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An experimental study on the quality of flow-formed AA6061 tubes

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ABSTRACT

Flow-forming is one of the effective processes for manufacturing thin-walled seamless tubes. Experiments were performed on annealed AA6061 tubing preform to produce seamless thin-walled tubes. The final dimensional accuracy and the surface quality achieved for various levels of process parameters were examined. It has been found that a number of factors affect the quality and dimensional precision of flow-formed tubes. In this investigation, the effects of these process parameters on the quality of flow-formed tubes are discussed and the optimum process parameters for good surface characteristics are proposed. Preforms annealed for 90 min were found to possess good surface property. A depth of cut of 2 mm and a feed in the range of 50–100 mm/min produced tubes of sound surface characteristics. It was found that a minimum gap is required between the mandrel and the workpiece to avoid diametral growth.

1. Introduction

Flow-forming is a chip less, near net-shaped forming process used in the manufacture of seamless tubes and other axi-symmetric products. Many researchers have conducted a number of experimental- and numerical-based researches on flow-forming. Lee and Lu (2001) studied the flow-forming of cylindrical tubes using a rolling mechanism. Chang et al. (1998) studied the tube spinnability of AA2024 and 7075 aluminum alloys. Park et al. (1997) used an upper bound stream function method to analyse the tube spinning process. Large numbers of quality issues arise in the flow-forming process. Signs of metal smearing, galling, fish scaling, cracks and inclusions are harmful discrepancies in formed parts and are cause for rejection and likely scrapping of the defective piece (ASM, 2005). However, there are very few papers available on the quality issues of flow-forming. Wong et al. (2005) studied the effect of roller path and geometry on the flow-forming of solid cylindrical components. They developed a finite element model to simulate the process. They concluded that the final dimension of the flow-formed feature depends largely on the roller geometry, feed rate and the amount of deformation. Gur and Tirosh (1982) performed an experimental investigation to study the plastic flow instability of preforms under compressive loading during shear spinning process. They found that, for flow-forming thin-walled tubes, a sound product will be formed if the roller-workpiece contact area is more in the circumferential region than in the axial region. A defect in the form of bulge will be formed if the alternative is true. Hua et al. (2005) performed a three-dimensional finite element analysis for analyzing the tube spinning process. Singal and Prakash (1990) performed experimental study on the shear spinning of long tubes of hard-to-work materials. Kawai et al. (2001) performed a die less shear spinning of truncated conical shells and developed forming limits to prevent the occurrence of wall fractures and flange wrinkles. Kemin et al. (1997)

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performed an elasto-plastic FEM analysis to study the diametral growth in tube spinning. They determined the distributions of stress, strain, residual stress and residual strain in a workpiece and the expansion of the plastic deformation regions in the process of loading during tube spinning. They analyzed the influences of various process parameters on the diametral growth of tubes.

Large numbers of process parameters namely the depth of cut (radial feed), the speed of the mandrel, the axial feed, the starting dimensions of the preforms, the starting heat-treatment condition of the performs, etc. affect the quality of the flow-formed tubes. Also, complex inter-parameter relationships exist among the above-said parameters, which are very hard to control and predict. Therefore, to produce tubes of enhanced strength and sound surface qualities, the reason for the above discussed defects and the ways to avoid it should be found out. In this investigation, the effects of the various flow-forming process parameters on the quality of flow-formed tubes are discussed and the optimum process parameters for good surface characteristics are proposed.

2. Experimental work

2.1. *Material*

The material used for the present investigation is AA6061 alloy. The major alloying elements are Al–1Mg–0.6Si–0.25Cu–0.2Cr. AA6061 has moderate strength, excellent corrosion resistance and high plane strain fracture toughness. This alloy can be used in aircraft fuselage skins, automobile body panels, torpedo structural applications, etc. The main constituents of AA6061 are Mg and Si. This alloy is heat treatable and it derives its strength from the precipitation-hardening phase, Mg_2Si.

