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Experimental Investigation of Nanostructured Tube by Accumulative Tube Bonding as a Novel Severe Plastic Deformation Process

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Abstract

A novel severe plastic deformation (SPD) process for manufacturing high strength multilayer tubes titled accumulative tube-bonding (ATB) is proposed in this article. By conducting numerous runs of the ATB process, grain refinement as well as mechanical characteristics were investigated experimentally and numerically. The original tube size sample had a 200 mm length, 25 mm diameter and a thickness of 3-mm. ATB procedure involved three passes of the tube through the die. After the third pass, the strength gradually increased significantly. The grain size of copper tube sample was reduced to 133 nm after three passes of ATB, which was confirmed by electron beam electron backscatter diffraction. Mechanical properties such as ductility, ultimate tensile strength, and hardness were also studied. The microhardness value of the tube increased after the third pass of the SPD process. The enormous increase in strength is due to a slight reduction in ductility. The tube demonstrated exceptional hardness by growing its microhardness from 60 Vickers hardness number to 135 Vickers hardness number by ATB process. Samples for scanning electron microscope (SEM) were polished using a polishing machine.

Keywords

Tube sample, Grain refinement, Scanning electron microscope, Microhardness, Tensile stress

Introduction

For a long time, a large number of authors have been conducting comprehensive studies on SPD methods. Accumulative tube bonding is one of the most efficient SPD methods to produce nanostructure or ultrafine grain (UFG) materials [1, 2]. Since last decade most of the work is done on plate material while very less work is done on microtube forming and tube severe plastic deformation. So, in this work experimental investigation on nanostructured tube by ATB is explored. In order to treat metal, Torkestani and Dashtbayazi [3] innovative technology of SPD considers both high hydrostatic pressure and shear deformation. Today's SPD techniques are built on this. The Hall-Petch equations [4, 5] state that the strength of a material dramatically increases at standard ambient temperature as the grain size [6, 7] decreases. Microstructural characteristics and temperature at room temperature affect a material's structural mechanical characteristic.

Bell et al. [8] focused their research on the numerical simulation of cold-drawn steel tubes with straight internal rifling. He examined different roll diameter pulling forces in kilonewton. Limited hydrostatic compressive stress levels and negligible grain boundary angles can be found in unoriginal metal forming techniques [2, 9]. There have been several SPD approaches planned during the past 20 years. These techniques are suggested to produce nanograined and UFG materials. The cold working technique is utilized in the majority of sectors to produce a variety of components. Below the recrystallization temperature for metals and alloys, cold drawing is used.

The surface finish of the tube is impacted by the die angle; a mild angle produces an excellent surface finish, while a steep angle produces a harsh surface finish. Using equal channel angular pressing, Faraji and Kim [10], and Kim and Yoon [11] worked on the finite element analysis of steel tubes. The most typical SPD procedure for producing UFG metal, equal channel angular pressing, was the subject of his research. Mesbah et al. [12] and Faraji et al. [13] investigated tube channel angular pressing (TCAP) and parallel tube channel angular pressing (PTCAP) and found that the comparable plastic strain contour is denser in PTCAP than in TCAP. He worked on finite element analysis of two routes; route A and route C ECAP process, and discovered that the grain size is lesser in route C as compared to route A. On AA 6061, Jafarlou et al. [14] and An et al. [15] used TCAP. He discovered that the most efficient method for applying significant equivalent plastic strain (EPS) via the sample tube is TCAP. Using the fem approach, he illustrates the distribution of EPS within the sample. Due to the corner angle, he discovered that the EPS was 0.7 at the top surface of the tube. The observed EPS value for the bottom area was 0.57. He measured the tube homogeneity in the middle of the tube route and discovered that p2 has a lower level of EPS value whereas p3 and p4 had larger levels. Few papers [16-18] reported the work on how tool profile enhances the mechanical and microstructure properties of AA5052/SiC composites by friction stir processing.

To this date, so many authors have worked on SPD process to produce UFG material from plate. However, it is important to note that academic research on tube deformation and tube micro-forming and their creators is limited. So, in this work accumulative tube bonding method is discussed to investigate the mechanical properties and microstructure of copper tube.

Experimentation

This experiment used copper tubes with a minimum commercial purity of 99.90%. Their outside diameter was 1 inch, the length was 120 mm, and the thickness was 3 mm. After two hours of annealing at 600 °C, the tubes' structure was thoroughly recrystallized and uniform before the ATB process [5] was implemented. Up to three iterations of the ATB protocol were performed at room temperature with a 5 mm/min punch speed. Prior to treatment with ATB, die components were hardened to 55 HRC. The die configuration consists of a punch, a fixed mandrel, a seal, and a die. As depicted in figure 1, the procedure commences with the insertion of a mandrel-equipped cylindrical tube into the die. The mandrel will be removed, and the previous procedures will be repeated. Metal is expanded via extrusion to generate the requisite backpressure for the operation. This method is repeated for the first pass, second pass and so on. ASTM E8 describes tension-testing methods to determine yield strength, ultimate strength, and percentage elongation of material [18]. Figure 2 presents the original copper tube and ATB processed pass 1. Figure 3 presents the ATB-SPD processed pass 2. Figure 4 presents the polishing machine - Microhardness test sample. The image of the I-section for tensile testing based on ASTM standards for 100 x 12 mm is shown in figure 5. The image of the I-sections made from the processed copper tube is shown in figure 5.

