Optimization of Process Parameters for Axial Flow Forming of OFE Copper and Characterization of Product

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***Abstract*— Flow forming is an advanced eco-friendly chip less metal forming process, which employs an incremental rotary point deformation technique. Flow forming offers a remarkable increase in tensile properties due to strain hardening and provides excellent dimensional accuracy and surface finish for the flow formed part. Flow forming is an advanced, often net shape, hot and cold working process for manufacturing seamless, dimensionally precise tubular and other rotationally symmetrical products. With the introduction of heavy-duty CNC flow forming machines hard to work materials can be formed easily, thus enabling customers to optimize designs and reduce weight and cost, all of which are vital. The parameters affecting the flow forming process are feed, speed of the mandrel, depth of cut, roller diameter. Out of these parameters feed and speed of mandrel are predominant in affecting the flow forming process. The main objective of this research is to perform experimental work for various process parameters like mandrel speed, roller feed, depth of cut etc. and study it's affect on the dimensional accuracy of flow formed component. In connection to these parameters, to characterize for the metallurgical and mechanical properties of the perform material and flow formed tubes like hardness, microstructure, grain size, tensile strength. In this research, the optimized parameters for the flow forming of oxygen free electrolytic copper (OFE-Cu) has been established**

Keywords—Flow forming, OFE-Cu, CNC, Speed, Feed, Depth of cut, Microstructures, Grain size.

I. INTRODUCTION

Flow forming is a process whereby a hollow metal blank, a disc or a tube is mounted on a rotating mandrel and the material is made to flow axially along the rotating mandrel by one or more rollers.

Flow forming is mainly used to produce thin walled high precision tubular components. Due to flexibility and low tool load requirement the process is capable of being extended to manufacturing of shapes from bulk raw material, such as solid bar ingot, cast and forged performs. 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. 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[13].

The new approach is based on flow forming technology. Similar to many bulk forming processes, the predominating tri-axial state of compressive stress allows the achievement of high plastic strains in the work piece. Since it is an incremental process, flow forming is characterized by low power requirements and relatively small investments. In this process, an externally geared mandrel is fitted into a cup-like work piece. By reducing the cup's outside diameter, the cup inner wall is rolled into the mandrel's teeth, producing the gear's profile. Different flow forming principles that are suitable for the production of internally geared wheels are classified by their main contact zone geometry. According to the resulting tooling concepts, the terms three-rolls principle, multiple-rolls-principle and ring-principle were introduced for the investigation. Other applicable principles such as cold reducing or radial rolling were not part of the examination.

II. SCOPE OF WORK/AIM OF INVESTIGATION

The work has been carried out to benefit various research projects meant for defense applications being carried out at NFTDC, an autonomous R & D organization based at Hyderabad, India and also other organizations working on similar projects. The aim of this work was to select the proper process and material conditions to manufacture thin walled tubes of desired length and thickness having good surface characteristics and sufficient strength. Materials used for the research are copper and copper alloys (CRZ & CRZT).

III. LITERATURE REVIEW

Since time long, several scientists, researchers, investigators have conducted many experimental and theoretical studies in flow forming of cylindrical tubes to evaluate qualitative and quantitative requirements in flow forming as well as the influences of various process variables and parameters such as feed, speed, depth of cut, percentage reduction.

• Yao and Murata investigated experimentally the effects of feed rate on thickness strain, radial force, diameter accuracy and surface roughness for the flow forming of Aluminum tube. They concluded that, the increase in feed rate will increase spinning force, thickness strain, and surface roughness. In addition, dimensional accuracy will decrease with the increment of feed rate. [28]

• The influence of Flow Forming parameters and microstructure on the quality: M. Jahazi, G. Ebrahimi shown the effects of feed rate, the shape of the contact line, the roller angle and the percentage reduction on the elimination of spinning defects such as a wave-like surface, micro cracks and bore were studied. Also, the influence of the preheat temperature, the holding time and the cooling rate on the microstructure and mechanical properties of the material was investigated. [2]

