the rollers either traverse the mandrel or the mandrel passes between the stationary, rotating rollers exerting as much as 75,000 pounds per square inch per roller. The output is a tube whose material has been significantly cold worked and dimensionally controlled by the process to produce extremely uniform or variable wall thickness, diameter and length features. When the component has one closed or semi-closed end, such as a vessel, the bottom rests against the face of the mandrel while the material being flow formed is moved in the same directions as the rollers. This technique is called forward flow forming. When the component has two open ends, such as a tube, reverse flow forming is used, in which the force applied by the rollers pushes the material against a serrated ring at the end of the mandrel. The ring is driven by and rotates with the mandrel. As the rollers compress and extrude the material against the ring, the material flows under, and in the opposite direction, of the rollers.

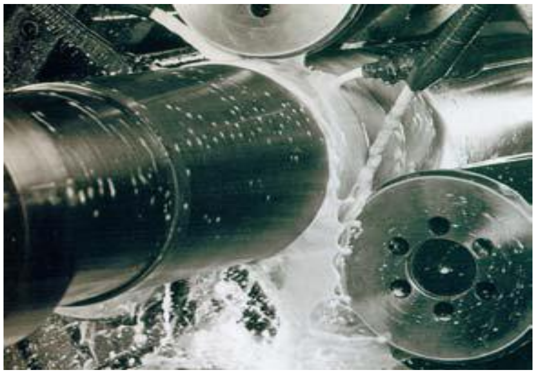

Fig.3

When the component has one closed or semi-closed end, such as a vessel, the bottom rests against the face of the mandrel while the material being flow formed is moved in the same directions as the rollers. This technique is called forward flow forming. When the component has two open ends, such as a tube, reverse flow forming is used, in which the force applied by the rollers pushes the material against a serrated ring at the end of the mandrel. The ring is driven by and rotates with the mandrel. As the rollers compress and extrude the material against the ring, the material flows under, and in the opposite direction, of the rollers.

In either variation, the finished part is thinner and longer than the original preform, although the volume of material remains constant. As shown in Fig.4, the final tube thickness $t_{f,}$ is determined by the roller-to mandrel spacing. Using multiple rollers that may be staggered and set at different gaps, it is possible to make multiple reductions in a single, economical machine pass.

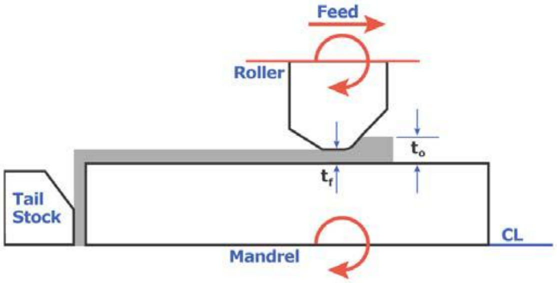

Fig.4

Shear Spinning

In this second method of flow forming, conical and other axis-symmetric parts i.e. hemispherical, hemi ellipsoidal or more complex profiles are produced from simply a flat blank or more complex shape that is "sheared" by one or more rollers over a rotating mandrel. As with tube spinning no material is lost in the process. The relationship between the initial and final material thickness can by defined mathematically by the Sine Law,

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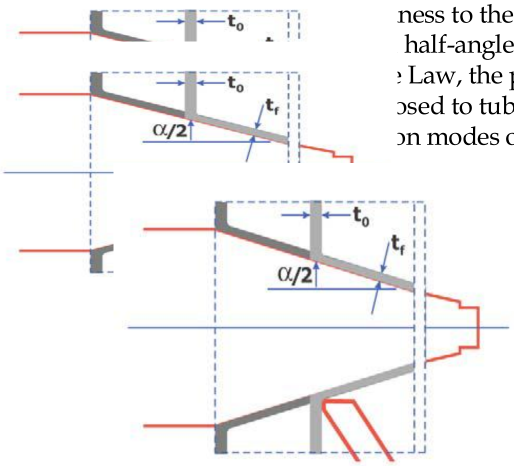

Fig.5

2.2 The Flow forming Process Details:

In flowforming, as shown in Fig.6. , the blank is fitted into the rotating mandrel and the rollers approach the blank in the axial direction and plasticise the metal under the contact point. In this way, the wall thickness is reduced as material is encouraged to flow mainly in the axial direction, increasing the length of the work piece. The flow of metal directly beneath the roller consists of two components, axial and circumferential. If the length of circumferential contact is much longer than the axial contact length, then the axial plastic flow will dominate the circumferential one. In this case, reduction in thickness will resemble that of plane strain extrusion and a sound product will be produced **[2]**. On the other hand, if the opposite is true, then circumferential flow will dominate leading to high constraint of flow in the axial direction. This situation will normally give rise to bulges in front of the rollers causing defects. As the workpiece volume is constant, with negligible tangential flow, the final component length can be calculated as **[3]**:

$$L1 = L_0 \frac{S_0 (di + S_0)}{S_1 (di + S_1)}$$

where *L*1 is the workpiece length, *L*0 is the blank length, *So* is the starting wall thickness, *S*1 is the final wall thickness and *di* is the internal diameter, F_R=radial Force, F_T=tangential force

