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Experimental Approach to Predict the Forming Limit in Aluminum Alloy Tubes with Electromagnetic and Roll Forming Process

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Abstract: Tube compression forming is defined as the ability of a metal to deform plastically or change the shape of the tube into a new desirable shape without failure. To control the operation of tube compression forming without failure, a FLD (formability limit diagram) is invariably used to determine the acceptable range of critical deformation. Every tube has its own limit of ductility, which determines its formability and strain state. FLD can be evaluated by using theoretical, experimental and simulation approaches. In this paper, the experimental evaluation of the forming limit for an aluminum alloy tube in electromagnetic forming under various energy levels, and roll forming under different pressures, are discussed. This method allows the determination of the forming-limit, and the strain and stress diagrams. Further this study makes an analysis of the influence of the material behaviour parameters under various energy and pressure levels. It is found that the electromagnetic compression forming processed aluminum alloy tubes have good formability behaviour compared with roll compression forming.

Keywords: Aluminum alloy, electromagnetic forming, roll forming, FLD (formability limit diagram).

1. Introduction

Weight reduction in a vehicle is one of the major concerns in the automotive industry. Consequently, the application of aluminum and its alloys which provides low density and high strength- to- weight ratio, has largely increased in the automotive sector. Aluminum alloys have been the most commonly used experimental material in electromagnetic forming, because of their high electrical conductivity and formability, studied by Kleiner et al. [1]. EMF (electromagnetic forming) is a non-conventional metal working process that relies on the use of electromagnetic forces to deform metallic work pieces at high speed. EMPT (electromagnetic pulse technology) uses the stored energy from a charged capacitor bank to deliver the current to a coil. The resulting eddy current in the skin of the tube produces a repulsive force that can be used to deform or join components. Electromagnetic forming technology has unique advantages in the forming, joining, and assembling of light weight metals such as aluminum, because of improved formability, strain distribution, reduction in wrinkling, active control of spring back, minimum distortions at local features, local coining, and the use of the simple die, as broadly reviewed by Daehn et al. [2] and Seth et al. [3]. The roll forming process is one of the most commonly used techniques in the forming process to obtain a product as per the desired shape. The roll forming process is used mainly due to its easiness in forming useful shapes such as tubes, rods, and sheets.

Fjeldbo et al. [4] revealed that the tube is formed by the hydro forming process using aluminum alloy

(AA6063); they also conducted the numerical and experimental study of the tube forming process. In this paper, the expansion of the tube using a mandrel and hydro forming process is carried out. The results show good correlation with the standard values. Lindgren [5] revealed that the experimental and computational investigations show that the roll forming process is feasible to develop the profiles successfully, on the complex geometries in high strength steels. Further, the finite element simulation can be a useful tool in the design of the roll forming process. The modelling and simulation of the process were carried out to create an FE model, and to improve the simple theoretical models, thereby providing a better design of the roll forming process.

Kore et al. [6] reported about the feasibility of electromagnetic impact welding of Cu-to-Cu sheets by using Al as the driver sheet. A study has been carried out to characterize the electromagnetic impact welding of 0.5 mm thick Cu sheets. The results of the microstructure and tensile shear strength tests are reported. The tensile shear strength of the Cu-to-Cu EM weld was stronger than that of the parent metal. The SEM analysis of the EM weld of Cu- to-Cu sheets confirmed the continuity of metal between the two welded sheets. It showed the wavy interface at the weld zone, and the entrapped oxide and other impurities at the no weld zone. The compressed grains at the interface led to an increase in the strength of the EM weld over the parent metal.

Vivek et al. [7] reported that the diameters of high strength steel tubes could be reduced in a nearly axisymmetric manner by the standard electromagnetic forming process. The velocity, primary current, secondary current and temperature changes were measured during the experiment. The experimental data were compared with a numerical model. With these observations, some of the practical limitations in reducing tube diameters were addressed. It was reported that increasing the forming energy or reducing the compressed length, effectively increased the extent of tube diameter reduction.

