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ORIGINAL ARTICLE

A new approach in producing metal bellows by local arc heating: a parametric study

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Abstract Recently, dieless forming processes have been introduced to prevent the high costs of dies and tools. Local heating and axial compression process is an innovative method for producing metal bellows. In this research, producing metal bellows using simultaneous local electric arc heating and axial compression has been explained and investigated. SUS304 tubes with an outer diameter of 19 mm and a thickness of 1 mm have been employed to implement the tests. Various parameters could affect the process. Among these parameters, effects of applied displacement and device current, influencing convolution shape, thickness, and required forming force, are studied experimentally. It is found that the height, radius, and angle of the convolution and also the forming force could be controlled by alteration of these parameters. Furthermore, the result of buckling test showed that energy absorption capacity of the manufactured metal bellow has been increased in comparison to a typical tube. This method could be a suitable alternative for induction local heating and can reduce the high equipment costs.

Keywords Metal bellows · Local heating · Electric arc heating · Dieless forming

1 Introduction

Metal bellows are thin-walled wavy tubes which are used for flexibility when exposed to axial loads, internal pressures, and bending moments [1]. Actually, they possess elastic properties and are used mostly to improve high-temperature capabilities, strength, and flexibility. Both mechanical vibrations and dimension changes occurred by heating and cooling can be absorbed by means of these tubes [2]. Recently, there has been an increasing demand of using the metal bellows in medical equipment and small sensors [3]. Thus, various shapes of them are needed for different applications. SUS304 and 316 austenitic stainless steels are usually used materials for metal bellows. Besides, titanium alloys, nickel-based alloys, Monel, Inconel, and Hasteloy can be used in particular applications [4, 5]. General production methods for metal bellows contain welding, machining, and forming. Welded metal bellows are formed by welding pairs of washer-shaped discs of thin sheet metal [6]. Some of the bellow-forming processes need dies and tools such as: hydroforming [7], tube bulging and folding [8], combination process of bulging and upsetting [9], gas bulging at elevated temperatures [10], and roll-type incremental forming [11]. Because of high cost of dies and leakage problems, dieless forming processes have been developed [12]. Development of semi-dieless forming using local heating technique [13], experimental study of incremental forming of metal bellows by high-pressure waterjet [14], investigation of deformation behavior of aluminum alloy tube in semi-dieless metal bellow forming [15], and development of the dieless metal bellow forming [16], have been conducted during recent years.

There are various methods for local heating used in different forming processes. Laser heating system causes increased formability in incremental sheet metal forming [17] and spinning processes [18]. Moreover, local heating using near-infrared rays has been proposed as a forming process in order to decrease springback and increase hardenability of non-quenchable steels [19]. Additionally, electromagnetic induction is a method for desired heating. An

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induction heating system is composed of induction coil, an alternating-current power, and a workpiece [20]. In recent studies, the induction local heating has been utilized to produce metal bellows [13, 15, 16].

An electrical arc is formed between an electrode and the workpiece in arc welding processes. The welding arc is a sustained electrical discharge through high-temperature conducting plasma which produces sufficient thermal energy for joint metals by fusion [21]. In this paper, a cost-effective alternative method has been proposed for heating, i.e., implementing the electric arc heating method in dieless metal bellow-forming process. By applying the arc on the rotating tube, the yield stress of a narrow part of the workpiece reduces. Then, the tube was subjected to axial compressive force resulting in occurring buckling in the heated region. Hence, the convolutions could be formed one by one. The purpose of this study is to introduce a new local heating method in dieless metal bellow forming. Firstly, the materials and experimental setup have been declared. Next, the effective parameters of the process have been investigated, such as applied displacement and device current. In addition, a bucking test has been done, and the results have been compared with the results of a typical tube. The tests have been performed on stainless steel SUS304 tubes with an initial outer diameter of 19 mm and a thickness of 1 mm.

2 Material and methods

This article describes electric arc local heating method used in metal bellows dieless forming process. Firstly, the tube was mounted on a rotator and arc torch was placed next to the tube with a specific distance. Then, arc generator was activated while the tube was rotating at 500 rpm. The electric arc generated and exerted heat on the tube like a ring. Finally, by decreasing flow stress in the heated region, the axial compressive force was exerted on the free end of the tube simultaneously causing buckling. After formation of the first convolution with desired dimensions, the electric arc and the axial force were removed to prevent extra deformations. When the deformed area was cooled, further convolutions were created in a similar way by moving the torch in an axial direction (in this study, the distance between heating regions was 14 mm). The convolutions were considered to be equidistant since the aim of this paper is to introduce a new method. A load cell was settled between the free end of the tube and location of applying force for the required forming process force to be measured. A schematic view of the apparatus is illustrated in Fig. 1.