• A review of spinning, shear forming and flow forming process: In the last few years or so spinning and flow forming have gradually matured as metal-forming processes in production of engineering components from small to medium batch quantities. C.C. Wong and T.A. Dean have introduced the process details of the flow forming and tube spinning in this work. Also the direction of research and development of future industrial application have been indicated. They have shown that combined spinning and flow forming techniques are being utilized due to the increasing flexibility provided for producing complicated parts nearer to net shape, enabling customers to designs reduce weight and cost, all of which are vital in automobile industry. [1]

• K.M.Rajan, P.U. Deshpande and K. Narasimhan, studied the effect of heat treatment of perform material on the mechanical properties of the flow formed part and using empirical relations in predicting the properties of the flow formed components. [15]

IV EXPERIMENTAL SETUP DETAILS OF FLOW FORMING

The flow-forming machine is powered by a hydraulic power pack which is run by a 10HP, 1440 rpm electric motor. The pump can deliver 27 LPM of oil from a tank of capacity 200 liters. The oil from the hydraulic power pack is fed into the hydraulic pump through servo actuator. The signals to the actuators are provided from servo drives which are controlled by a CNC unit. Depending on the value of the input signal received (+- 10 V), the actuator makes the hydraulic pump rotate in either a clockwise direction or anti clockwise direction. Four movements of the roller arms are possible (X,Y,A& B).X and Y arms are controlled by two hydraulic pumps of which X axis can move at a maximum of600 mm/min and the Y axis can move at a maximum speed of 300 mm/min. The torque from the motor is converted into linear movement through lead screws. A mandrel is fitted between the head stock side of the machine and the tailstock end .It is run by a 2 phase induction motor (50 HP, 1440 rpm).To vary the speed, a variable frequency drive (VFD) is used. The tail stock end of the mandrel is held by a revolving center. It is powered by a 120 bar pressure regulator supplied by the power pack.

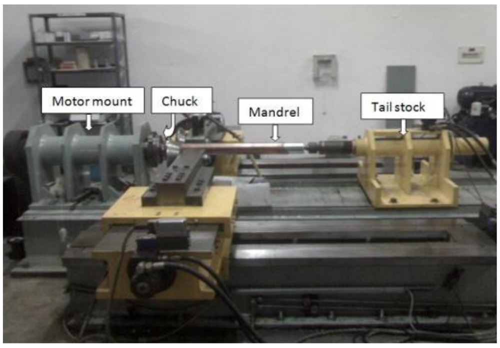


Figure 4.1 Flow forming machine

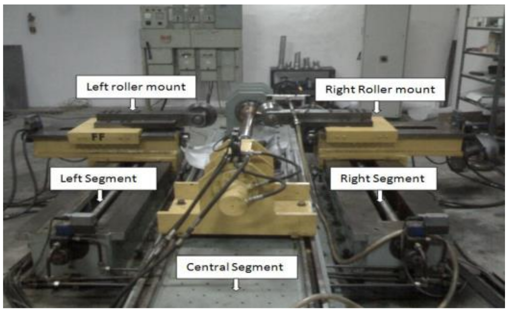


Figure 4.2 Flow forming mach

V RESULT AND DISCUSSION

5.1Effect of heat treatment and percentage reduction.

5.1.1 Optimization of annealing Cycle for OFE-Cu.

The perform material should have sufficient ductility after heat treatment to be flow formed into
final part and at the same time have sufficient strength after flow forming. Typically, a very soft perform would have very good flow formability, but will develop poor strength after flow forming. On the contrary, a very hard perform may not flow form at all to the required size and shape of the final product or may develop cracks during flow forming [15].Hence, optimization of heat treatment with the final required mechanical properties of the flow formed tube is important. Initially, an attempt was made to flow-form in the as-forged condition. But, after two cycles, fish scales formed and it could not be flowed further due to the strain hardening effect. An annealing treatment produced the desired result. However, performs treated for different annealing temperatures yielded different strength values and elongations. So, an analysis was made to the optimal annealing temperature. All the OFE-Cu samples were subjected to same flow forming cycles i.e., heating the sample to the

temperature, soaking it for 2 hours and then cooling the samples in furnace for 2 hrs and then natural air cooling. Annealing temperature range for OFE Cu was selected according to ASM Handbook i.e, 350-650^{0}C.Vicker hardness was taken for all the samples. Load was kept constant at 5 kgf and time 10 sec. Annealing temperature of 600^0 C gave good results.