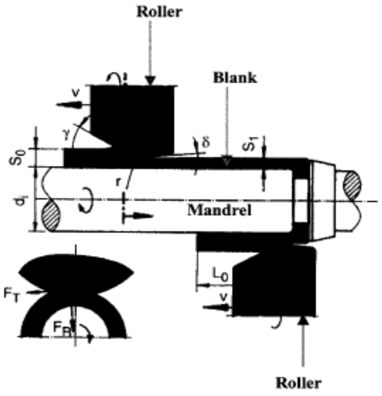

Fig.6. Principle of Flow forming

2.2.1 Tool, Materials, Classification and features of Forming techniques

Due to the pressures involved in the flow forming process, flow form tools i.e. rollers and mandrels must be made from hardenable steel that is heat treated and drawn to a temper that makes the tool hard but yet not brittle. Since the metal is extruded in a rotary fashion rather than stretched over the mandrel, the flow form mandrel will last for many thousands of pieces, as long as care is taken during setup and the mandrel is stored properly.

2.2.2 Three-Rolls-Principle

Flow forming is characterized by low power requirements and a relatively small investment **[4]**.Starting from common three-roller flow forming machines, the three-rolls-principle was developed **[5,6]**.The working principle of the three-rolls-concept is shown in Figure 7,

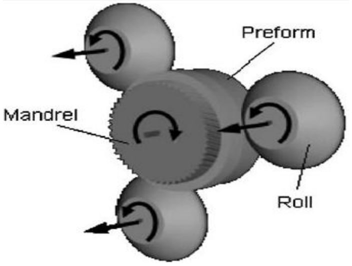

Fig.7

In the process of flow forming, there are two forces acting on the circle dish material by each roll, one is push force another is roll pressure; therefore the material is squeezed deformation. There are three component forces, FR along with diameter, F_θ along with Circumference, FZ along with stalk.

2.2.3 Materials Used in Flow forming

- Stainless Steel,
- Carbon Steel
- Maraging Steel
- Alloy Steel
- Precipitated Hardened Stainless Steel
- Titanium
- Inconel
- Hastelloy
- Brass
- Copper
- Aluminum
- Nickel
- Niobium

2.2.4 Classification of Flow Forming Process

Flow forming which involves only compressive force is classified under DIN Standard 8583. A thick walled cylindrical part is lengthened through flow forming by decreasing the wall thickness. The machine stretches the preform on a rotating cylindrical mandrel by means of mechanically guided rollers form the initial wall thickness 't' to final wall thickness 't_1' in one or several working cycle. The relative changes in shape is defined there by as

$$R = \{(t_o - t_1) * 100\%\}/to$$

Relative changes in shape of more than 95% can be achieved. The accuracy achieved is extremely high. Post forming devices permit vary in the wall thickness over the length of the parts as well as forming thickness, flanges and so on. The saving in working time and material wastage in contrast to customary manufacturing procedures such as turning is considerable. Depending on the flux direction of the formed material, flow forming is divided forward and backward flow forming.

In forward spinning the roller moves away from the fixed end of the work piece, and the work metal flows in the same direction as the roller, usually toward the headstock. The main advantage in forward spinning as compared to backward spinning is that forward spinning will overcome the problem of distortion like bell-mouthing at the free end of the blank and loss of straightness **[7]**. In forward spinning closer control of length is possible because as metal is formed under the rollers it is not required to move again and any variation caused by the variable wall thickness of the perform is continually pushed a head of rollers, eventually becoming trim metal beyond the finished length.

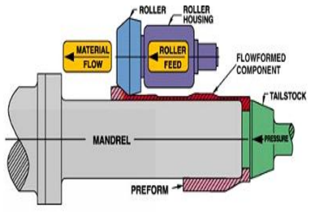

Fig.8 Forward Flow forming

The disadvantage of forward flow forming is that the Production is slower in forward spinning because the roller must transverse the finished length of the work piece.

2.2.5 Reverse flow forming

In backward spinning the work piece is held against a fixture on the head stock, the roller advances towards the fixed end of the work piece, work flows in the opposite direction in Fig.9.

The advantage of backward flow forming over forward flow forming:

1. The preform is simpler for backward spinning because it slides over the mandrel and does not require an internal flange for clamping.

