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Experimental Study on Warm Incremental Tube Forming of AA6063 Aluminum Tubes

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ABSTRACT

Effect of temperature on formability of AA6063 aluminum tubes in incremental forming process was investigated. Experiments are performed on AA6063 aluminum tubes. A spirally moving tool incrementally expands the tube wall. The tube is clamped from both ends while the deformation zone is not in contact with the die. A circumferential heating system is used to heat the tube due to the low formability of aluminum alloys at ambient temperature. The effects of process parameters including temperature, radial feed, axial feed and tool linear velocity are investigated in order to obtain the highest formability and surface quality. The results show that with a temperature rise from 100°C to 300°C, the expansion ratio increases from 28% to 34%. Axial feeding and temperature are the most effective parameters on the surface roughness and bulge diameter, respectively.

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1. INTRODUCTION

Single-point incremental forming (SPIF) process is a technique for forming of sheet metals in job shop manufacturing, especially for rapid prototyping [1]. The sheet is first clamped along its circumference using a fixture or a blank-holder. Then a forming tool, usually having a spherical tip, contacts the sheet and moves incrementally along a predetermined path to form a desired shape. Tool rotational speed, linear velocity, and feeding depth are the most important parameters affecting the formability, surface roughness and thickness distribution of the product. This process has been considered by researchers to produce prototype sheet metal parts because of its high flexibility and low production cost [2].

Aluminum alloys exhibit low formability at room temperature. Therefore, high temperatures are typically used to enhance their formability. The single-point incremental forming of different materials at elevated temperatures has been studied by several researchers. Ambrogio et al. [3] showed that the highest formability of AZ31 magnesium alloy in incremental forming is achieved at 250°C. Ji and Park [4, 5] numerically and experimentally studied the incremental forming of magnesium sheets at various temperatures up to 250°C. They concluded that the highest formability was obtained at 150°C. Fan et al. [6, 7] used electric current for heating the sheet in incremental forming process.

Zhang et al. [8] showed that the anisotropy effect on the surface quality of the AZ31 sheets is decreased by increasing the temperature during the incremental forming. Kim et al. [9] increased the limit drawing ratio (LDR) of magnesium products using a localized heating and cooling technique. Al-Obaidi et al. [10] investigated the incremental forming of high-strength steels with the local heating at the tool/sheet contact point using an induction coil. They showed that the forming angle is increased in addition to the reduction of the forming force. Galdos et al. [11] used hot fluid to achieve a uniform temperature distribution in incremental forming of magnesium sheets. Based on their results, the maximum formability of AZ31 alloy obtained by this heating method is 250°C. VanSy and ThanhNam [12]

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incrementally formed AZ31 and AA5055 sheets at high temperatures and examined the effect of temperature on the surface quality of the products.

Metal tubes are widely used in the construction of lightweight structures [13]. One of the widely used processes for changing the cross-sections of metal tubes is the tube hydroforming process (THF). In this process, the internal pressure and feed loading paths have a significant effect on the formability. Seyedkashi et al. [14] used the simulated annealing (SA) optimization method to achieve the highest expansion ratio in the hydroforming of copper tubes. Elevated temperatures are also used in this process to increase the formability. Several heating mechanisms have been used in the THF process, such as hot fluid bath [15], induction coil and heating element in the fluid [16], and using a preheated fluid [17]. However, in addition to the sealing problems and the need for high fluid pressure, the warm hydroforming process has a temperature limitation due to the maximum temperature of the available fluids.

It is also possible to form metal tubes using a single-point incremental tube forming (ITF) process. For this purpose, a rotary tool changes the tube cross-section by moving along a predetermined path inside or outside of the tube. This process can be very effective, especially for the production of centrally bulged tubular products. There is limited literature about ITF process. Several researchers have focused on incremental forming of a flange on the perforations formed on the tube surface. Teramae et al. [18] investigated the forming of flanges on the tube numerically and experimentally. According to their results, by increasing the work hardening exponent of the material, the thickness distribution in the formed flange becomes more uniform. Yang et al. [19] showed that the flange dimension depends on the tube diameter and the hole size. Wen et al. [20] carried out the ITF process under four different conditions and compared the produced parts with die casting. Seyedkashi et al. [21] performed free bulging of copper tubes by incremental tube forming, and studied the effect of process parameters on the thickness distribution and surface roughness. Rahmani et al. [22] experimentally studied the incremental tube forming to convert copper circular tubes into square cross-sectional parts. In addition, quantifying the residual stresses, is a key step in determination of the integrity of engineering and structural components. Faghidian et Al. [23] predicted the residual stresses by elastic–plastic bending using an approximate analysis and the finite element method. Axisymmetric bulging of tubes can be done using different processes. Rubber pad forming is one of these processes which can be used for axisymmetric bulging of tubes [24]. In the tube hydroforming process, quality of final product depends on forming parameters like internal pressure and axial feeding [25]. Many researchers have investigated the bulging of tubes using hydroforming process.

