Fabrication of Aluminum Rectangular Twist Waveguides: Experimental Investigation and FEM Simulation

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ABSTRACT

Waveguides, used in electronic industries, are structures for transferring electromagnetic waves. A twist waveguide is a device used to change the polarization of waves. In this study, a process for fabricating an aluminum rectangular twist waveguide was designed and some guidelines were introduced. The preliminary profile was obtained by a forward extrusion process. In order to study the effect of strain hardening, the twisting process was studied for annealed and non-annealed samples after the extrusion process. The results revealed the necessity of annealing the samples before the twisting; otherwise, local deformation would occur. Measuring the applied torque showed that as the process progressed, the required torque for an annealed sample would increase due to work hardening, while for a non-annealed sample the torque would decrease after local deformation. Furthermore, the simulation of twisting process was performed using Deform software. No inconsistency was observed between numerical and experimental results. Moreover, investigating the cross sectional distortion showed an undesirable cross sectional distortion for the unfilled sample whereas the cross section in the sand-filled sample stayed rectangular.

1-Introduction

Waveguides are electronic structures for transmitting radio waves, especially microwaves. Waveguides are hollow tubes with circular or rectangular cross sections. They are made of metals that have low resistivity such as aluminum, copper, brass, and silver [1-3]. Sometimes it is required to rotate the electromagnetic field to change the phase. A twist waveguide is implemented for this purpose [4]. Waveguides have standard dimensions. WR abbreviation represents waveguide rectangular and the number nearby WR expresses the inner width dimension in hundredths of an inch [3].

Many studies have been carried out on the twisting of hollow profiles. In most of these studies, the shear stress and twist angle were investigated. For example, Bredt calculated the resultant shear stress and twist angle due to a specific torque in the elastic region by using thin-walled theory [5, 6]. The calculation of shear stress and twisting angle for a thick wall cross section was performed by Marshall [7-9]. Ellis et al. [9] compared the experimental torque-twist behavior, obtained by torsion test, for rectangular hollow cross sections with finite element analysis and Marshall's theory results. Hematiyan and Doostfatemeh [10] introduced a formulation for the calculation of shear stress and angle of twist in the torsion process of thin

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walled and moderately thick walled hollow profiles with polygonal shapes. Gonçalves and Camotim [11] studied the buckling phenomenon caused by torsion process for thin-walled polygonal tubes using generalized beam theory. Argyridi and Sapountzakis studied warping and torsional distortions in the cross section of hollow rectangular beams according to the sequential equilibrium scheme [12].
Shen et al. [13] emphasized the importance of investigating cross sectional distortion during the bending process of rectangular waveguides. They used finite element analysis in order to study the dependence of cross sectional distortion on the stress components. Amiri and Ebrahimi [14] designed and simulated a new method in order to fabricate rectangular twist waveguides utilizing a twisted die and a forward extrusion process. Their results indicated the importance of the length of the twist die in order to reach the required angle of twist in the waveguide.
In this paper, a simple method was proposed for the fabrication of rectangular twist waveguides, and several guides were presented. The offered process was investigated by both experimental approach and finite element method. The simplicity of this process increases its potential to be used in industrial applications.

2- Experimental Procedure

In the current study, a cold forward extrusion process was used to obtain the preliminary profile for the twisting process. During the extrusion process, a cuboid billet made of commercially pure aluminum AA1050, with outer dimensions of 28.86 mm × 16.16 mm, inner dimensions of 22.86 mm × 10.16 mm, and a height of 25 mm is extruded so as to reach the final external dimensions of 24.86 mm × 12.16 mm while the internal dimensions were constant. The chemical composition analysis of the utilized aluminum is reported in table 1. The angle of extrusion die was supposed to be 20°. A rectangular mandrel, connected to an extrusion ram, was used to keep the inner shape unchanged. The internal dimensions of 22.86 mm × 10.16 mm are the dimensions of a specific waveguide, WR90 [15]. The obtained profiles from the extrusion process are illustrated in Fig. 1. Due to the redundant work and heterogeneous deformation during the extrusion process, the cross sections of the extruded specimens were not planar [16]. This problem would be solved by cutting the edges of the samples. After cutting, a profile with a height of almost 65 mm would be attained. This value would be considered as the height of the workpiece in the simulation of the twisting process.