2. The roller transverse only 50% of the length of the finished tube in making a reduction of 50% wall thickness and only 25% of the final, for a 75% reduction. We can procedure 3 m length tube by using of mandrel.

The major disadvantage of backward tube spinning is that backward flow forming is normally prone to non uniform dimension across the length of the product **[8]** and the first portion of spun tube must travel the greatest distance and is therefore the most susceptible to distortion shown in figure. The disadvantage is seldom critical then the spinning tubes of constant wall thickness. However when the preform has weld sculptures of substantially greater thickness than the tube wall, distortion can be a problem. If a circular blank is used as initial work piece which is laid on and stretched in one working cycle the ratio D/d rules relating to simple pressing apply here. (D-round blankdiameter, d-inside diameter of work piece).

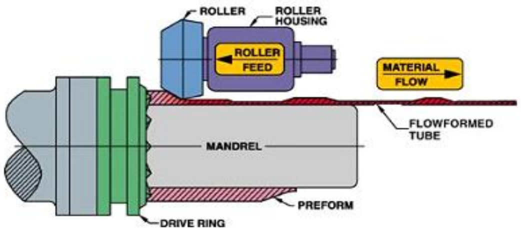

Fig.9 Reverse Flow Forming

Xu et al. **[9]** and Li et al. **[10]** adopted finite element simulation to study the deformation characteristics and the axial displacement distribution, in flow forming of tubes. Li et al. observed that material was displaced in the same direction as the axial feed around the undeformed tube while it flows in the opposite direction to the feed of the roller primarily in the deformation zone, thus elongating the spun parts in backward method. In the spun section, metal flow was mainly in the negative direction due to the push of local plastic deformation. Over the thickness, the tangential displacement was larger in the external layers than in the internal layers. Xu et al. analysed the deformation mechanism and concluded that for the same process conditions, there is no obvious difference in stress and strain rate on the surface between forward and backward tube spinning.

Most modern machines employ the three-roller configuration mainly to achieve a better balance of loads for flow forming precision parts. Normally, the three rollers are spaced circumferentially at 120^{0}part, providing a uniform load distribution to prevent the mandrel from being deflected from the centre line. Furthermore, the rollers can be offset or staggered **[11, 12]** at a particular distance in the axial and radial direction to improve dimensional accuracy and surface finish.

2.3 A Power, forces and process parameters

Many researchers have investigated the effects of process variables on different components of force, power, surface finish and mechanical properties. There are several scientific papers and articles on flow forming/flow forming of tubes with regard to the development of the theoretical methods for forces and power **[7, 13–17].** The results of the investigations are described below.

Research work was done on theoretical analyses of power and force in tube spinning.

In 1972, Theoretical analysis of the plastic flow mechanism of tubes, involving the use of grid-line analysis was carried out by Mohan and Misra **[13]**. The effective strains and roller forces were then calculated using the plastic work deformation by assuming that the strain path during deformation was linear and the strain components in three principal directions can be evaluated from the total displacement after deformation. They reported that the values of axial, radial and tangential force showed good agreement with the experimental results for commercially pure copper.

Later, Hayama and Kudo **[14]** attempted an analysis to estimate the working forces and the diameter accuracy by using the energy method. The calculated and the experimental values were in good agreement over a wide range of conditions such as angle of the roller, feed rate and the reduction in thickness.

A plain strain model and slip line field method was adopted by Wang et al. **[15]** to solve for the forces involved in three dimensional flow forming. They reported that the results correlate well with those of Hayama and Kudo **[14].**

In 1990, Singhal et al. **[7]** proposed a generalized expression for the power required in tube spinning for hard materials, by assuming no build up of material, so that it is applicable to both forward and backward tube spinning, assumed a constant friction factor between the roller and material with diametral growth not taken into consideration.

Park et al. **[16]** adopted the upper bound stream function method to calculate the total power consumption required in deformation and the related tangential force. Trapezoidal and spherical velocity fields using the stream function were suggested and found that the trapezoidal velocity field had a better correlation to the experimental results.

A generalized theoretical model using the upperbound method for force calculation was developed by Paunoiu et al. **[17]**. In their method, deformation with flat roller nose was considered, with roller nose radius divided using different triangular velocity fields. In this way, the number of velocity fields could be chosen in such a way that the more accurate values of forces could be attained. They proposed that the method could be extended by considering more than one-stream line of velocity and could be applied for analysing other manufacturing processes. Based on their theoretical results, they concluded that flat roller nose will produce higher force as compared to roller with nose radius.