SUS304 steel tubes with a height of 100 mm, outer diameter of 19 mm, and thickness of 1 mm were used in the experiments. Generator voltage and the gap between torch and the tube were 85 V and 5 mm, respectively. Various parameters could affect the convolution shape including material, diameter, initial thickness, torch gap, rotator speed, applied displacement, and device current. By performing initial tests as a screening phase, it was observed that in order to form a uniform-heated ring on the tube, the rotator speed must be greater than a specific amount. In this experiment, the least amount for the rotator speed to form a uniform-heated ring was 500 rpm. In further experiments, it was perceived that augmenting the rotator speed to more than 500 rpm did not affect the tubes geometry and the required forming force remarkably. Also, there is a standard electrode gap in which the arc plasma occurs using of a specific voltage and electrons could flow [21]. Based on the mentioned standard, the gap distance was fixed on 5 mm. Evidences demonstrate that applied displacement and device current are more effective in the proposed process. Hence, other parameters for the forming process were considered constant for all of the experiments like rotator speed and torch gap, and influences of the two parameters on the convolution shape, thickness distribution, and maximum required force for forming were examined.

To study the effect of applied displacement, displacements of 1, 2, and 3 mm were applied to the free end of the tube, while the device current was set to 70 A. Moreover, in order to examine the effect of device current, currents of 50, 70, and 80 A were used, while the displacement was set to 3 mm. It should be mentioned that six convolutions have been made on a tubes for each test by fixed and variable parameters.

To compare the energy absorption capacity of fabricated metal bellows and a typical tube, a compression test was performed for a sample with speed of 5 mm/min (compression machine type: SANTAM-STM-50). Table 1 illustrates the carried out tests in the experiment.

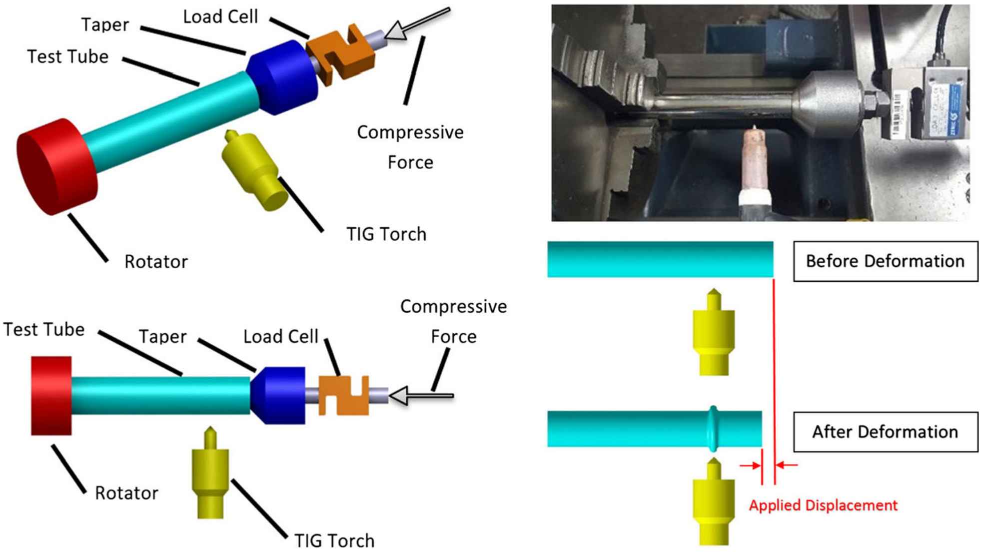
3 Results and discussion

Effects of the parameters on the shape (height, outer and inner diameters, tip angle, and thickness distribution) and required force for forming will be discussed. Eventually, compression test (buckling test) results of a produced metal bellow will be compared with that of a typical tube having the same length.