Table 1. The chemical composition of utilized aluminum.

Chemical composition of AA1050, wt%	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti
	99.3	0.118	0.3	0.012	<0.001	0.002	0.021	0.004
	V	Cr	Ni	Ga	Pb	Sn	Co	Ag
	0.013	0.006	0.027	0.013	0.013	0.088	<0.003	0.002

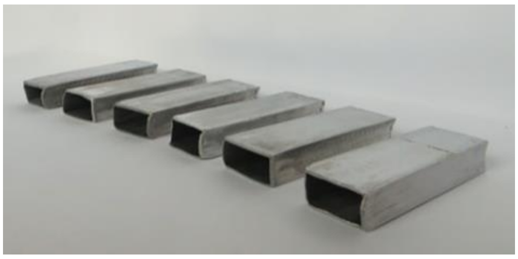

Fig. 1. The obtained profiles from the extrusion process.

Two jigs, whose drawing is shown in Fig. 2, were designed to accomplish the twisting process. The workpiece would be inserted into the groove. If the groove is excessively shallow, the workpiece would exit from the groove during the twisting process. On the other hand, in case of having an unnecessarily deep groove, the ultimate product height would be short.
Therefore, the depth of the groove was important and was considered to be 4 mm.

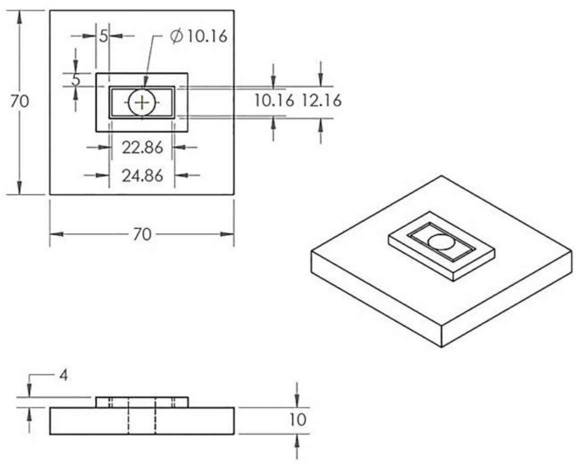

Fig. 2. The drawing of designed jigs.

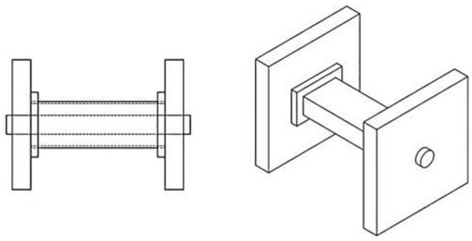

Fig. 3. The assembly of the jigs, workpiece and rod.

A rod was passing through a hole in the middle of the jigs so as to prevent the workpiece buckling. The diameter of the rod was supposed to be equivalent to the inner width of the rectangle. Moreover, one end of the rod was threaded. Fig. 3 depicts the assembly of the jigs, workpiece, and rod.

Furthermore, a torque wrench was utilized to find the values of the required torque to fulfill the twisting process. The angle of twist was measured by a protractor which was installed on one of the jigs. Actually, the fabrication of the jigs in a square shape made the measurement of the angle of twist much more possible. In addition, a hexagon bar was welded to one of the jigs in order to connect the jig to a torque wrench. The twisting process was carried out without the application of any die. In order to perform the twisting process, one of the jigs was fixed in a four jaw chuck of a lathe machine and on the other side, the tailstock tip would be tangential to the torque wrench surface. The torque wrench rotation caused the workpiece to twist. The jigs utilized in the experimental procedure are illustrated in Fig. 4, and the location of all tools before the beginning of the process is shown in Fig. 5.