In Proceedings of the World Congress on Engineering 2010 Vol II[18], attempt was made to determine the power and forces for making of long thin wall tubes of small bore with Titanium using three rollers at angular speed 69 rad/sec which were mounted on the chuck.. All of the possible parameters with the exception of diametric growth, which had a negligible effect, have been taken into account by following the equation of volume constancy. They found the average yield stress value for titanium with the help of curve fitting. Under plane strain condition, ductility of the material improved by about 15%, because of the presence of hydrostatic stress in conformity to the Birdgeman Law. Constitutive equation was developed and value of average yield stress of the material was calculated to be 791MPa. It was found that with increase in % reduction there is increase in power consumption, radial force and axial force. They also found that as the roller flattens, then diameter of the roller increased and consequently there was increase in power consumption, axial force and the radial force. The optimum roller angle α was in the range of 20^o-25^o.

Comparison has been made for these values of average yield stress vs. % reduction with investigations of [7] [14] and [18] as in Fig10**. ,** and the same trend has been found in the work of Hayama and Kudo while working on soft materials**.** Thus the author concludes that hard materials required more energy, axial force and radial force as compared to soft materials.

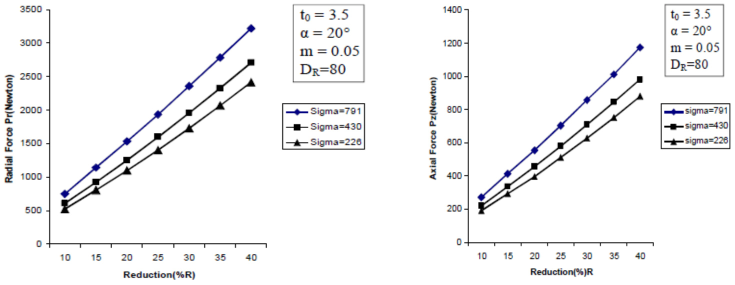

Fig.10

2.3.1 Effects of process parameters

The ratio of circumferential to axial contact under the roller will influence the plastic flow instability such as waviness or bulges (called 'fish skins') on the outer surface of the formed blank [2]. A small circumferential to axial contact ratio leads to geometrical inaccuracies [2, 19].

On the other hand, very large circumferential to axial contact ratio will cause the metal to flow at an angle smaller than the attack angle, leading to wave like surface and differences in thickness. Similarly, too large an attack angle will increase the required power and decrease the efficiency of the forming process. Therefore, an optimum balance between the percentage reduction and attack angle is necessary [2].

Using the basis of minimising the resultant spinning force, Ma [20] concluded that the optimal angle of attack decreased with increasing roller diameter and friction factor, but increased with larger feed rate, reduction and initial thickness of the tube wall.

To achieve suitable flow in flow forming and achieve the desired surface finish, a compromise has to be established between the feed rate, thickness of blank and rolle profile [19]. If too low a feed rate was used for a particular blank thickness, the material would tend to flow in the radial direction, increasing the internal diameter of the blank. On the other hand, when high feed rates were employed, defects such as nonuniform thickness, reduction in diameter as well as a rough surface would result [21]. If the feed rate exceeds a certain limit, it would spoil the surface finish and produce thread-like serrations on the tube [1, 21]. This is because with very large feed rates, the materialwould tend to flow underneath the roller in the opposite direction to the roller axial movement.

The effects of feed rate on thickness strain, radial force, diameter accuracy and surface roughness for the flow forming of aluminium tube were investigated experimentally by Yao and Murata [22]. They concluded that the increase in feed rate would increase spinning force, thickness strain and surface roughness. In addition, diametral accuracy would decrease with the increment of feed rate.

Over the years, tube spinnability (maximum reduction) has also been an area of investigation [1, 23, and 24] in flow forming. The earliest investigation was carried out by Kalpakcioglu [23]. He reported that complete similarity was observed for cone [25, 26] and tube spinnability for the maximum reduction with tensile reduction of area. He concluded that among the process parameters i.e. nose radius, roller angle and feed. Feed rate had a significant influence on spinnability.

Xu and Feng [28] studied the spinnability of steel castings nd concluded that the main factor in affecting the spinnability was the tangential tensile strain that caused diametral rowth during the forming process.

The research[29] investigated the possibility to further nhance the properties of the a copolymer of polypropylene, roduced by ICI,supplied by GeorgeFischer Ltd 0]according to DIN 8077/88 Standards with beige colour aving an external and internal diameters of 50.5± 0.1 mm nd-40.6±0.05mm respectively by Dual directional flow-forming. The Dual directional flow-forming was achieved by two passes forward flow-forming process on a conventional lathe, using a twin-rollers system, with a change in the spindle direction for the second pass. The effects of varying the percentage thickness reduction on the hardness, tensile and fracture toughness properties were studied at three major orientations: along the pipe axis, along the helix angle and transverse to the helix angle. The hardness of the inner and outer surfaces was found to increase with the increase in percentage thickness reduction. Along the helix direction, the yield, ultimate tensile strength and secant modulus at yield were found to increase with increasing percentage thickness reduction whilst the elongation at break decreased. In the direction perpendicular to the helix, no significant tensile property change was observed. The critical stress intensity factor values were observed to increase to twice as high for tubes flow-formed to about 70% reduction in the helix direction. In the transverse direction, the critical stress intensity factor values dropped for 50% to 60% reduction pipes to values below the unflow-formed pipes, but increased slightly to above the values of the unflow-formed pipes at 65% to 70% reduction. The microfibrillar model of oriented polymer was found to provide a satisfactory explanation to the change in mechanical properties, the present dual directional double passes flow-forming method did not establish a distinct crisscrossed fibrous structure in the pipe material.