Table 5.1 Hardness value of annealed OFE-Cu samples

Temperature	Vicker hardness (VHN)
650	37
600	38.3
550	43
500	43.7
450	51
400	55.5

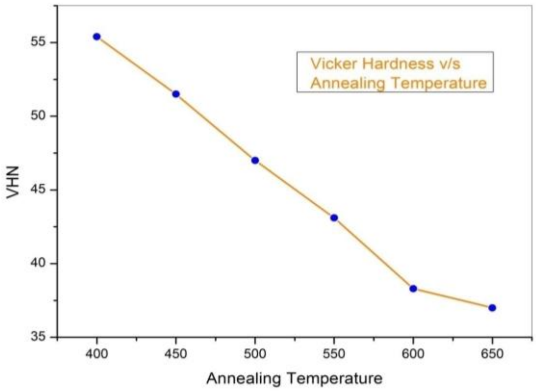


Figure 5.1 Graph between Vicker hardness number and annealing temperatures for OFE-Cu samples.

5.1.2 Optimization of percentage reduction

As the strength of the flow formed tube is strongly affected by the characteristics of the deformed microstructure, it is necessary to perform a detailed evaluation for microstructure, hardness of OFE-Cu. Compression test was performed on annealed OFE-Cu at different percentage of reductions from 10-70 % .Microstructure and Vickers hardness value for all the samples were taken out. The microstructures were taken out at a magnification of 50x.After 50% reduction the hardness value is increasing very abruptly. During flow forming, after 50% reduction of the perform fish scales will start appearing as visible in the microstructure.

A. Hardness Test

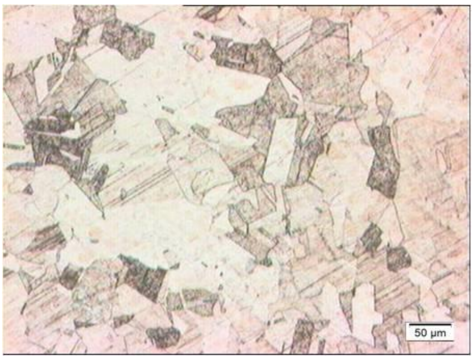
All the hardness readings were taken via the Vickers hardness method in SHIMADZU HSV20 hardness testing machine. The Vickers test method uses a diamond shaped indenter pressed into the surface of material using a force of 5 kgf and held for 10 seconds. The hardness values are shown in the table below.

Table 5.2 Hardness value of OFE-Cu compression tested samples.

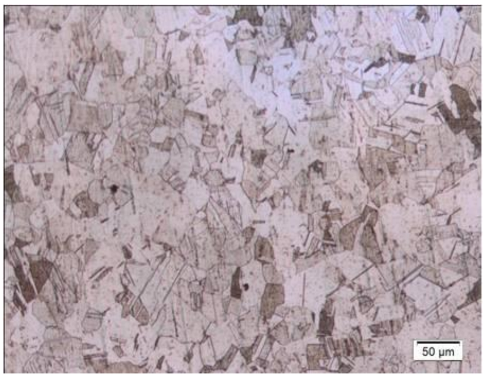
S No.	0% reduction	10% reduction	20% reduction	30% reduction	40% reduction	50% reduction	60% reduction	70% reduction
1	38	41.3	47.27	73.93	100	112	141	192
2	39.4	41.2	48.4	75	98.7	109	144	193.1
3	39.1	43	49	76	97	110	142.2	189
Avg.	38.83	41.83	48.22	74.97	98.5	110.3	142.4	191.36

B. Microstructure

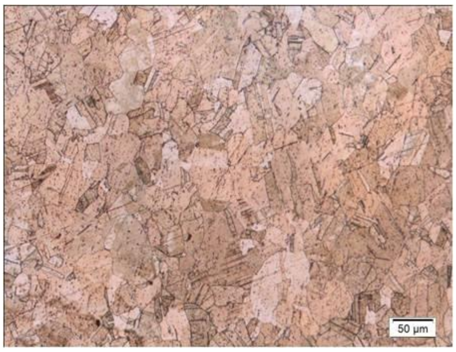
All the microstructures were taken out using optical microscope at a magnification of 50x.The grain size reduces with increase in percentage of reduction and becomes very fine. Required microstructures are shown below:



(a) 0% reduction

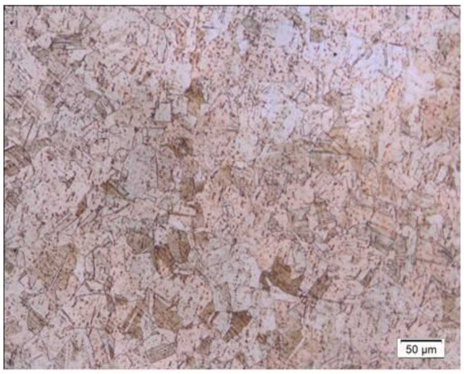


(b) 10% reduction

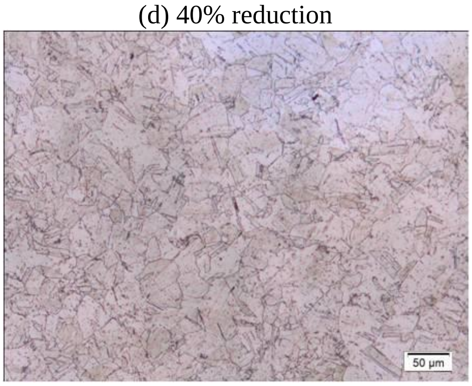


(c) 20% reduction

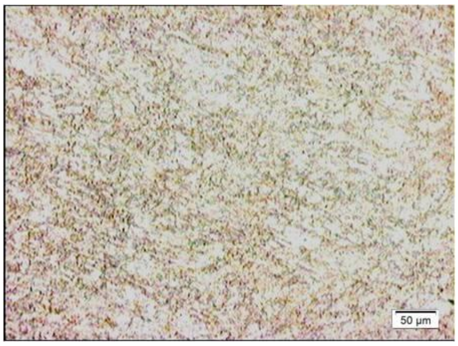
(d) 30% reduction



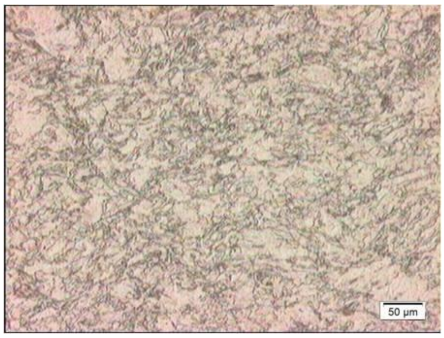
(d) 40% reduction



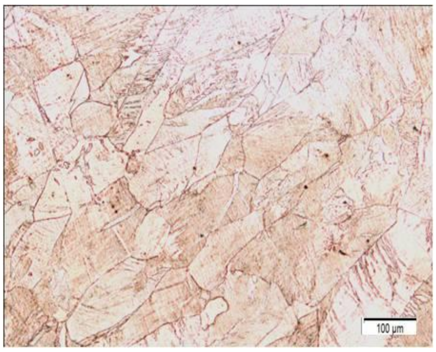
(e) 50% reduction



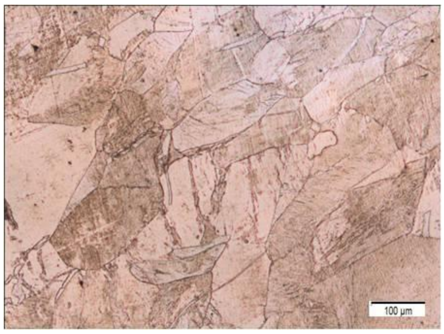
(f) 60% reduction



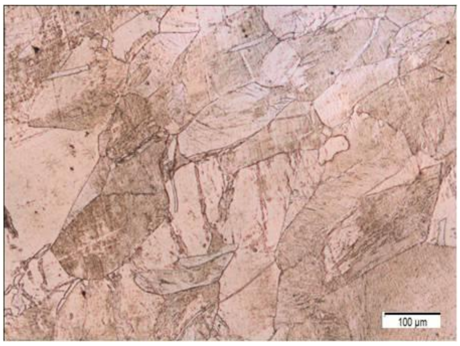
(g) 70% reduction



(h) 70% reduction



(i) 60 % reduction at 100x



(j) 70 % reduction at 100x

Figure 5.2 Microstructures of compression tested OFE Cu samples

5.2 Effect of process parameters

5.2.1 Cold working of OFE-Cu

*A. **Effect of feed rate***

Different feed rates ranging from 20 mm/min to 50 mm/min were tried. During the initial stage of deformation, a feed rate of less than 20 mm/min resulted in an increase in internal diameter. This is because, the plastic deformation initiated by the depth of cut (radial feed) is retarded by the lower feed rate and instead of flowing in the axial direction; the plastically deformed material flowed in the radial direction resulting in diametral growth. A feed rate more than 70 mm/min produced a wave like surface. A high feed rate makes the roller move faster through the mandrel, denying the plastic deformation. However, heavier depth of cut combined with high feed makes the surface wavy. However, during the final stages of flow-forming cycle, a feed rate of around 40 mm/min. With small depth of cut in the range of 0.1-0.3 mm is required for fine surface finish.

B. Effect of speed of Mandrel