3.1 Effect of applied displacement

Three tubes were produced using constant current and different displacements as illustrated in Fig. 2. The convolution height in tubes (a), (b), and (c) is 2.74, 3.31, and 3.99 mm, respectively. These values show that the convolution height increases by augmentation of the applied displacement. As it is evident in Fig. 2, convolution pitch decreases by increasing the applied displacement, and actually, the convolutions become closer to each other. The effect of the applied displacement on the convolution shape is presented in Fig. 3.

Fig. 1 Schematic view of the apparatus used in dieless metal bellows forming process (applied displacement: displacement along longitudinal axis of the tube by applying compressive force)



According to Fig. 3, by increasing the applied displacement outer and inner curvature radius and tip angle of convolution have been decreased.

Figure 3 indicates that more material flows by increasing the applied displacement and height of the convolution increases. Therefore, by enhancing the material flow in radial direction, the convolution tip becomes sharper. Thus, both the tip angle and convolution radius diminish.

High-quality pictures of the convolutions were taken for the bellows produced using 70 A current and wall thickness of the convolutions was measured. Thickness distribution around the crown point is displayed in Fig. 4. In spite of other typical manufacturing methods, like hydroforming [22], the thickness in the convolution zone was grown in this method. Hence, an increment could be achieved in the strength of manufactured bellows. As it could be figured out from Fig. 4, increase of the applied displacement thickens the tube wall in the crown point. The crown thickness for the tubes (a), (b), and (c) was 1.24, 1.26, and 1.29 mm, respectively. For all the tubes, the wall thickness decreases gradually in both the left and right sides of the crown point. Then, it improves slightly and diminishes again till reaching to initial thickness (1 mm) at longitudinal distance of 5 mm. Later, thickness enhancement occurs in lower regions with curvature. Flow of the material caused by the compression from both sides of the inflection points in lower curvatures could be the reason for this phenomenon. It is clear that this thickness increase for tube (a) occurs in the distances far from the crown point. Flow of the material from one side of the tube is the reason for the asymmetry distribution in the diagram.

Applied heat flux has a normal distribution form, and the heat concentration is located in the central point. Performing initial heating before applying displacement thickens the tube. By applying displacement, the material flow occurs and material accumulates at that region. That is why the thickness of the crown point in all the tests is the largest one. By the grace of the material flow, the thickness of the adjacent region reduces in this stage in comparison to increased initial thickness.

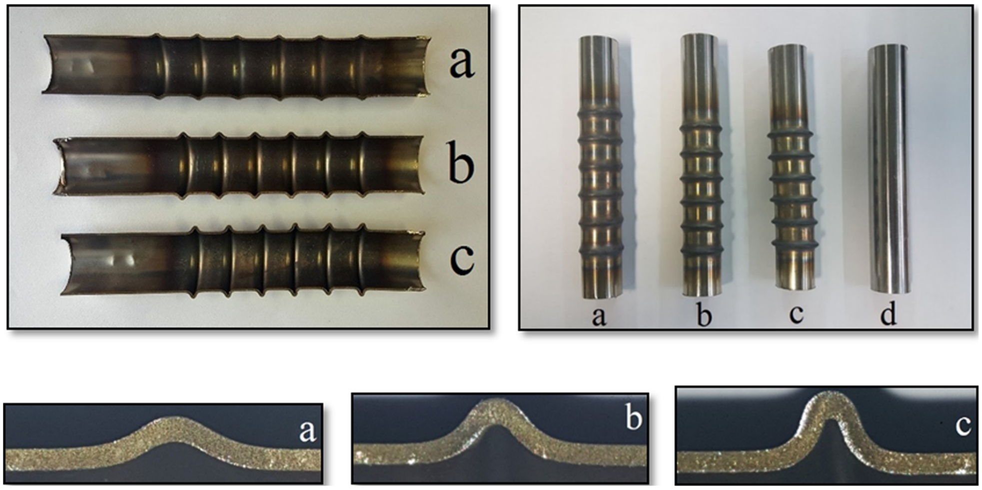
Maximum force (F), heating time before applying displacement (t_1), and total time (t_T) were measured for each tube, and average value for six convolutions has been reported in Table 2. Total time for all the experiments was about 15 s. According to Fig. 5, forming of tube (c) needs a maximum force, a few more than tube (b), and tube (a) requires the minimum one.

The deformation augmented by increasing the applied displacement. By considering the strain rate to be constant, bigger force amounts are required for higher deformations.