Abdelhafeez et al. [8] compared two hardening material models that were used in previous research. The comparison was made between the results of the numerical simulations and the experimental results obtained from literature. The used FE model is based on the modified loose coupling scheme. The simulation results reveal that the rate dependent power law hardening model gives the most accurate results with small average deviation, compared with the experimental data. It reveals also that modified loose coupling between the mechanical and electromagnetic aspects is an efficient tool for getting accurate simulation results within a short time.

The forming limit diagram is a representation of the critical combination of the two principal surface strains, major and minor, on the tube specimens formed with the onset of necking, and beyond which there is a risk of localized necking. The FLC (forming limit curve) provides excellent guidelines for deciding the material for the forming, tooling and tribological conditions, described by Keeler et al. [9] and Goodwin [10]. The acceptable area is under the forming limit curve and the fail area above it. In this paper, the FLDs of electromagnetic and roll forming processed aluminum alloy tubes, are obtained experimentally using the Goodwin and Keeler theory.

2. Experimental Procedure

2.1 Specimen Preparation

The chemical compositions of the aluminum alloy tubes used in the experimental study are shown in Table 1.

Grid circles of 5 mm diameter were initially photo gridded on the tube surface of the specimens for the purpose of strain measurements. Fig. 1 shows the view of grid marking on the tube. The various energy levels used in the electromagnetic forming, and the different pressures used in the roll forming of an aluminum alloy AA6101 seamless tube of 40 mm diameter and thickness of 2 mm, are shown in Table 2.

Table 1 Chemical compositions of aluminum alloy AA6101.

Material	Fe (%)	Si (%)	Mn (%)	Cu (%)	Ti (%)	V (%)	Pb (%)	Mg (%)	Ni (%)	Cr (%)	Al (%)
Aluminum alloy (6101)	0.209	0.384	0.020	0.002	0.002	0.010	0.023	0.387	-	-	Rem.

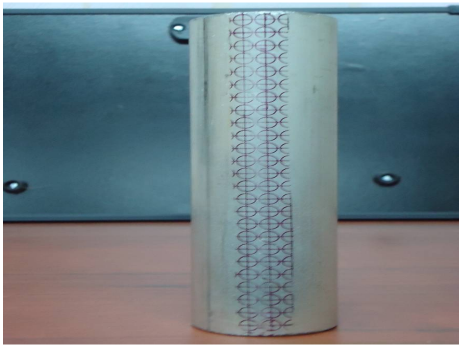

Fig. 1 View of grid marking on the AA 6101 tube.

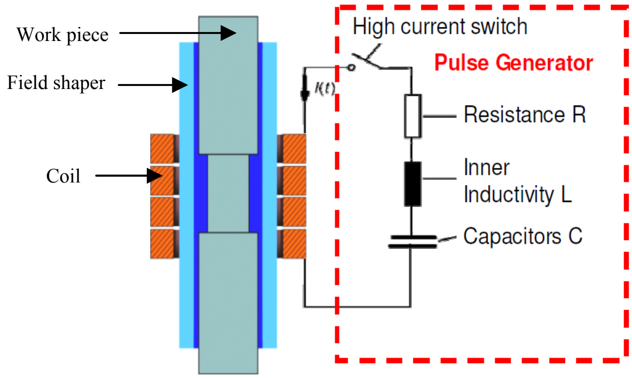

Fig. 2 Schematic representation of the electromagnetic forming setup.

Table 2 Process parameters for the study.

SI. No.	Electromagnetic forming	Roll forming
	Types of process	
	Process parameters	
	Energy levels (kJ)	Pressure levels (kg/cm^2)
1	6	14
2	10	21
3	12	28
4	14	35
5	18	42

2.2 Electromagnetic Forming Process

Electromagnetic forming systems consist of three major parts: the capacitor banks, a coil and a field shaper. The schematic diagram illustrating the experimental set-up is shown in Fig. 2. The capacitor banks used in the experiments are capable of discharging within microseconds. A capacitor bank has the maximum capacity of 20 kJ with the maximum charging voltage of 10 kV. This unit has a total capacitance of 400 µF, and an internal inductance which is proprietary, and is switched by 4 ignitron switches that are located on each of the 4 capacitor banks.