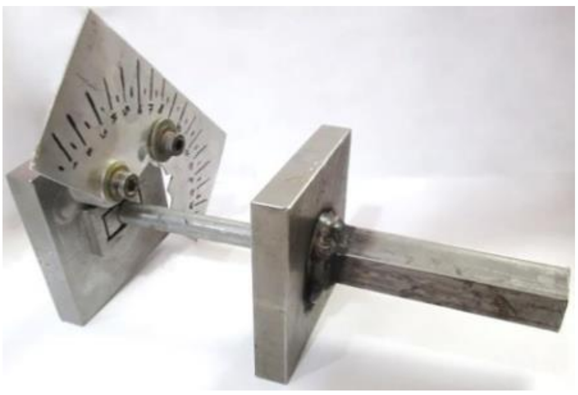

Fig. 4. The utilized jigs in the experiment.

Fig. 5. The location of tools before the starting of the twisting process.

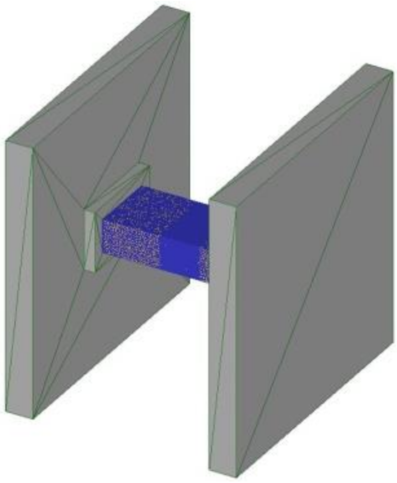

Fig. 6. The simulated model in the software.

To investigate the effect of strain hardening, the workpieces were twisted in two different states. In one case, the twisting process took place after annealing the extruded samples in a furnace at the temperature of 450 °C for 2 hours and furnace cooling the samples. In the other case, the samples were twisted after the extrusion process without any heat treatment. Moreover, for the purpose of studying the cross sectional distortion, the twisting process would be carried out for uniformly sand-filled and unfilled samples.

3- Finite Element Analysis Procedure

The twisting process was simulated using 3D-Deform software. The workpiece was considered to be a hollow profile with a height of 65 mm and the outer cross sectional dimensions of 24.86 mm × 12.16 mm and 1 mm thickness, identical to the extrusion process output. Two jigs were also designed in accordance with the manufactured ones in the experimental procedure. The geometries were designed with Solidworks software and then imported to Deform software. During the simulation, one of the jigs was assumed to be fixed and the other one was considered to rotate with a speed of 0.7 radians per second clockwise. A rod was also placed in the middle of the workpiece. Fig. 6 shows the simulated model in the software.Tetrahedral elements were used to mesh the workpiece. After investigating the mesh validation, in order to reduce the simulation time, the regions in contact with the twisting jigs and the middle of the workpiece were meshed with elements with a size of 0.4 mm while the size of the elements in the other regions was considered to be 1 mm. The torque-angle of twist diagram in the elastic zone would be obtained by considering the workpiece type to be elastic with $E\left(Young's\ modulus\right)=70$ (GPa) and $\upsilon\left(Poisson's\ ratio\right)=0.33$. To evaluate the behavior of the object in the plastic region, the object type was supposed to be plastic. The engineering stress-strain curves obtained by tensile tests for annealed and non-annealed extruded samples are illustrated in Fig. 7. The stress-strain relationships would be determined by converting the engineering stresses and strains to true ones in uniform plastic zone. The obtained stress-strain relationships would be used to define the plastic behavior of the materials in simulation, which were considered as $\sigma = 129\varepsilon^{0.28}$ (MPa) and $\sigma = 165\varepsilon^{0.05}$ (MPa) for two annealed and non-annealed extruded samples, respectively.

No lubricant would be consumed in the twisting process; therefore, the friction factor, calculated by barrel compression test [17], was assumed to be 0.2, which is of no importance since there is no relative motion between the tools and the workpiece [18].

4- Results and Discussion

4-1-Twisting process for an annealed sample

The final product of an unfilled and annealed sample is illustrated in Fig. 8. As can be observed, the final shape in the simulation was consistent with that in the experiment. In this case, the occurrence of a uniform deformation was obvious.