In this paper, the axisymmetric bulging of aluminum tubes using the warm incremental tube forming (WITF) is proposed. The forming tool moves spirally inside the tube and incrementally increases its diameter at each step. During the forming process, the middle part of the tube is free without any contact with the die. The effects of different process parameters, such as temperature, radial feed, axial feed, and linear velocity of the tool, have been experimentally studied. The radial feed is increased until the tube rupture. After the forming process, the final tube length, the inner surface roughness, and the maximum bulge height before rupture are measured and the effects of studied parameters on these responses are compared.

2. MATERIAL AND METHODS

Aluminum tubes used in this research are made of AA6063 alloy and have an outer diameter of 40 mm, initial thickness of 1.5 mm and initial length of 60 mm. The seamless tubes had been produced by extrusion. Chemical composition of AA6063 is given in Table 1.

There is no limitation on the cross-sectional shape of the final piece in the ITF process. Even an asymmetric cross-section can be formed. The forming tool is mounted on a CNC milling machine and the die assembly is clamped to the machine table. At the beginning, the forming tool enters into the tube and stops where the bulge is about to start. Then, it moves radially and causes the tube to deform. This amount of radial movement is called "radial feed, F_r". The longitudinal tool axis always remains parallel to the tube axis. Then, the forming tool moves spirally along the tube free length. Therefore, the free section of the tube will expand. In this research, the tool is not rotatable. The tool's linear velocity is constant along the path. This value is one of the most important parameters affecting the process. Due to the free space between the top and bottom dies, various shapes can be produced based on the tool path. "Axial feed, F_a" is the distance that the tool moves along the tube axis in each rotation, same as the "pitch" in a spring. After the first forming stage, the tool vertically returns to the initial starting point. If higher expansion is required, the next stage begins again with subsequent radial feed and spiral movement. In order to increase the dimensional accuracy of the corner fillets of the final product, the tool starts and ends each stage with a full circular movement without any axial feed.

TABLE 1. Chemical composition of tube material

Al	Mg	Si	Fe	Zn	Cu	Mn	Pb	Ti	Sn	Ni	Ga
Base	0.47	0.44	0.30	0.08	0.06	0.03	0.03	0.03	0.017	0.02	0.01

Figure 1 shows the experimental setup and tool path. Two ends of the tube are placed in the upper and lower clamps (die). The height of each die is 20 mm and the inside diameter is equal to the outer diameter of the tube. So, the radial movement of the tube is restricted by the die, while its axial movement is limited only by friction force at the tube/die interface. The tube is heated by a ceramic heating element which is shown in Figure 1(a).

The main objective of this paper is to investigate the effects of process parameters on the final form of the aluminum tubes in the incremental forming process. For this purpose, important parameters including temperature (T), radial feed (F_r), and axial feed (F_a) are selected at different levels. Then, the forming process has been performed. The full factorial design of experiments (DOE) is used to study all the main effects and interactions of effective parameters. Three levels are considered for each parameter as shown in Table 2. Hence, 27 experiments are needed to be performed with three replications. The linear velocity of the tool is held constant at 800 mm/min. Three responses are also considered; tube length (L), surface roughness (R_z) and maximum bulge (D) after forming.

Based on the experimental tests and measurements, the obtained response values for each treatment are presented in Table 3.

3. RESULTS AND DISCUSSION

Three samples formed at different temperatures with axial and radial feeds of 0.5 mm are compared in Figure 2. By increasing the temperature, the bulge height increases, but the tube length decreases.