Table 1 Experiment detail

Test	Fixed parameter	Variable parameter	Variation range	Output
Effect of applied displacement	Material, dimensions, gap and device current	Applied displacement	1 to 3 mm	Convolution shape, thickness distribution and the force required to forming
Effect of device current	Material, dimensions, gap and applied displacement	Device current	50 to 80 A	Convolution shape, thickness distribution and the force required to forming

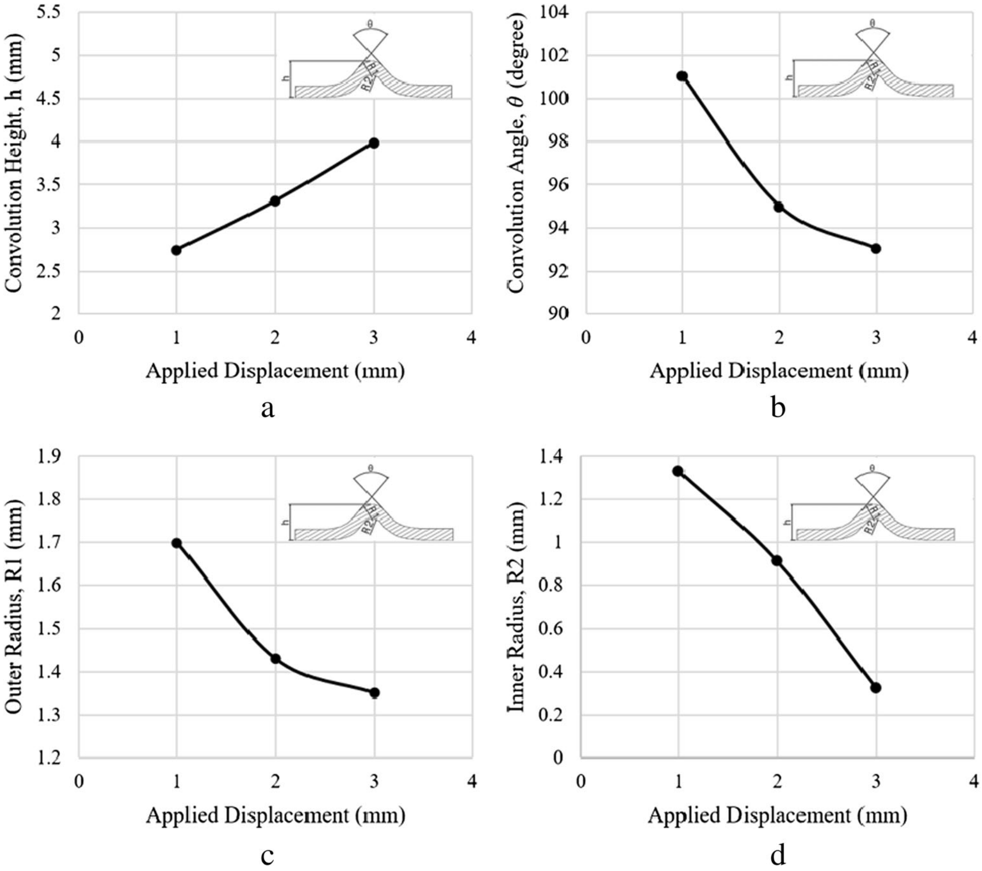
Fig. 2 Metal bellows produced with a current of 70 A with applied displacements of **a** 1 mm, **b** 2 mm, **c** 3 mm, and **d** initial tube



3.2 Effect of device current

Three tubes were produced having constant displacement yet different current values as illustrated in Fig. 6. The convolution height of tubes (a), (b), and (c) was 3.68, 3.99, and 4.16 mm, respectively. Therefore, the convolution height increased by raising the device current. According to Fig. 6, by increasing the device current, both the outer curvature radius and tip angle of the convolution lessened. Effect of the device current on the convolution shape is reported in Fig. 7. According to Fig. 7, by increasing the device current, outer curvature radius and tip angle of the convolution diminished. Inner curvature radius of convolution, nevertheless, decreases first and then increases by increment of the device current from 70 to 80 A.