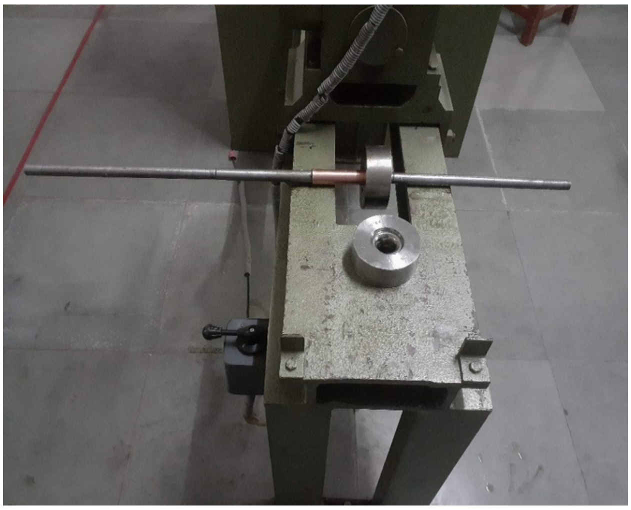

Figure 1: Experimental set up showing copper tube and Laxmi make die.

Tensile testing has been carried out and the corresponding tensile strength, yield strength, and percentage elongation are discussed below in table 1.

Results and Discussion

Uniaxial testing machine at advanced mechanical testing facility at IIT Bombay is shown in figure 5. The tensile test specimen was prepared as per ASTM E8 standard as shown in figure 5b.

Mechanical properties

The microstructural and mechanical properties change as the metal is deformed and strain is induced in them. In the orthodox metal making process, materials might be strong, but they might not essentially be ductile, and the reverse is also true. The stress-strain curves after three passes of the SPD process for different copper tube samples are shown in figure 6. After ATB process, the identified mechanical properties of a tube such as ductility, ultimate strength, and yield strength significantly changes. For different materials, strength as well as ductility are imperative mechanical properties.

The engineering stress vs strain curves of the original tube and processed tube are shown here. The ductility value, ultimate strength, and yield strength for the initial sample of copper tube is low as shown. After the second and third pass of the ATB process, the ultimate strength, yield strength goes on increasing. A material must absorb force and deform plastically without fracturing in order to be durable. The mechanical properties of accumulative tube bonding processed tubes were studied over a uniaxial tensile test machine and microhardness tester. The testing samples required for uniaxial testing were prepared as per ASTM E8/E8M-9 standards. It is carried out parallel to the axis of the tube. The deformed region was

Figure 2: Original copper tube and ATB processed pass 1.

Figure 3: ATB-SPD processed pass 2.

Figure 4: Polishing machine - Microhardness test sample.

Table 1: Tensile testing results.

Test specimen	No. of layers (2^n) n-pass	Universal tensile strength (MPa)	Yield strength (MPa)	Percentage elongation
Annealed	-	205	75	55%
Pass 1	2	345	175	41%
Pass 2	4	386	310	37%
Pass 3	8	410	350	34%

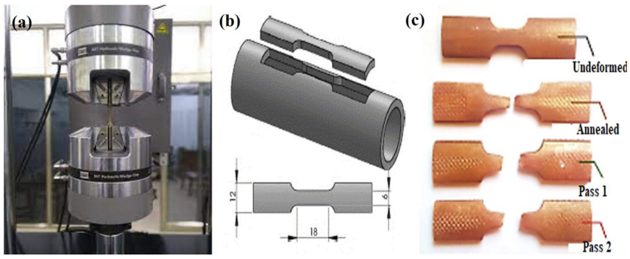

Figure 5: **(a)** Uniaxial tensile test machine, **(b)** ASTM E8 standard I-section for tensile testing, and **(c)** I-sections of copper tube test specimens.

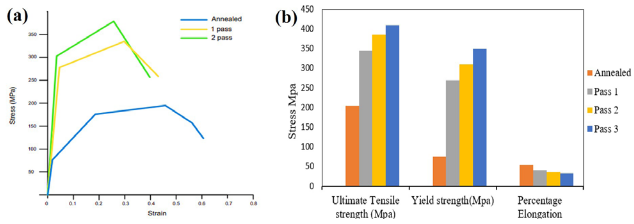

Figure 6: **(a)** ATB processed tube for stress-strain diagram and **(b)** Stress vs elongation graph.

marked for or gauge zone, which is located in the middle of the tube and more deformed. The length of the gauge region was 18 mm. The width of the gauge region was 6 mm. The depth of the gauge region was 3.5 mm. Generally, the tensile test goes at room temperature. The uniaxial tensile tests have to be executed at the strain rate of 1 x 10^{-4} s^{-1}.