S. H. Teoh and E. H. Ong[31] observed that Structurally altered high density polyethylene pipes were produced by flow-forming copolymer of polyethylene produced by Eurapipe and supplied by ERIKs Ltd. Only pipes within 39.4 ± 0.05 mm were used in flow forming. The process was performed by using three rollers on a conventional lathe machine. The variation of mechanical and pressure rupture properties (tensile strength, yield strain, toughness and hoop stress) with percentage reduction were studied. The stress-strain behavior of the flow-formed pipe exhibited less yielding and cold drawing as percentage reduction increased, significant increase in the tensile strength was observed for reductions above 20%, Improvement (exceeding 300%) of toughness was observed in the axial and hoop direction. Pressure rupture tests revealed that the hoop stress of the flow-formed pipes increased only after 50% reduction. Both tensile and pressure rupture tests revealed that the ductility also increased with percentage reduction. This was well demonstrated by the extensive bulging during pressure rupture tests. Scanning electron micrographs revealed a significant amount of structurally altered macro fibrils in the flow-formed pipe.

Theoritical and experimental analysis were carried out by K.M Rajan, P.U Deshpande, K Narasimhan for AISI 4130 steel tube on heat treatment[32] and burst pressure[34].Experiments were performed on four-axis CNC with three roller and three pass sequence. From[32] they found that the Preforms processed through hardening and tempering route gave better performance of UTS (1200),0.2%PS(900MPA).The strength coefficient K and strain hardening exponent n of equation $\sigma=K\varepsilon^n$ were determined from stress–strain curves under different heat treatment conditions. The effect of cold work on mechanical properties of flow formed part for a given reduction in area (RA) was predicted using empirical relations published in literature[33].To validate the hypothesis of prediction of cold worked material properties after flow forming, a few flow forming experiments were carried out. The preform dimensions were worked out based on constant volume principle. A three pass flow forming sequence was followed and the properties were measured for about 88–90% thickness reduction. Comparison of the experimental results and the properties of the flow formed tubes predicted using empirical relations showed that empirical relations can be used for predicting the properties of flow formed tubes with reasonable accuracy. These results would be useful for design of performs for manufacturing of large number of high strength pressure vessels successfully.

The suitability of the burst pressure[34] prediction formula available in literature[35][36] and its modification for thin-walled high strength pressure vessels manufactured by a flow forming technique was studied and new model was proposed by modifying Svensson model which accounts for anisotropy in flow formed pressure vessel and errors less than 2.85%.

In the work reported in [37], a simple flow forming facility was established to enable the effects of roller path and geometry, on the flow of metal, to be examined. Flow forming experiments were undertaken utilizing an NC lathe. Only a single roller tool was used in each experiment, which simplified the set-up and enabled metal movement in the deformation zone, to be analyzed more clearly. The 'flat' roller had a 90◦ approach angle along the work piece axis and a contact width of 8.5 mm. The 'nosed' roller had a 30◦ approach angle and a radius of 4mm in the work piece contact region as shown in Fig11. The results showed that, for a cylindrical roller moving axially along a work-piece, metal moved predominantly in a radial direction, forming a flange of increasing diameter. A flat faced roller moving axially produced a radial flange. A roller with a non-orthogonal approach face (nosed), moved metal largely axially, as a bulge, ahead of it. Axial movement of either roller caused metal at the free end of the work-piece, to move in the direction opposite that of the tool, to form a shallow crater. Radial tool movement reduced work-piece diameter and formed a thin walled 'cup' or a 'boss' on the end of the work-piece. The dimensions of the feature would depend on the roller geometry, feed rate and amount of deformation. FE modelling and simulation was used with success, to predict formed shapes. The accuracy of forces predicted, using FE, varied, but given the lack of a failure/instability criterion in the software and the neglect of roller/work-piece friction, the use of FE was a useful load estimating tool. The results illustrated the ability of flow forming to be used for production of shapes of thin section, which would be difficult and expensive to be made by press forming.