Fig. 3 Effect of applied displacement on convolution shape: **a** convolution height, **b** convolution angle, **c** outer radius, and **d** inner radius



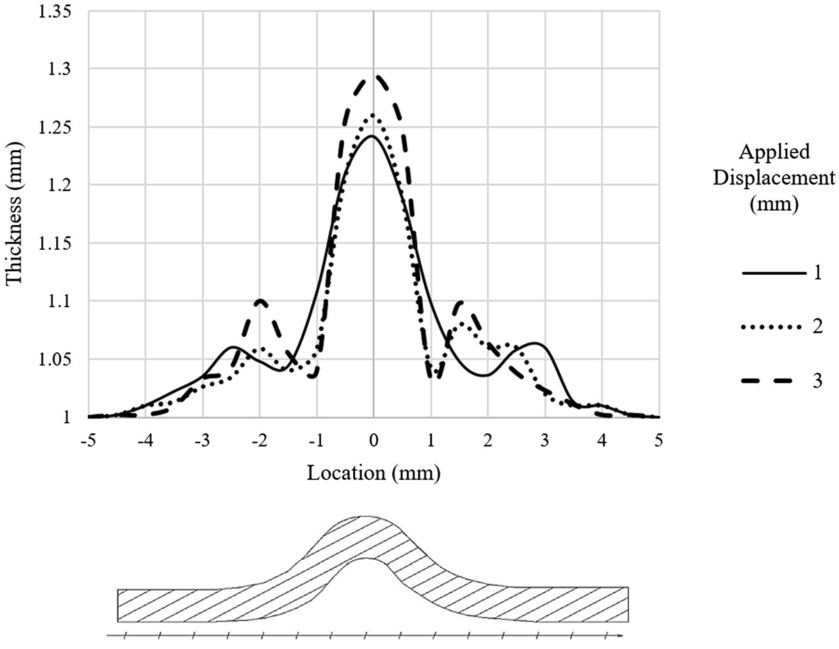


Fig. 4 Thickness distribution around the crown point for metal bellows produced with current of 70 A

By increasing the device current, heat flux transition elevated and heating time decreased accordingly. Thus, less heat was distributed, and the material had to move in radial direction through a narrow area. Therefore, height of the convolution increased. As a result, the tip of the convolution became sharper, and both the convolution angle and outer curvature radius decreased. More initial thickening occurred in the tube at higher currents due to thermal concentration and inner radius variation trend was changed. In fact, accumulation of material in heated region prevents decreasing the inner radius.

Furthermore, other pictures were taken from convolutions of the bellows produced by applied displacement of 3 mm, and wall thickness of the convolutions was measured. Thickness distribution around the crown point is shown in Fig. 8. As it is observable in Fig. 8, increasing the device current from 50 to 70 A thickened the tube wall in the crown point. However, by enhancing it from 70 to 80 A, the thickness remained almost the same. Crown thickness for the tubes (a), (b), and (c) was 1.15, 1.295, and 1.3 mm, respectively. For all the tubes, the value of wall thickness gradually decreased in the left and right sides of the crown point. Then, it increased slightly, and finally decreased again till reaching to initial thickness (1 mm) at longitudinal distance of 5 mm. Due to higher heating time in the tube (a), which was produced by the current of 50 A, the heat was distributed in a wider region. Considering this, the increase occurring in the thickness was fewer in the tube.

As explained in Fig. 4, similar influence laws could be declared about the curves of Fig. 8. Besides, by increasing the device current, heat flux proliferated and heating time reduced. Then, because of more heat concentration resulting from higher currents, more thickening occurred in the initial stage.

Table 2 Maximum force and time required to forming of the metal bellows

Applied Displacement (mm)	F (KN)	t_1 (s)	t_T (s)
1	2.55	8	14.2
2	3.14	8	15
3	3.19	8	14

F Maximum force required to forming, t_T Total time (from arc generation to stop applying displacement), t_1 Heating time before applying displacement