In Fig. 9, the predicted torque-angle of twist diagram in the simulation for an unfilled and annealed sample was compared to the results obtained from the experiment for an annealed sample in both filled and unfilled states. It would be deduced from the diagram that for an annealed sample the diagram had an ascending behavior which could be attributed to the work hardening phenomenon. Moreover, the applied torque in the experiment for both filled and unfilled samples were almost identical due to the fact that sand cannot sustain shear stress. In addition, the simulation and experimental results were congruent. The deviation between the experimental and simulation data in the elastic region was attributed to utilizing a type of torque wrench having low measurement precision in this range.

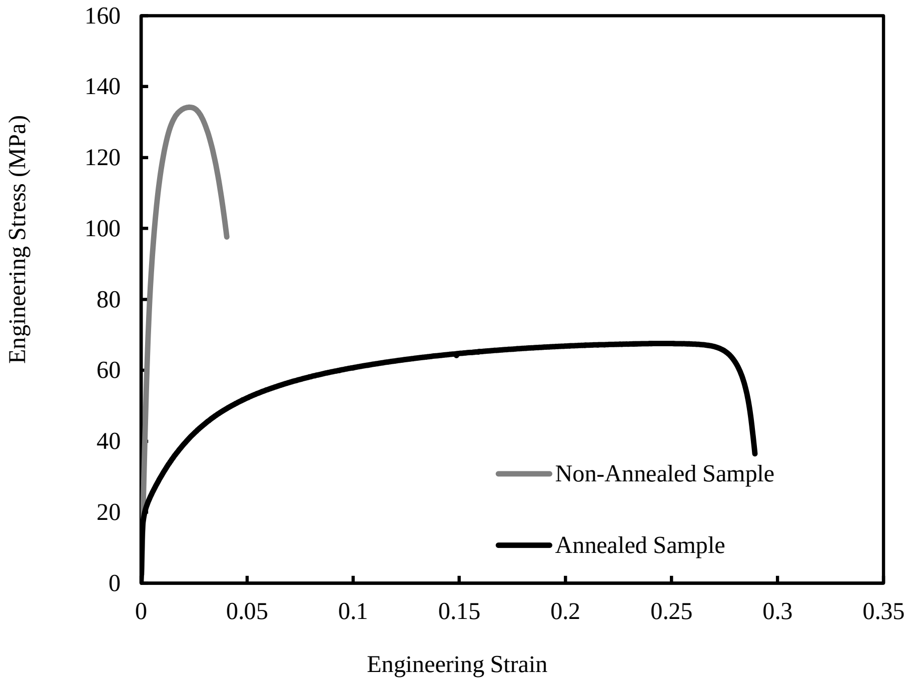

Fig. 7. The tensile engineering stress-strain curves for annealed and non-annealed samples.

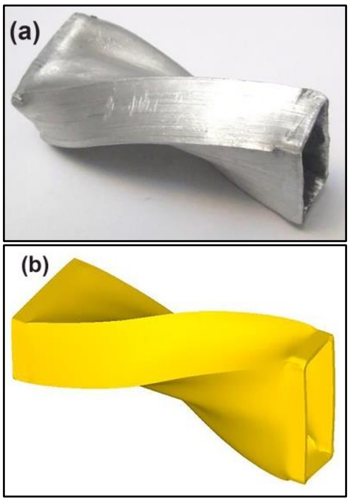

Fig. 8. The annealed and unfilled twisted sample in the: (a) experiment, (b) simulation.

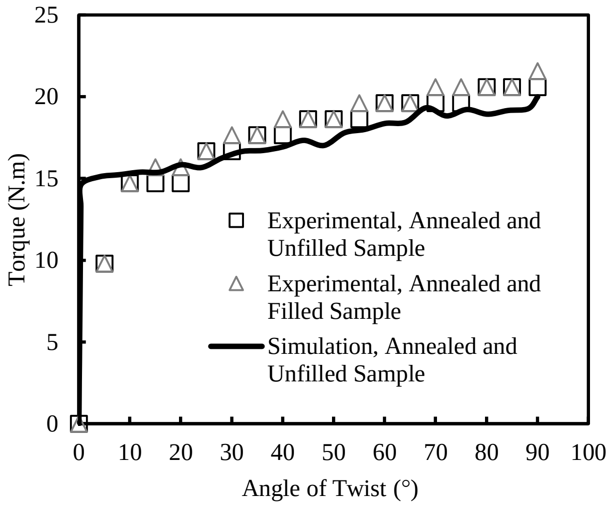

Fig. 9. The Comparison of torque-angle of twist diagram for an annealed sample using the simulations and experiments.