2.2. *Preform design*

A preform is the starting material in flow-forming. It was designed based on two factors namely maximum possible deformation and constant volume principle. These preforms were manufactured by hot forging leaving some machining allowance on external diameter and then machined to fit in the mandrel. The preforms were then annealed at a temperature of 416 °C for two different soaking times namely 60 min and 90 min and quenched in water. The flow-forming mandrel is made of tool steel. A slight taper is given in the mandrel for easy ejection of the product.

2.3. *Flow-forming*

A four-axis CNC flow-forming machine with a single roller was used to produce the AA6061 alloy tubes (Joseph Davidson et al., 2008). The roller travels parallel to the axis of the mandrel with a feed rate, V mm/min and reduces the wall thickness of the preform when a depth of cut, Dc mm is given. The depth of cut is given by maintaining the gap between the mandrel and the roller less than the thickness of the preform. The preform is reduced to a final thickness by elongating it without change in the inside diameter of the tube. Due to volume constancy, this reduction in thickness of the preform leads to an increase in length of the tube. It is desired to produce seamless tubes of maximum percentage elongation ratio and good strength with minimum or no surface damage.

3. Results and discussion

3.1. *The effect of feed rate*

Different feed rates ranging from 30 mm/min to 175 mm/min were tried. During the initial stage of deformation, a feed rate less than 50 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 the plastically deformed material, instead of flowing in the axial direction, flows in the radial direction resulting in diametral growth.

A feed rate more than 100 mm/min produced a wave-like surface. Fig. 1 shows a flow-formed tube with waviness on its outer surface. A high-feed rate makes the roller move faster through the mandrel, denying the plastic deformation. 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 30 mm/min with small depth of cut

Fig. 1 – A flow-formed tube with wave-like surface-type quality problem.

in the range of 0.1–0.3 mm is required for fine surface finish.

3.2. *Effect of depth of cut*

An optimum depth of cut is required for good surface characteristics. Depth of cuts ranging from 1 mm to 5 mm was tried. Very small depth of cut strain hardened the workpiece, resulting in fish scaling marks on the surface. Very high depth of cut retarded plastic deformation and produced highly strained roller profiles on the surface of the workpiece. Two millimeter was found to be the optimum depth of cut. A perfect extrusion-like plastic flow was felt in the gap between the workpiece 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 decrease in feed rate and increase in depth of cut in this feed rate region.

A heavier depth of cut in the final stage of flow-forming resulted in premature bursting of the tube. On the contrary, smaller depth of cut in the initial stage of flow-forming resulted in highly non-uniform deformation. The surface layers of the tube experience the bulk of the deformation while the underlying material undergoes very little deformation resulting in uneven plastic deformation in the preform–roller interface region. This uneven plastic deformation initiate cracks on the mandrel side of the tube wall. This fracture is called as central burst which can be avoided by increasing the depth of cut. A tube that faced bursting problem is shown in Fig. 2.

A small depth of cut in the range of 0.1–0.3 mm in the final flow-forming cycle was found to improve the surface finish.

Fig. 2 – A flow-formed tube with premature burst-type quality problem.

Fig. 3 – A flow-formed tube annealed for 1 h showing initial stage of fish scale.

3.3. *Effect of speed of mandrel*

A heavier speed of the mandrel 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 qualities. Also, large speed increased the adiabatic temperature of the preform resulting in plastic instability of the material. A high speed produced excellent surface finish up to a particular level and further increase in speed reduced the surface finish due to vibration problems.

3.4. *Effect of starting heat treatment condition*

An optimum annealing temperature and time is required for proper deformation and good surface quality. Different annealing times were tried on the preform. A constant annealing temperature of 416 °C was used. A preform annealed for 1 h showed fish scales and a continuous flow-forming operation performed on such a preform resulted in cracking of the tube much before the required deformation level. Tubes with fish scales are shown in Figs. 3 and 4. A preform annealed for 90 min showed good plastic deformation and excellent surface characteristics.