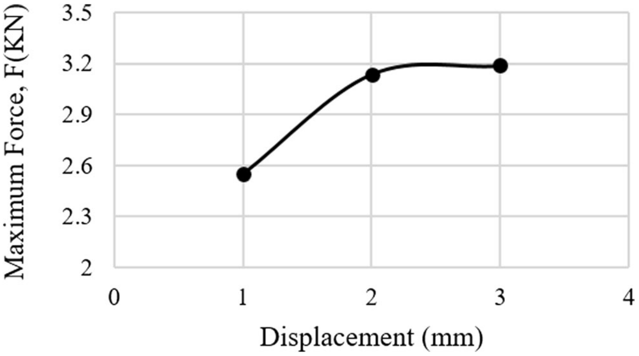


Fig. 5 Effect of applied displacement on maximum force required for forming

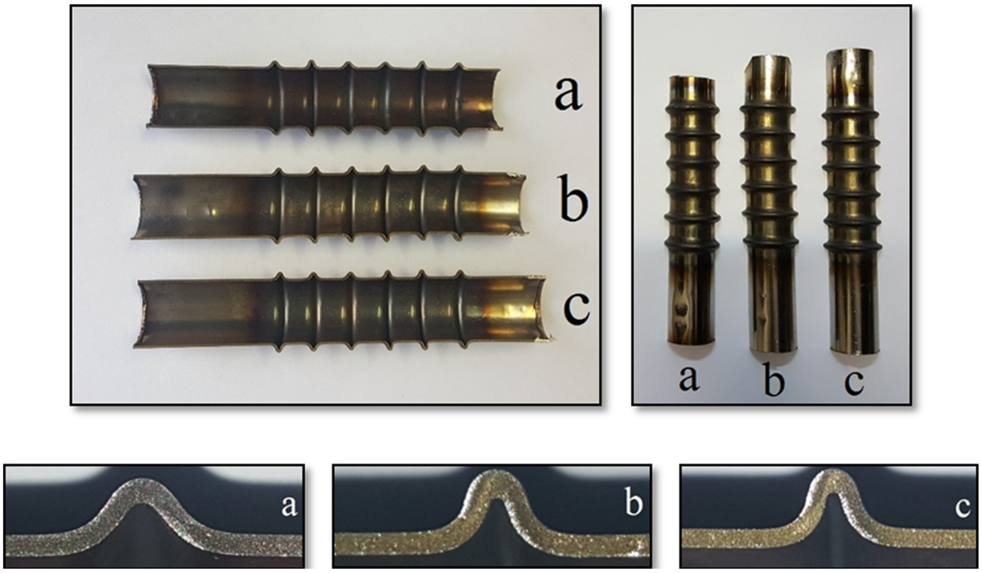


Fig. 6 Metal bellows produced using displacement of 3 mm having currents of **a** 50 A, **b** 70 A, and **c** 80 A

For each tube, maximum force (F), heating time before applying displacement (t_1), and total time (t_T) were measured, and average value for six convolutions is reported in Table 3. Total time for each test is a diverse value. Actually, it clarifies that heating and total forming time depends on the device current. By means of using higher current amount, the time diminished. According to Fig. 9, maximum force required for forming has been increased by changing current from 50 to 70 A and then decreased. Higher temperature was achieved by using a current of