The custom solenoid coil was fabricated by PSTproducts, GmbH, Alzenau, Germany [11]. The coil was based on a 4-turn helix of copper, aluminum and reinforced plastics, that were potted in a filament wound composite casing. It was designed to withstand a maximum electromagnetic pressure of 110 MPa. The inner diameter and the working height of the coil were 154 and 134 mm, respectively. A field shaper made of aluminum was used. A tape with enough dielectric strength was applied around and inside the field shaper to prevent arcing. Energy levels lesser than 6 kJ were not considered, as they had no appreciable formability. The maximum energy was limited to 18 kJ, as further increase in the energy level would have caused failure. Hence, experiments were conducted at energy levels 6, 10, 12, 14 and 18 kJ. The electromagnetically compressed aluminum alloy tube specimen at a forming energy of 18 kJ is shown in Fig. 3.

2.3 Roll Forming Process

In roll forming, the rollers act as a die to form the required shape of the tube. It is made of mild steel to withstand the high load. It consists of two rollers, namely, an inner and an outer roller. The experimental set up of the roll forming process is shown in Fig. 4.

The aluminum alloy AA6101 tube is placed over the shaft and the inner roller. The tube lies in between the rollers (Inner and Outer) and the formable portion is placed properly over the inner roller. In the rolling operation, the outer roller is moved in the Y-direction

Fig. 3 Electromagnetically deformed tube specimen at a forming energy of 18 kJ.

Fig. 5 Roll forming test specimen at a forming pressure of 42 kg/cm^2.

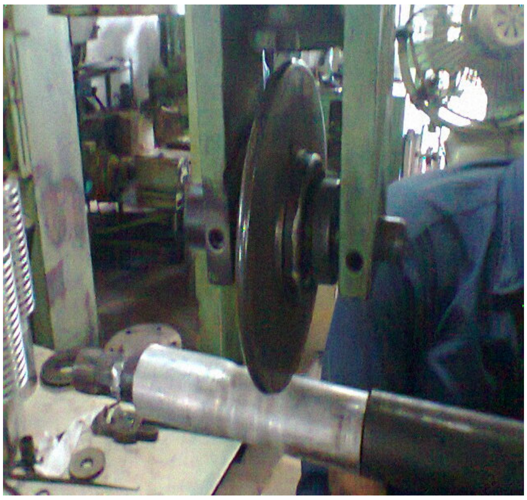

Fig. 4 Experimental set up of the roll forming process.

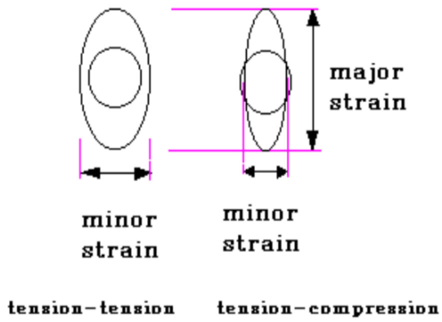

Fig. 6 Major and minor strain measurement.

$$\text{Major strain} = \frac{(\text{major axis length} - \text{original circle dia})}{\text{original circle dia}} \times 100 \quad (1)$$

$$\text{Minor strain} = \frac{(\text{minor axis length} - \text{original circle dia})}{\text{original circle dia}} \times 100 \quad (2)$$

to provide the required pressure from the hydraulic cylinder and its capacity of 0.1 to 50 kg/cm^2. This process is carried out till the required shape of the tube is obtained. Pressure levels less than 14 kg/cm^2 were not considered as they had no appreciable formability. The maximum energy was limited to 42 kg/cm^2 as further increase in the pressure level caused failure. Hence, experiments were conducted at pressure levels 14, 21, 28, 35 and 42 kg/cm^2. The roll forming compressed aluminum alloy tube specimen at a forming pressure of 42 kg/cm^2 is shown in Fig. 5.