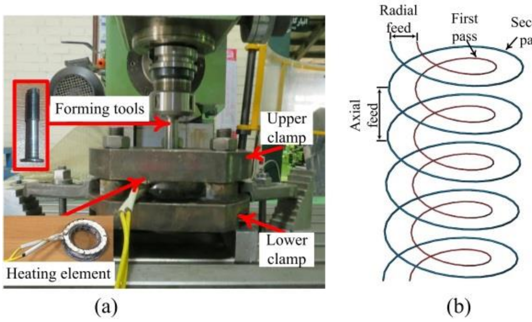


Figure 1. a) Experimental setup; b) Tool path

TABLE 2. Input parameters and their levels

Parameter	Level 1	Level 2	Level 3
Axial feed, F_a (mm)	0.5	1	1.5
Radial feed, F_r (mm)	0.5	0.75	1
Temperature, T (°C)	100	200	300

TABLE 3. Tube length, diameter and roughness values obtained in experiments

Factors			Responses		
T (°C)	F_a (mm)	F_r (mm)	L (mm)	D (mm)	Rz (μm)
300	0.5	1	60.3	54	6.91
300	1	1	60.18	53.5	7.9
200	1	0.75	61.35	51.95	7.34
300	0.5	0.75	61.1	54.57	6.84
100	0.5	0.75	62.11	52.05	5.02
200	0.5	0.5	61.6	53.54	5.45
100	1.5	0.75	61.83	51.56	7.32
200	1.5	1	60.64	50.7	7.98
200	0.5	0.75	61.2	53.02	5.92
200	0.5	1	60.8	52	6.327
100	1	1	61.7	50.22	6.51
200	1	1	60.85	50.75	7.64
300	1	0.75	60.85	54.02	7.92
200	1.5	0.5	61.5	51.9	7.74
300	0.5	0.5	61.15	54.69	5.83
100	0.5	0.5	62.74	52.82	4.75
300	1.5	0.75	60.8	53.28	8.34
300	1	0.5	61.25	54.44	7.83
300	1.5	0.5	61.4	52.76	8.14
100	1.5	1	61.05	50.3	7.98
100	1	0.75	62	50.62	5.92
100	1	0.5	62.4	51.08	5.56
200	1	0.5	61.51	52.7	7.49
300	1.5	1	60.56	51.48	8.78
100	1.5	0.5	62.54	51.66	6.62
100	0.5	1	61.7	51.01	5.55
200	1.5	0.75	60.96	51.3	7.82

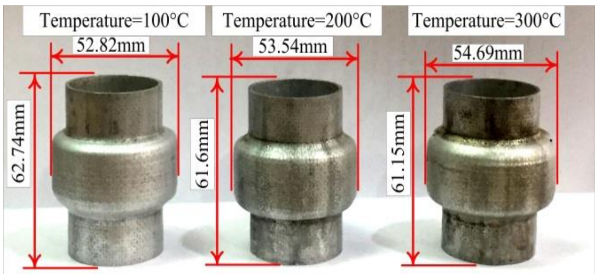


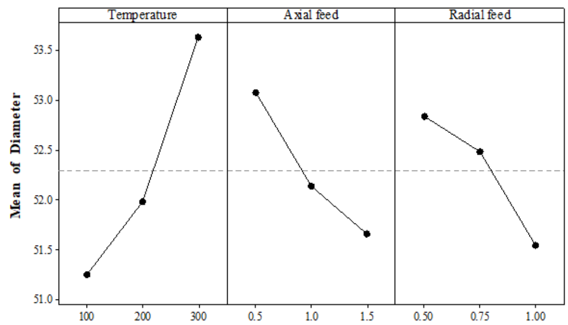
Figure 2. Bulge diameter and length of the formed samples at different temperatures

Table 4 shows the analysis of variance (ANOVA) table for the parameters affecting the bulge diameter. The most important parameter which is critical for interpretation is P-value. The others are used mainly for intermediate computational purposes. If the p-value is less than the significance level of 0.05, the corresponding parameter is statistically significant.

Temperature is the most effective parameter on the bulge diameter with a contribution of 54.96%, while radial feed has the lowest effect with a 16.45% contribution. As shown in Figure 3, bulge diameter is also increased by increasing the temperature. Nevertheless, the increase in diameter is doubled with the temperature change from 200 to 300 °C compared to the temperature change from 100 to 200 °C. This happens due to the changes in aluminum microstructure at about 300 °C, which alter its mechanical properties. By increasing the axial feed, the bulge diameter is reduced. The rupture of all specimens occurs near the upper side of the bulge. The lower the axial feed, the more uniform thickness distribution in a longitudinal direction is. However, when the axial feed is increased, the tube wall in the corner becomes more elongated and thinning increases. The radial feed effect is similar to that of the axial feed, and the tube formability is decreased with its increase (see Figure 3).