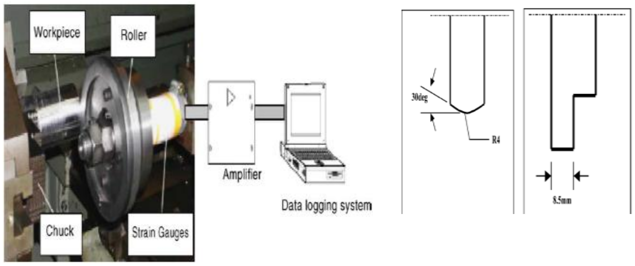

Fig.11

In [38], Experiments were conducted on (18% Ni) C-250 maraging steel pre-form tubing, acquired according to standard AMS 6512C [39] (double vacuum melted VIM-VAR) to find effect of aging treatment on mechanical properties. Various heat treatments were then conducted on the tube to strengthen the material. 480 ◦C/6 h/AC aging treatment generated a highest hardness of 55.1 HRC, which was derived from the combined effect of work hardening and precipitation hardening. Its YS and UTS exceeded the specification requirements by 16% and 12%, respectively with loss of ductility in percentage elongation. The test pieces that were flow-formed and received heat treatments of solution, homogenization and "homogenization + solution" before aging treatment showed a decrease of hardness by 3.8–4.7%, indicating that the distortion and associated residual stress of the microstructure have been eliminated. The radial cross-section hardness values of the test pieces that received various heat treatments and that of the directly aged test piece were essentially the same, and they also showed a level distribution of the values. This indicated that after solution and homogenization treatment, the distortion in the fibrous C-250 maraging material due to cold work had been homogeneously recrystallized. Through "solution + aging" treatment, the steel's ductility was much improved and tensile properties met the specification. The pre-treatment of high homogenization temperature could produce coarse lath martensitic microstructure and resulted in a decrease of the tensile strength of the C-250 steel. Furthermore, the C-250 steel also showed the presence of seemingly globular precipitates within the lath structure with better ductility. However, the author expressed that the possible component distortion due to excessive solution annealing temperature may become a concern to the structure designer.

Forward flow forming of tubes has been simulated using an explicit commercial finite element program. Variation of contact geometry considering plastic flow [40] has been calculated based on the proposed criterion. Also flow formability of tube materials have been calculated during forward flow-forming process. Contact geometry simulation resulted, as the variation of S-to-L ratios with feed rates and two attack angles have been compared with outcomes of geometrically based equations. The effects of attack angles and feed rates on the flow formability have also been evaluated. For predicting contact geometry and flow formability, extensive simulations had been carried out. Explicit code was chosen as better alternative for simulation of flow forming and for assessing results and to establish correlation between feed rates, axial and angular velocities .Simulation of flow-forming and flow formability test were inherently very time-consuming and involved large computational resources. Contact geometries were defined using simulations. By introducing eTotal-to-yield ratio of simulation, S-to-L ratios that could be indicative of plastic instability during flow-forming process had been calculated. It has been shown that S-to-L ratio increased with increasing attack angle and feed rate. Calculation of contact zone based on the flow-forming simulation had the advantage that not only contact shape could be predicted but also the effect of material behavior and plastic flow beneath the rollers. Thee geometrically based formulation has not taken into account the material behavior in contact zone. Although differences were found between simulation and experimental results, the trend in simulations and experiments was the same. Therefore, the results of simulations could be used for prediction of flow formability as a prior action before any experimental work. Simulation results showed that, by increasing feed rate, flow formability decreased and attack angle had no significant effect on flow formability.

In 2008, M. Joseph Davidson, K. Balasubramanian, G.R.N. Tagore have carried experiments on a four-axis CNC flow-forming machine with a single roller. Their investigations included the prediction of percentage elongation by Taguchi method [41], surface roughness by Design of Experiments[42] and Quality [43] of annealed AA6061 aluminum tubing.

The results of [41]showed that the flow-forming process produced a maximum percentage elongation of 18% when the process parameters were set at their optimum values.The optimum forming condition were depth o fcut =2mm,speed 250 rpm, and feed = 50 mm/min to ensure significant improvement in the response function. They concluded that the depth of cut was the most important process parameter affecting the percentage elongation.

They developed a mathematical prediction model of the surface roughness [42] in terms of speed of the mandrel, the longitudinal feed and the amount of coolant . The effects of these parameters have been investigated using response surface methodology (RSM). Response surface contours were constructed for determining the optimum forming conditions for a required surface roughness. The surface roughness increased with increase in the longitudinal feed and it decreased with decrease in the amount of the coolant used. The validity of the developed model predicted surface roughness within 6% error. The verifying experiment showed that the predicted value agreed with the experimental evidence.