When a tube is deformed by the electromagnetic and roll forming process, the grid circles changed into ellipses of different sizes. The major and minor strain measurement is shown in Fig. 6, and the formula is expressed in Eqs. (1) and (2):

3. Results and Discussion

The values of the major and minor strains determined experimentally are shown in Table 3.

The experimental forming limit curves of the aluminum alloy, using the electromagnetic and roll forming process, are shown in Figs. 7 and 8. Fig. 7 represents a typical FLD for the electromagnetically formed aluminum alloy AA6101 tubes. It can be seen from the shape of the FLD in Fig. 7, that the acceptable component is obtained without failure through the electromagnetic forming process, and the corresponding major and minor strain limits are 9% and –15.6%. Fig. 8 represents a typical FLD of the roll formed aluminum alloy AA6101 tubes. It can be seen from the shape of the FLC in Fig. 8, that the acceptable

Table 3 Strain distribution in the electromagnetic and roll forming process.

SI. No	Strain distribution for electromagnetic forming specimen at a forming energy of 18 kJ		Strain distribution for roll forming specimen at a forming pressure of 42 kg/cm^2	
	Major strain (%)	Minor strain (%)	Major strain (%)	Minor strain (%)
1	3	-8	7	-5.6
2	4	-9.6	9.6	-9.2
3	6	-12	12	-10.8
4	8	-14	13.2	-13.6
5	9	-15.6	13	-20.8

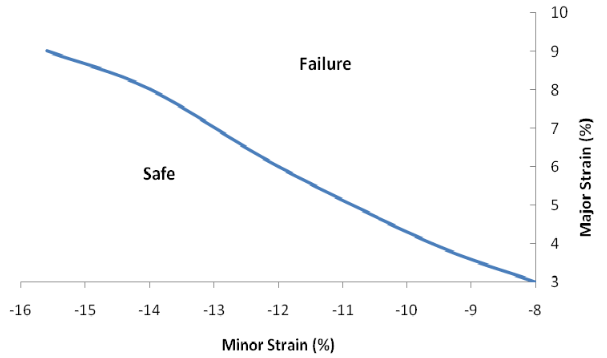

Fig. 7 Strain distribution for the electromagnetic formed AA6101 specimen at an energy of 18 kJ.

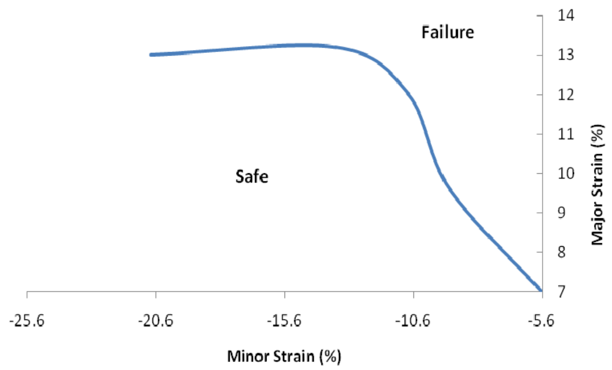

Fig. 8 Strain distribution of the roll formed AA 6101 specimen at a pressure of 42 kg/cm^2.

component is obtained with the possibility of failure in the roll forming process and the corresponding major and minor strain limits are 13% and –20.8%. The strain state above the FLD shows the likely failure zone, and the points below this curve are the safe zone. In the EMF, the tube ductility increases with the applied energy of 18 kJ, while in roll forming the ductility limit is lower with a high strain state. This enables the enhancement of the formability of the tube in the EMF of about 4% compared to the roll forming process.

4. Conclusions

EMF (electromagnetic forming) processes are known to increase significantly the ductility of aluminum alloys. The goal of the present work is to make a comparison of the formability behavior of the electromagnetic and the roll compression forming processes of aluminum alloy tubes. This work provides an experimental study for the determination of the FLD, using the Goodwin and Keeler theory. It is observed from the study, that the electromagnetic forming processing of an aluminum alloy tube improves the formability of the material with an improved strain state when compared to the roll forming process. The present experimental comparison between the electromagnetic and the roll forming process based on the FLD concept shows the EMF to achieve forming with better ductility limits.

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