TABLE 4. ANOVA table for the bulge diameter

	DF	Seq SS	Contrib. %	Adj SS	Adj MS	F-Value	P-Value
T	2	26.777	54.96	26.777	13.388	145.67	0.000
F_a	2	9.353	19.20	9.353	4.676	50.88	0.000
F_r	2	8.013	16.45	8.013	4.006	43.59	0.000
$T \times F_a$	4	3.103	6.37	3.103	0.775	8.44	0.001
Er.	16	1.471	3.02	1.471	0.091		
R^2			98.34				



(a) (b) (c)

Figure 3. Effect of a) temperature, b) axial feed and c) radial feed on the bulge diameter

According to Table 4, the interaction between temperature and axial feed on the bulge diameter has a high significance as shown in Figure 4. Here, it is seen that the highest bulge diameter is achieved when the process is carried out at the highest temperature and the lowest axial feed. In fact, the material is in its highest formable state by choosing these values, because the fracture strain is increased at higher temperatures. On the other hand, by decreasing the axial feed, the forming velocity and hence the strain rate decreases.

Table 5 shows the effects of process parameters on the final length of the samples. Temperature and radial feed have a high level of significance, while the axial feed is not significant.

As shown in Figure 5(a), the length of the formed specimens is reduced when temperature increases. This is consistent with the increase in the bulge diameter at high temperatures. The higher the temperature, the higher the amount of material flow between the dies is. Thus, the sample length decreases. The decrease of the sample length by increasing the temperature can also be related to the increase of friction coefficient at high temperatures, as explained before.

According to Figure 5(b), the axial feed has no considerable effect on the tube length after the forming. Based on Figure 5(c), the tube length decreases when the radial feed increases.

One of the important issues in incremental forming is the surface roughness of the formed section. The internal surface roughness increases due to the contact with the

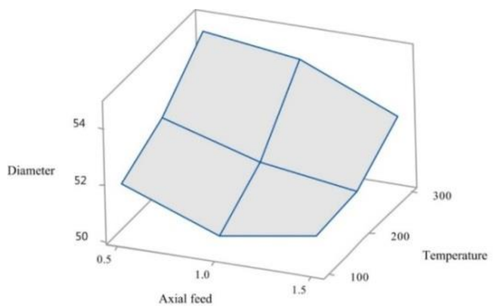
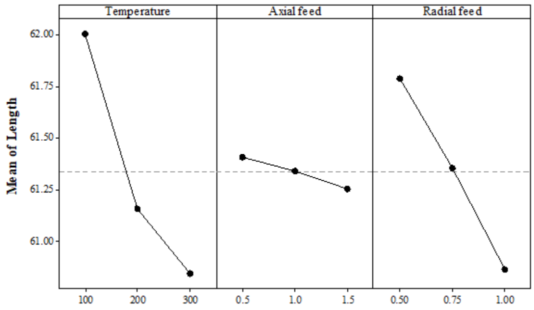


Figure 4. The interaction effect of axial feed and temperature on the bulge diameter

TABLE 5. ANOVA results for the final tube length

	DF	Seq SS	Contrib. %	Adj SS	Adj MS	F-Value	P-Value
T	2	6.5355	58.80	6.5355	3.26775	104.44	0.000
F_a	2	0.1128	1.01	0.1128	0.05638	1.80	0.191
F_r	2	3.8417	34.56	3.8417	1.92083	61.39	0.000
Er.	20	0.6257	5.63	0.6257	0.03129		
R^2			94.37				



(a) (b) (c)

Figure 5. Effect of a) temperature, b) axial feed and c) radial feed on the final tube length

tool. The average roughness (R_z) of the tubes before forming was 0.83 μm.

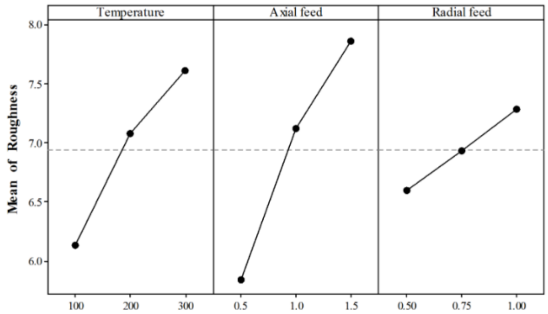
According to Table 6, the analysis of variance for surface roughness shows that in addition to the significance of the main parameters, the interaction between temperature and axial feeding is also significant. In terms of the relative importance of input parameters, axial feed with a 57.23% contribution is the most influential parameter on surface roughness, while the contribution of temperature is 30.68%, radial feed 6.47%, and the interaction of temperature and axial feed 2.51%.