In the research work[43], the flow-forming process parameters that affect the quality of flow-formed tubes were analyzed and found that depth of cut, the feed, the starting dimension of the preform, the starting heat-treatment condition of the preform and the speed of the mandrel had significant role in the quality of the final product. The effects of these process parameters on the quality of flow-formed tubes, the optimum process parameters for good surface characteristics were proposed. They found that the Preforms annealed for 90 min possessed good surface property. Tubes of sound surface characteristics were produced for a depth of cut of 2mm, feed in the range of 50–100mm/min and a minimum gap between the mandrel and the work piece to avoid diametral growth.

The distribution of equivalent plastic strain through the thickness of several AISI 1020 steel plates formed over a smooth cylindrical mandrel using a three-stage single roller forward flow forming operation was studied[44] by measuring the local micro-indentation hardness of the deformed material using Berkovich micro-indentation hardness tester manufactured by Micro Materials Ltd. The correlation of the Berkovich hardness values to equivalent plastic strain were accomplished by deforming as-received AISI 1020 steel plate to different levels of plastic strain through cold-rolling and uniaxial tensile deformation. The average percentage variation in the hardness was about 8% at any given value of equivalent plastic strain, this percentage increased to 16% when the plastic strain was low. For the highly deformed rolled specimens, the scatter diminished to 4%. The equivalent plastic strain was higher at the inner and outer surfaces and lowest at the center of the work piece. The work piece experienced increased plastic strain in subsequent forming passes with material near the mandrel and the roller displaying elevated equivalent plastic strain, which was dependent upon thickness reduction, during the final forming stage. This coincided with the onset of complete contact between the work piece and the mandrel. It was also observed that as reduction increased, the local plastic strain increased more rapidly at the roller interface than at the mandrel interface. This trend increased very rapidly between 51.8 and 52.9%. Therefore, it was suggested that since there was a substantial increase in plastic strain at the roller interface when the thickness reduction was about 52%, this represented the maximum equivalent plastic strain that can be imparted to the 1020 steel by flow forming prior to the onset of roller-induced defects on the surface of the work piece.

In [45], the optimum variables for flow forming process of AISI 630 Stainless Steel were obtained by using the finite element method and its results were compared with the experimental process. The variation of thickness of the sample was examined by the ultrasonic tests for the five locations of the tubes. To simulate the process, the ABAQUS explicit was used. The effects of flow forming variables such as the angle of rollers and rate of feeding of rollers, on the external variables such as internal diameter, thickness of tube and roller forces were considered. The study showed that the roller force and surface defects were reduced with low feeding rate and low rollers attack angles. They found, the sample internal diameter increased at low feeding rate and low rollers attack angles.

M.S. Mohebbi, A. Akbarzadeh [46] studied the evolution of redundant strains in AA 6063 alloy a single-roller flow forming process in one pass. A coupled set of experiments and numerical simulations using the commercial finite element code ABAQUS/Explicit were used. The forming process was simulated and simulation results were in agreement with the experimental results, and the maximum relative error was less than 17.8%. The modified embedded pins were used to evaluate the shear strains. It was shown that high shear strains occur not only at the longitudinal but also at the cross section. Sketched longitudinal lines also showed that the cylindrical coordinate system cannot be neglected. Beside shear strains, reversal straining was recognized as another type of redundant work. It was shown that this type of redundant strain resulted from the incremental nature of flow forming process in which the deformation was highly localized. Good agreements between the force measurements of frictionless model simulations with the experiment implied that the frictional work could be neglected in comparison to the redundant work.

A.R. Fazeli & M. Ghoreishi[47] dealt with the influences of major process parameters of thermo mechanical tube-spinning process such as preform thickness, thickness reduction, mandrel rotational speed, feed rate of rollers, solution treatment time and aging treatment time on internal diameter growth and wall thickness changes for manufacturing of 2024 aluminum spun tubes using design of experiments by forward tube spinning process as large number of effective parameters were involved. Experimental results were analyzed by analysis of variance and empirical models of internal diameter growth and wall thickness changes were developed. They found that lower thickness reduction with thinner preform thickness, higher feed rate of rollers; slower mandrel rotational speed and lower solution treatment time had advantages for obtaining smaller internal diameter growth and wall thickness changes. Low levels of preform thickness, high level of feed rate of rollers minimized the value of internal diameter growth. The preform thickness, thickness reduction and feed rate of rollers had more effect on the internal diameter growth. They verified that the developed model had an acceptable rate of errors. According to the results, the predicted error ranged within 13.63% for internal diameter growth and 9.16% for changes in wall thickness. There were significant interactive influences among input parameters such as initial thickness and thickness reduction, mandrel rotational speed and initial thickness, thickness reduction and solution treatment time, Mandrel rotational speed, and solution treatment time. Furthermore, small thickness reduction, slower mandrel rotational speed, lower solution treatment time and high feed rate of rollers lead to smaller wall thickness changes. Blocking and center points had insignificant effects on the internal diameter growth and the wall thickness changes. They concluded that uncontrollable factors had no effect on spinning process and the process could be modeled with two levels for each input parameters.