3.5. *Effect of starting dimension of the preform*

The starting dimension of the preform is an important parameter affecting the surface qualities of flow-formed tubes. The gap between the inside diameter of the preform and the mandrel is an important parameter that decides most of the quality

Fig. 4 – A flow-formed tube with fish scale-type quality problem.

Fig. 5 – A flow-formed tube with crack-type quality problem.

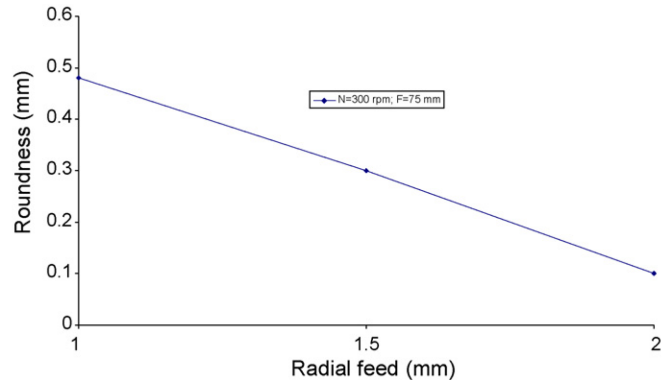

Fig. 6 – Graph showing variation of roundness error with the radial feed (depth of cut).

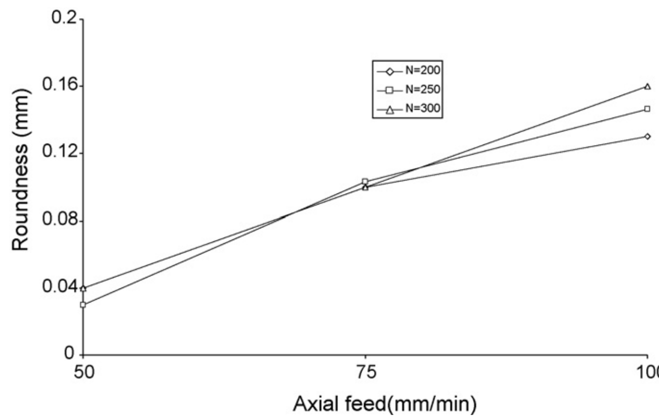

Fig. 7 – Graph showing variation of roundness error with the axial feed.

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 radial direction than in the axial 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 more than the axial direction resulting in cracking. A tube that has bulged and cracked at the end is given in Fig. 5.

3.6. *Roundness error*

The parameters that have more influence on roundness error are the depth of cut and the axial feed. Fig. 6 shows the variation of roundness with the depth of cut. Increased depth of cut was found to decrease the roundness error. The reason is that, at increased depth of cut, the preform material got deformed uniformly in between the mandrel and the roller and an extrusion-type deformation was experienced. However, a depth of cut in excess of 2 mm showed roller marks and waviness on the tube surface affecting the accuracy of the roundness values. Fig. 7 shows the variation of roundness error with the axial feed for different speed of the mandrel.

It is found that at decreased axial feed, the roundness error is less and it increases with increase in feed. Irrespective of the speed of the mandrel, the roundness error is found to be minimum at a feed of 50 mm/min.

4. Conclusions

In this research work, the flow-forming process parameters that affect the quality of flow-formed tubes were analyzed. It was found that the 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 following parameters are recommended for good quality product:

1. The preform should be annealed at 416 °C for 90 min.
2. A feed less than 50 mm/min and more than 100 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.
3. A depth of cut of 2 mm produced optimum results.
4. Too big a gap between the mandrel and the preform results in bulging of the tube which should be avoided.
5. A feed of 50 mm/min is recommended to avoid roundness error. Because, irrespective of the speed of the mandrel, the roundness error was found to be minimum at a feed of 50 mm/min. Also, an optimum depth of cut of 2 mm produced excellent roughness values.

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