A high mandrel speed was found to unify the surface avoiding some of the surface defects. However, excessively high speed produced vibration in the machine resulting in decreased surface quality. A high-speed produced excellent surface finish up to a particular level after which it reduced the surface finish due to vibration problems.

C. Effect of depth of cut

An optimum depth of cut is required for good surface characteristics. Depths of cuts ranging from 0.1 -0.5 mm were tried. A very small depth of cut strain hardened the work piece, resulting in fish scaling marks on the surface, cracks and fracture. Very high depths of cut retarded plastic deformation and produced highly strained roller profiles on the surface of the work piece. The optimum depth of cut was found to be 0.4 mm. A perfect extrusion like flow as felt between the gap between the work piece and the roller at this depth of cut. A heavier depth of cut combined with lower feed rates produced diametral growth. The diametral growth was found to increase with a decrease in the feed rate and an increase in the depth of cut in this feed rate region

*D. **Effect of starting heat treatment condition**.*

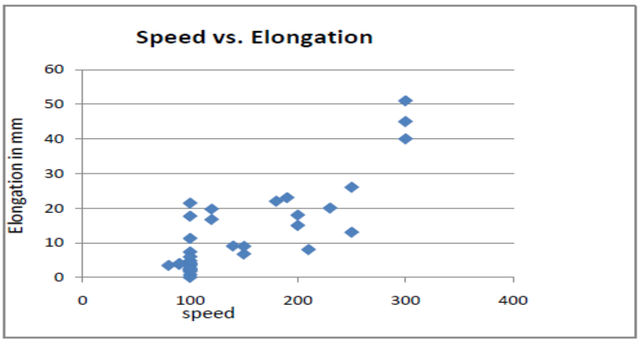
An optimum annealing temperature is required for proper deformation and good surface quality. Different annealing temperatures were tried on the preform. Earlier a constant annealing temperature of 416°C was used. A pre-form annealed for 1 hour showed fish scales and a continuous flow-forming operation performed on such a preform resulted in cracking of tube much before the required the deformation level. Tubes with fish scales are shown in Figure 5.3 Optimized heat treatment is annealing temperature of 600°C was used at the later stages.

Figure 5.3. Fish scales on preform

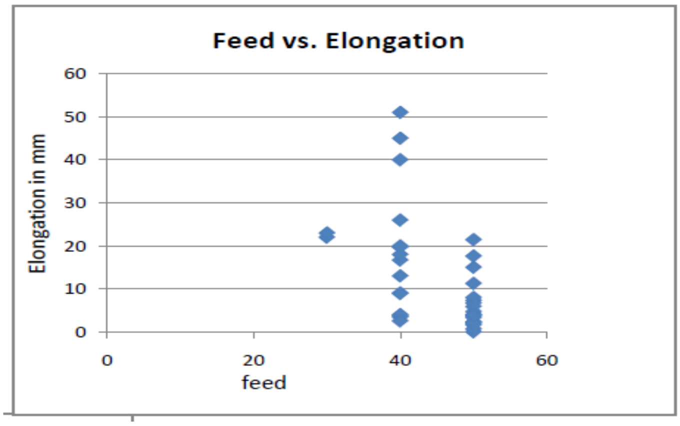
E. Effect of starting dimension of the preform