4-2-Twisting process for a non-annealed sample

Fig. 10 depicts the final product of a non-annealed sample. It could be concluded that for a non-annealed sample, the deformation would be localized on one side of the workpiece, resulting from the reduction of strain hardening exponent which shows the reduction in the tendency of the material to be work hardened. The strain hardening exponent reduction could be observed in the attained power law equations which were outlined in section 3. Hence, the workpiece should be annealed before the twisting process in order to achieve a satisfactory product. Furthermore, as can be seen in Fig. 10, there was an acceptable similarity between the predicted shape in the simulation and the final shape in the experiment.

The torque-angle of twist diagram for a non-annealed sample is illustrated in Fig. 11 for both simulation and experiment. In this case, the applied torque gradually decreased due to the localization of deformation. Besides, the applied torque values were quite close for both filled and unfilled samples. Furthermore, to accomplish the twisting process, higher values of torque were required for the non-annealed sample in comparison to those required for the annealed sample, comparing Fig. 9 with Fig. 11.

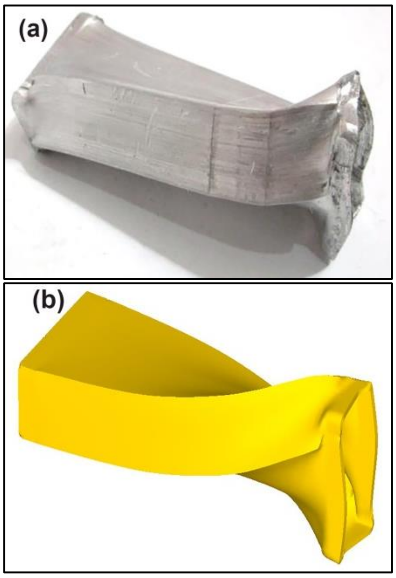

Fig. 10. Twisted non-annealed and hollow sample in the: (a) experiment, (b) simulation.

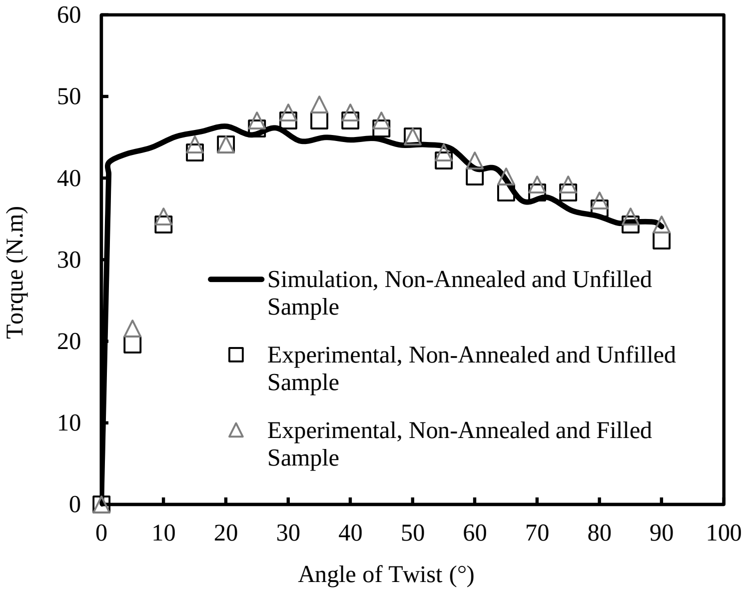

Fig. 11. The comparison of torque-angle of twist diagram for a non-annealed sample using the simulations and experiments.

4-3-Cross sectional distortion

Fig. 12 shows the cross section in the middle of the twisted samples using both experimental and simulated results. It could be observed that, in the unfilled sample, the cross section deviated from a rectangular shape whereas the cross section of the filled sample preserved its rectangular shape. Moreover, the observed cross sectional deviation in the middle of the unfilled workpiece in the simulation results, Fig. 12c, was consistent with the distortion in the experimental results. Hence, it was vital to fill the workpiece with a material possessing low shear strength before the twisting process.