As shown in Figure 6(a), surface roughness is increased by increasing the temperature. This increase can be related to the amount of friction at the tube/tool interface which depends on the temperature. The coefficient of friction increases at higher temperatures, hence the surface quality decreases. In fact, the higher the linear velocity of the tool, the longer the tube will remain at a high temperature creating more coarse grains. As shown in Figure 6(b), the surface roughness increases by increasing the axial feed. Figure 6(c) shows that increasing the radial feed leads to higher surface roughness, but the effect of this parameter is far less than temperature and axial feed. The higher the radial feed, the larger the contact area of the tube/tool is, which leads to a decrease in the surface quality.

TABLE 6. ANOVA table for surface roughness

	DF	Seq SS	Contrib. %	Adj SS	Adj MS	F-Value	P-Value
T	2	10.0209	30.68	10.0209	5.0104	79.16	0.000
F_a	2	18.6920	57.23	18.6920	9.3460	147.66	0.000
F_r	2	2.1131	6.47	2.1131	1.0565	16.69	0.000
$T \times F_a$	4	0.8213	2.51	0.8213	0.2053	3.24	0.040
Er.	16	1.0127	3.10	1.0127	0.0633		
R^2			96.90				

Figure 7 shows the interaction between axial feed and temperature. As the axial pitch increases, a more heterogeneous and non-uniform deformation occurs in coarse grains, and the surface roughness is increased. If the goal is to achieve a high surface quality, the lowest temperature and axial feed should be used. However, it should be noticed that lower temperatures reduce the formability.



(a) (b) (c)

Figure 6. Effect of a) temperature, b) axial feed and c) radial feed on surface roughness

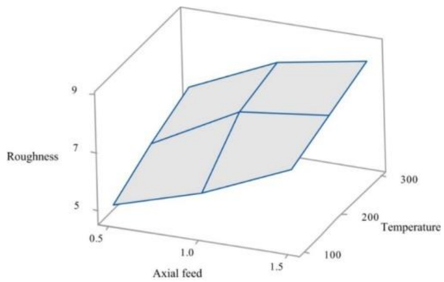


Figure 7. Interaction effect of axial feed and temperature on surface roughness on the bulge diameter

4. CONCLUSIONS

In this paper, warm incremental tube forming process was used to create an axisymmetric bulge in AA6063 aluminum tubes. The tubes are uniformly heated to increase the formability.

The maximum expansion of 36.7% was achieved at 300°C. Temperature, axial feed and radial feed are the most effective parameter on the bulge height, respectively. To achieve the maximum bulge diameter, the lowest axial and radial feeds should be used. According to the experiments, there is no significant relation between the bulge diameter and the final tube length. The radial feed has the largest effect on the tube length, while the axial feed is not significant. On the other hand, the results show that the axial feed is the most important parameter affecting the surface roughness. The friction between the tool and the tube is increased by temperature, hence increases the surface roughness.

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Persian Abstract

چکیده

روش جدیدی برای شکل‌دهی یک برآمدگی مطلوب با استفاده از فرآیند شکل‌دهی تدریجی گرم لوله بررسی شده است. آزمایش‌های تجربی روی لوله‌های آلومینیومی AA6063 صورت گرفته است. در این روش، یک ابزار چرخان با حرکت مارپیچ خود و به‌صورت تدریجی، دیواره‌ی داخلی لوله را بسط می‌دهد. در زمان انجام فرآیند شکل‌دهی، لوله از دو انتها مهار شده و در ناحیه‌ی تغییر شکل، سطح خارجی لوله با قالب در تماس نمی‌باشد. به دلیل پایین بودن شکل‌پذیری آلیاژهای آلومینیوم در دمای محیط از یک سیستم گرمایش محیطی برای ایجاد توزیع دمای یک‌نواخت در سطح لوله استفاده شده است. به منظور دست‌یابی به بیشترین شکل‌پذیری و بالاترین کیفیت در قطعات، اثر پارامترهای فرایند شامل دما، تغذیه‌ی شعاعی، تغذیه‌ی محوری و سرعت خطی حرکت ابزار بر نتایج بررسی شده است. نتایج نشان می‌دهد که با افزایش دما از ۱۰۰ به ۳۰۰ درجه، نسبت انبساط متوسط لوله‌ها از ۲۸٪ به ۳٤٪ رسیده است. تغذیه‌ی محوری و دما به ترتیب مؤثرترین پارامترها بر زبری سطح داخلی لوله و قطر برآمدگی می‌باشند.