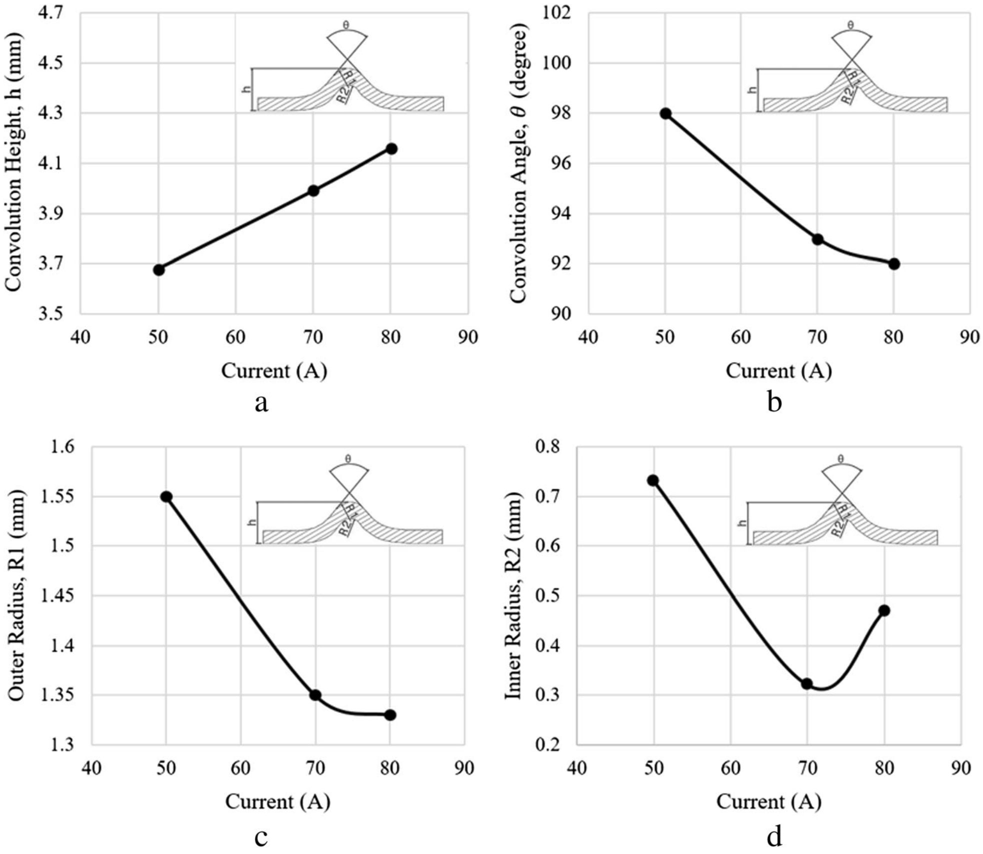


Fig. 7 Effect of device current on the convolution shape: **a** convolution height, **b** convolution angle, **c** outer radius, and **d** inner radius

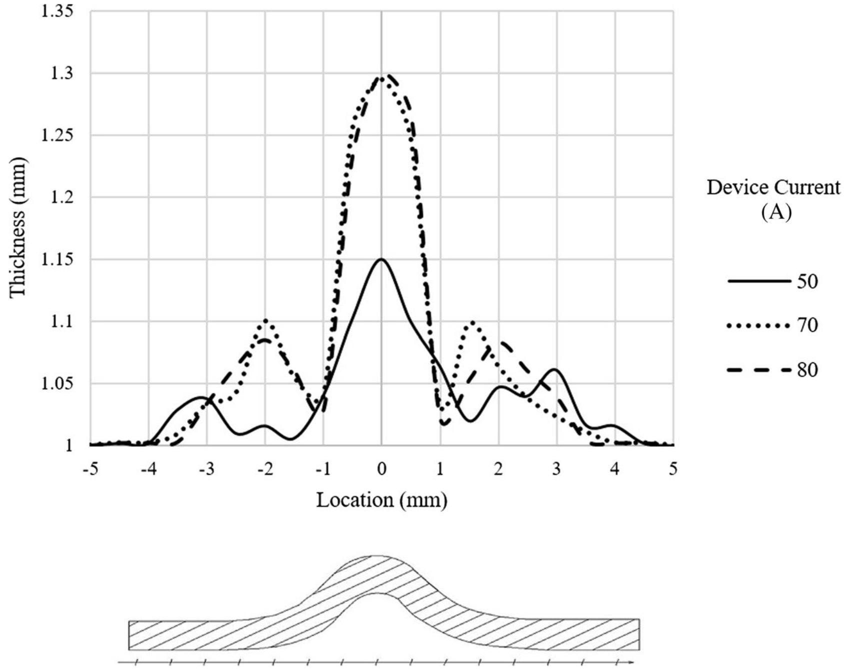


Fig. 8 Thickness distribution around the crown point for metal bellows produced by applied displacement of 3 mm

80 A. So, maximum forming force for tube (c), having lower flow stress, is less than tube (a).

By increasing the device current to 70 A, maximum required force increased. This may be due to higher deformation in comparison to 50 A, which leads to higher required forming force. By increasing the current to 80 A, yield strength of the material decreased that caused the forming force to be decreased.

3.3 Stability (buckling) of produced bellows

Buckling test results point out that energy absorption capacity in manufactured metal bellow (produced by current of 70 A and applied 3 mm) was increased. Thus, the tube could be used as a shock absorber expansion joint. The area under the force-displacement diagram represents work or energy. As illustrated in Fig. 10, this area for the metal bellow is higher than the area for the typical tube. In fact, the absorbed energy for metal bellow and typical tube is 388 and 186 J, respectively. By increasing the height of the convolutions and decreasing their pitch of displacement, absorption capacity may be improved. This issue was not investigated because of the purpose of this study, i.e., introducing a new method and study of the effect of parameters on shape and force.