The manufactured waveguides from filled and annealed profiles are illustrated in Fig. 13. The ultimate products were satisfactory, which showed the effectiveness of the selected method.

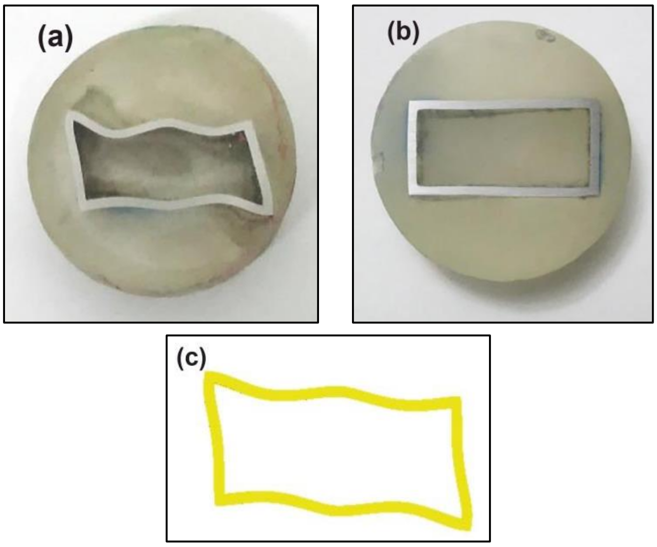

Fig. 12. The cross section in the middle of the twisted sample: (a) unfilled, in experiment, (b) sand-filled, in experiment, (c) unfilled, in simulation.

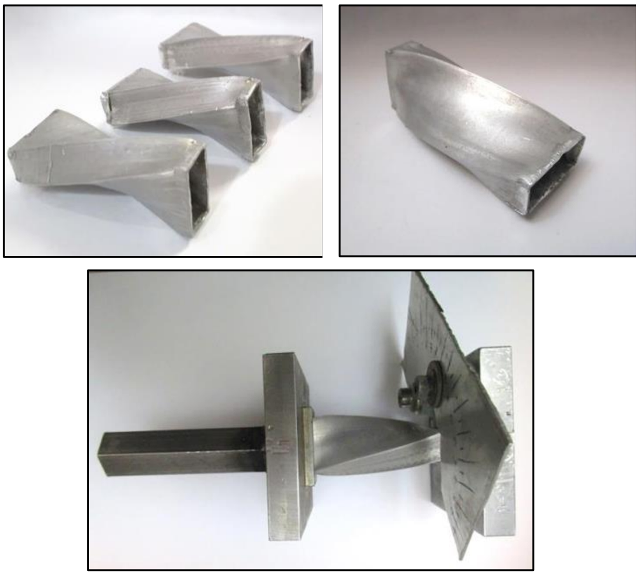

Fig. 13. The ultimate products of filled and annealed samples.

5-Conclusion

The aim of this study was to manufacture a twist waveguide and some guidelines were proposed to reach this goal. In order to reach a satisfactory product, different cases were studied. The preliminary profiles for twisting process, obtained from an extrusion process, were chosen in two states, annealed and non-annealed. The results indicated that in order to fabricate a desirable twist waveguide, it was essential to anneal the sample before the twisting process; otherwise, local deformation, ascribed to strain hardening exponent reduction, would occur. In addition, during the deformation, the applied torque and corresponding angle of twist were measured. It was concluded that as the process proceeded, for the annealed sample the required torque would increase due to strain hardening, while for the non-annealed sample the localized deformation would cause a reduction in the applied torque. So as to investigate the cross sectional distortion, the twisting process was carried out under two different circumstances; sand-filled and hollow profiles. The results showed that the applied torque for the unfilled sample would not be much different from the torque for the sand-filled one. The twisting process for unfilled samples was simulated and no discrepancy was observed against the experimental results. The results demonstrated that the cross section of the unfilled sample would be distorted during the twisting process, which showed the necessity of filling the sample before the twisting process. The results of the current study revealed the great potential of the proposed method in order to be implemented in electronic industries.

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