The starting dimension of the pre-form is an important parameter affecting the surface qualities of flow formed tubes. The gap between the inside diameter of the pre-form and the mandrel is an important parameter that decides most of the quality issues. If this gap is very small, removal of the tube from the mandrel will be very difficult and the friction will produce scale marks on the inside diameter of the flow-formed tube. On the other hand, if this distance is very large, the material will flow more in the axial direction than in the radial direction resulting in bulging of the tube. A tube that bulges will fracture at the end of the tube, as the stress in the radial direction will be greater than in the axial direction resulting in cracking.

Thus the flow-forming process parameters that affect the quality of flow-formed Cu-OFE tubes have been analyzed. It was found that the depth of cut, the feed, the starting dimension of the pre-form, the starting heat treatment condition of the perform and the speed of the mandrel all have a significant role in the quality of the final product.



(a)



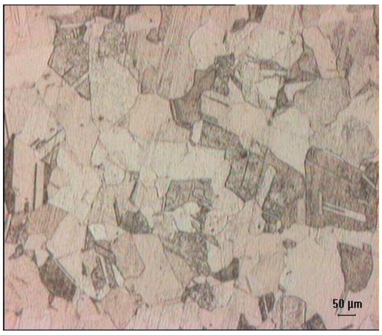
(b)

Figure 5.4 Graph between speed of mandrel v/s elongation (mm) and Feed v/s elongation

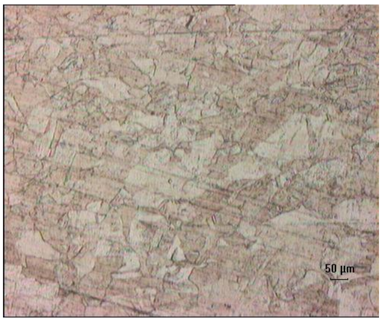
5.3 Characterization of OFE-Cu

5.3.1 Microstructure of preform and flow formed tube

The microstructure of OFE-Cu were taken out using optical microscope . Specimen taken from the flow formed tube surface shows Cu_2O (dark dots) caused by oxygen penetration during heat treatment



(a)



(b)

Figure 5.5 OFE-Cu parent material microstructure (a) and Product microstructure (b)

5.2.2 Hardness Test

All the hardness readings were taken via the Vickers hardness method. The Vickers test method uses a diamond shaped indenter pressed into the surface of material using a force of 5 kgf for 10 seconds. The resulting indentation diagonals were measured, and the hardness number is calculated by dividing the surface area of indentation.

Table 5.3 Hardness value of parent material and flow formed tube of OFE-Cu

Test No.	Parent Material (VHN)	Product Material (VHN)
1	66	112
2	65.3	110
3	66.1	110
4	65.7	109
Average	65.77	110.25

5.2.3 Tensile Test

Tensile tests were carried out in universal testing machine (UTM) and samples were prepared according to ASTM E8 standards. The effect of cold working can easily be seen from the ultimate tensile strength (UTM) values in the table below.

Table 5.4 Tensile test results of parent material and flow formed OFE-Cu tube

Material	UTS (MPa)	YPS (MPa)	% Reduction
OFE-Cu parent	181	110	54
	156	87	55
OFE-Cu product	257	254	66
	270	257	60

VI CONCLUSIONS

Based on the results obtained, the following parameters are recommended for good quality product for cold forming of OFE-Cu.

- The preform should be annealed at 600°C for 120 minutes and 120 min furnace cooled and then air cooled.
- A feed of less than 20mm/min and more than 70 mm/min should be avoided at the initial stage of deformation and to improve the surface finish a feed of 30 mm/min should be used in the final flow forming cycle.
- A depth of cut of 0.4 mm produced good results.

- Too big a gap between the mandrel and the preform resulted in bulging of the tube which should be avoided.
- Mandrel speed should be kept at 300 rpm to give good result.
- A feed of 40 mm/min is recommended to avoid roundness errors.
- The perform should be reduced in thickness upto 50% and should be annealed for further deformation process to get good quality product.

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