Table 3 Maximum force and time required for forming of the metal bellows

Device current (A)	*F* (KN)	t_1 (s)	t_T (s)
50	2.87	21.2	26.2
70	3.19	8	14
80	1.94	6.8	9.5

F Maximum force required to forming, t_T Total time (from arc generation to stop applying displacement), t_1 Heating time before applying displacement

4 Conclusion

In this research, a new method for producing metal bellows by local arc heating and applying axial compressive force was developed. The following conclusions were achieved:

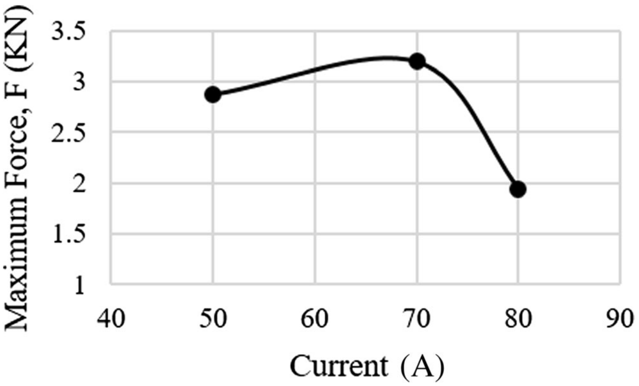


Fig. 9 Effect of device current on maximum force required for forming

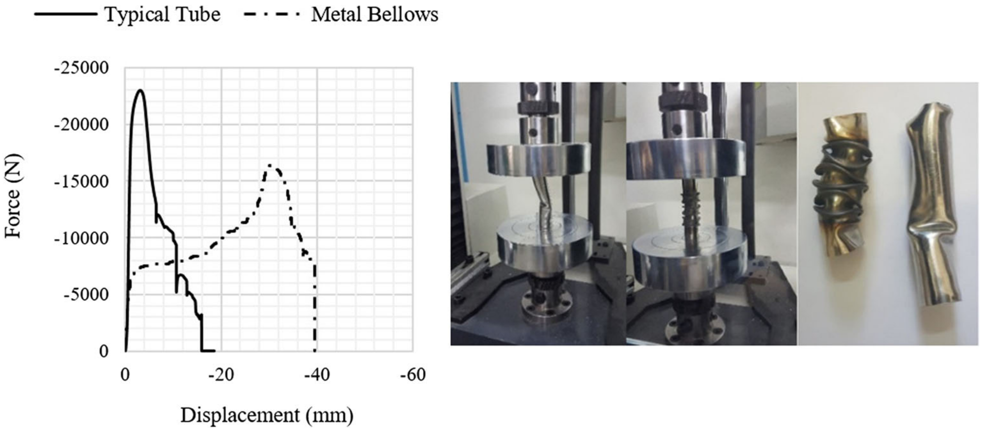


Fig. 10 Buckling test of a typical tube and a manufactured metal bellow (produced by current of 70 A and applied displacement of 3 mm)

- Cost of dies and tools could be eliminated because the process is fully dieless. This method can be used for producing metal bellows with various shapes.
- This method may be a suitable alternative for induction local heating and reducing the cost of high-frequency equipment. It is not necessary to utilize cooler rings to prevent heat distribution because of the heat concentration in electric arc heating in comparison with induction heating.
- Convolution height increased by 46% when the applied displacement increased from 1 to 3 mm. By increasing the current from 50 to 80 A, convolution height improved 13%. It clarifies that using higher currents, as well as higher applied displacements, leads to higher convolution height and lower convolution outer curvature radius. Nonetheless, effect of the device current on convolution height is less than the applied displacement.
- Increasing the applied displacement causes the required forming force to increase. Forming of tube with applied displacement of 3 mm has had the highest maximum required force. By increasing the current from 50 to 70 A, the maximum required force increased; however, due to high temperature and low flow stress, it decreased. Forming of tube with device current of 70 A has had the highest maximum required force among other tubes.
- Despite other forming processes, like bulge and hydroforming, in this method, thickness of the tube wall at the crown point region increased leading to higher strength. Crown point had the highest thickness among all of the samples, and in the tube which was formed by the current of 80 A and the applied displacement of 3 mm, thickness increased by the 30% in the crown point.

As described in the paper, it is predicted that the proposed method could be a suitable forming process for the metal bellows and controlling the parameters of applied displacement and device current could lead to precise shape of the convolutions.

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