The engineering stress vs strain curves were plotted for initial sheets and processed copper tubes in dissimilar passes of the ATB process. It is witnessed that the tensile strength of processed tubes is higher than in initial tubes. Based on the uniaxial tensile test, stress-strain diagram was plotted; ultimate tensile strain and elongation were calculated as shown in the figure 6.

Microhardness

The Vickers hardness test machine as shown in figure 7 is used to check the microhardness of the sample. For 20 s, a 50-g load was applied to get Vickers hardness number at the Vickers hardness test machine. Six randomly chosen cross-sections perpendicular to the drawing directions were used to conduct a microhardness test on all three-tube samples. Then for all three copper tube samples, Microhardness value was recorded.

In a TRB-250 DM microhardness-testing instrument, the tubes' hardness was determined using a Vickers indenter with a force of 100 g and a stop time of 15 s. The indenter was inserted perpendicular to the tube's axis into a cross section. The microhardness of five locations within the thickness of the tube was evaluated. From table 2 we can observe that the microhardness value goes on increasing from pass 1 to pass 3. Figure 8 presents the effect of ATB on microhardness vs pass number.

Surface morphology

Optical microscopy images for the respective passes of tube sample are shown in figure 9. The images were captured

Figure 7: TRB-250DM Microhardness testing machine.

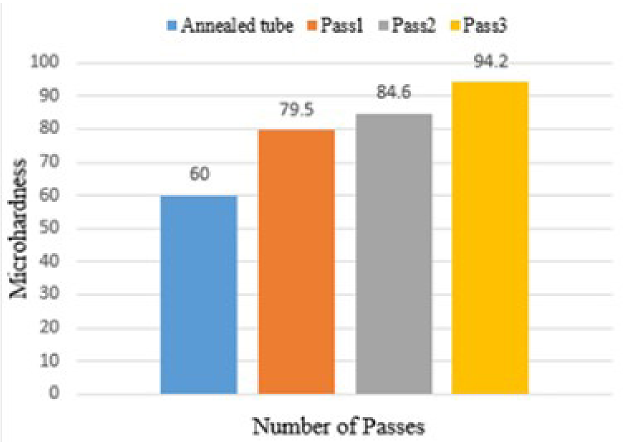

Figure 8: Effect of ATB on microhardness vs pass number.

Table 2: Microhardness values (HV) of tube samples after ATB process.

Annealed tube	Pass 1	Pass 2	Pass 3
60	84.3	83.8	85.8
75.1	79.2	85.4	92.1
76	84.5	81.4	94.5
75.4	79.9	86.9	94.9
74	79.5	84.6	94.2

at IIT Bombay on Zeiss machine. Surface roughness parameters Ra and Rq were derived to quantify the roughening defect evolution. Next paper will detail the correlation between these two microstructural metrics, particle size, and surface roughness. Surface roughness parameters are visualized as they change with particle size. Figure 10 shows the SEM images for respective passes of ATB process. As the grain size increases surface roughness value (Ra and Rq) also increases.

Conclusion

This work was carried out at Amity university in mechanics of solid laboratory. In this work ATB is announced as the new method of the SPD deformation process. In this method, pure copper pipe is passed through the die for several passes.

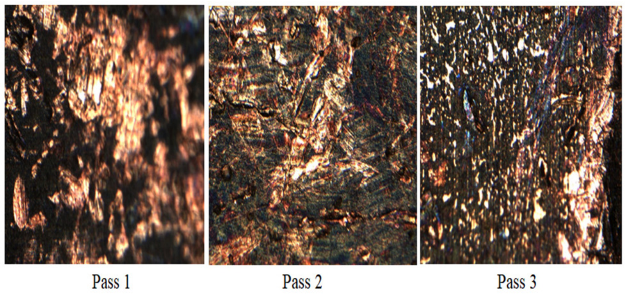

Figure 9: Optical microscope images for pass 1, pass 2, and pass 3.

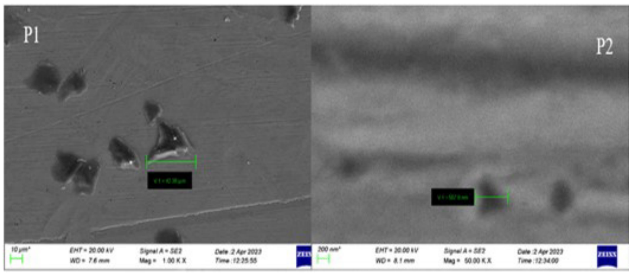

Figure 10: SEM images taken on tube surface.

Grain size after the three passes of ATB is extremely small as per electron backscatter diffraction analysis. The material's microhardness, ductility, and ultimate tensile strength were also measured. The yield strength and ultimate tensile strength of the material increased significantly. The ATB procedure increased the tensile strength to 270 MPa and the ultimate strength to 345 MPa from their respective original values of 75 MPa and 207 MPa, respectively. In addition, the elongation value decreased from 55% to 36% after just one pass of ATB. The loss of ductility was considerably less than with other SPD techniques.

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None.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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