The local variation in the Von-Mises equivalent plastic true strain within an AISI 1020 steel work piece that was fabricated by single-roller flow forming over a splined-mandrel was assessed using micro indentation hardness. The effect of thickness reduction on the equivalent plastic strain [48] was investigated by flow forming samples at thickness reductions of 19%, 25%, 39% and 51%. The largest equivalent plastic true strain occurred near the work piece/mandrel interface directly in front of the nose of the internal ribs and reached approximately 170% when the work piece thickness reduction was 51%. This represented that the forming limit for AISI 1020 steel when subjected to the flow forming parameters used in this study was sensitive to the geometry (depth, length, and spacing) of the mandrel splines. High levels of grain elongation were also observed in the work piece at the work piece/mandrel interface near the nose of the internal ribs and along the leading and trailing edges of the ribs.

2.3.2 Defects in flow forming:

The author in [49] presents experimental observations of defects developed during flow forming of high strength SAE 4130 steel tubes on 4-axis CNC flow forming machine with a 3-roller configuration. The major defects observed were fish scaling, premature burst, diametral growth, micro cracks and macro cracks. This paper analyzes that the presence of a large number of inclusions in the non-electro slag refined raw material and mechanical bond between the particle matrix experienced de-cohesion lead to cracking. The fish scaling was a result of the nonuniform grain size. Diametral growth increased with increase in percentage thickness reduction. The spring back value varied between 0.3 and 0.4 for a percentage thickness reduction of 60–88% in this experimental study. It has been shown by the various failure modes, that the material should have a uniform microstructure, a high level of cleanliness and excellent formability to achieve the high amount of cold working associated with the flow forming process. Tempered martensitic microstructure with a starting hardness of 220–245 HB and a grain size number of ASTM 6–8 has been found to be ideal for flow forming to 88–90% thickness reduction. These reductions produced a component that has 1250 MPa and approximately 7% elongation failure. Machine parameters such as feed rate, spindle speed and roller geometry were vital in achieving dimensional accuracy. The minimum percentage thickness reduction and the number of passes necessary to achieve the final thickness were 45% and three passes respectively. Based on the adverse effects of inclusions on the flow forming process, it was recommended that electro slag refined (ESR) grade steel be used. These observations were in agreement with published work on flow forming [50, 51].

The author in[52] discusses the reasons for crack generation and provides the remedial measures to avoid cracks during flow forming of Niobium alloy Nb–Hf–Ti sheets to make a conical divergent. During cold forming of the sheet, cracking was noticed on the surface. Visual observations of the cracks and micro structural and fractographic analysis revealed the presence of built-up layer and delaminations at the cracked site. Serration marks on the formed surface indicated a relatively higher feed rate. Work hardening of the material was also observed. It was found that although sufficient ductility was present (25–28% elongation) in the input sheet material, the material became work hardened significantly during the first pass. Traverse speed (feed rate) of roller was high, and the work-hardened material cracked at the surface as in Fig.12. The surface cracks propagated due to complex state of stress (tensile and bending at the crack tip). The author recommended that the feed rate of the material has to be reduced, the flow-forming process has to be interrupted and the material annealed at regular intervals to avoid significant work hardening.

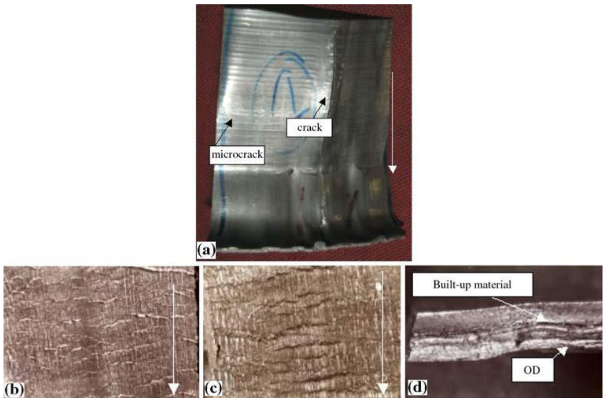

Fig.12

3 CONCLUSIONS

This paper reviews the developments in flow forming. To manufacture complex shapes which are being required in the increasing numbers by global manufacturing industries, to understand and quantify the mechanical properties of flow formed parts, flow forming has great potential in the development.

The research may be directed to manufacture parts with higher accuracy, improved performance for greater complex geometries, asymmetric parts. In recent years, a technique of combined spinning and flow forming has been developed to produce parts with complicated geometries. Further investigation in characterization of roller-induced defects created during high-strain flow forming, establish a distinct crisscrossed fibrous structure in the pipe material, hard to work materials and different materials that can be flow formed are to be conducted.

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