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Improving Mechanical Properties, Especially Increasing Tubes' Strength by Micro structuring Metals Using Severe Plastic Deformation Method

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Abstract: Increasing material's strength is of particular importance. Improving material's mechanical properties such as strength could reduce the size and weight of the structure. The size and weight of the structure are among the effective parameters in design. Since the past a variety of methods have been developed to increase the strength of metals that are capable of increasing metals' strength to a certain level. But most of these methods while increasing strength are associated with relatively high material formability properties. This is one of the most important limitations of the methods. Plastic deformation method is among the new methods that in addition to increasing the material's strength will strengthen other desired mechanical properties of the material by micro structuring the crystal lattice of a metal. The mechanical properties of the products of this process are so better than the original metal properties that they are known as super metals. Various methods have been developed to make the materials in tubes NANO structured. Products produced during these processes despite being thinner are less capable to withstand pressure and have higher corrosion and wear resistance compared to the tube manufactured by the conventional methods. Moreover they have the potential to be used at higher temperatures and have longer lifetime. These advantages have increased the importance of plastic deformation methods for the tubs. In this research while a brief discussion on the effect of severe plastic deformation on the material structure the conventional methods for manufacturing the tube are reviewed.

Keywords: high-strength tubes, severe plastic deformation, NANO structured materials

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1. Introduction

Studies show that the structure of the crystal lattice of metals has an impact on their mechanical properties. As the material is more micro-structured, it has higher strength. If the average grain size of the crystal lattice of metal is between 100 and 1000 nm, it is called ultra-fine-grained and if it is less than 100 nm, it is called NANO-structured. Mechanical properties of ultrafine grained and NANO-structured materials are significantly different and improved compared to the same material with macro structure such that metals with this crystal structure are called super metals due to the their good mechanical properties [1]. Severe plastic deformation method is one of the approaches to create a fine-grained structure in materials. These methods are developed for materials with different dimensions and geometries and they can be generally into three groups of innovative methods for bulk, sheet and tube materials. In all these methods the material is under extreme hydrostatic pressure which increases the plasticity of the material and prevents cracks in its structure. In these conditions severe plastic strain is repeatedly applied to the material. The size of this strain is much greater than the plastic strain applied in other methods of applying plastic strain. This process makes the size grain size of the crystal lattice finer and stores high strain energy in the grain boundaries [2-4]. Severe plastic deformation method increases the material's strength without reducing its ductility properties. This process increases the materials' resistance to heat, corrosion, and wear. Since the tubes are faced with these types of damages in most of their uses, using this method it is possible to reduce the tube's weight by manufacturing tubes with improved mechanical properties and increase their scope of application and lifetime. Accordingly developing this method for tubes is of great importance. One of the first methods invented for the tubes is high-pressure tube twisting (HPTT) developed by Toth (2009). Accumulative Spin-Bonding (ASB) method was proposed by Mohebi (2010) [6]. Zangiabadi et al (2010) provided Tube Channel Pressing (TCP) [7]. Faraji et al (2011) proposed Tubular Channel Angular Pressing (TCAP) [8]. Faraji (2012) also developed parallel tubular channel angular pressing (PTCAP) [9]. Torabzadeh et al (2015) invented cyclic flaring and sinking (CFS) method [10]. Babaei et al (2014) presented Tube cyclic expansion-extrusion (TCEE) [11, 12]. Jafarzadeh et al proposed Repetitive tube expansion and shrinking (RTES) [13].

2. Severe plastic deformation

Severe plastic deformation method is among the new approaches of creating microstructure in metals that has significant results in increasing material strength. In other common methods, increasing the strength is associated with a significant reduction in ductility unintentionally and this the main disadvantage of these methods. Plastic deformation method not only significantly increases the strength of the material but also increases other desirable material properties such as corrosion, wear and fatigue resistance and ductility. In the plastic deformation method the material is subject to huge hydrostatic pressure which increases ductility significantly and prevents cracks in the material. In this situation, by applying shear forces on the desired directions, the material is subject to severe deformation in the plastic zone compared with conventional deformations in thermo-mechanical processes. During this process a significant strain force is applied to the material. The material stores this energy in its structure by creating new grain boundaries within larger grains. This makes the grains micro structured. In the severe plastic deformation the processes should be designed to make the input and output dimensions similar and this issue is the underlying assumption of this approach. Since by increasing the strength and improving other mechanical properties of materials it is possible to reduce the structure's size and weight and increase its weight and scope of application, today many pieces in a variety of fields including military, medicine, automotive and aerospace industries are produced in this way [1, 3] [14-15].

a. The effect of severe plastic deformation on the material's strength

As the structure becomes fine-grained, the total grain boundaries in the material will increase. Failure occurs when the input energy to the material could overcome the energy of the crystal lattice of the material. Since the grain boundaries are energetic areas in the material structure, they act as a barrier against crack growth and creating separation. More energy should be applied fail a fine grained material so that it could overcome the grain boundaries' energy. In fact by applying severe plastic deformation a large amount of strain energy is stored in the material structure. When material is subject to loading the same amount of energy stored in the structure, more energy is required to overcome the links and fail the crystal lattice. In the conventional methods that increase material strength by work hardening, storing energy in the material structure is faced with huge limitation and it is possible to store a limited amount of energy in the material structure. In the conventional methods by applying strain energy on the material and increasing strength, material ductility is dropped inevitably and it becomes brittle and loses ability to absorb more energy by applying deformation. This is the difference between severe plastic deformation and other methods. In the severe plastic deformation the applied energy changes the grain size to grain size of below 100 nm and the material with the grain size in this range behaves differently compared to the same material with a coarser grain structure [16].

b. The effect of severe plastic deformation on material ductility

As the material structure becomes fine-grained, new grains with high angles are created between the grain boundaries. These grain boundaries with high angles could slip by applying energy and provide more deformation than the coarse grain structure [17]. Also the grain boundaries' slippage happens with dislocations' movement which leads to the continuity between the grains and this provides more plastic strain handling in the NANO-structured materials [18]. This makes the products of the process to lose their malleability according to their material and obtain more ability to withstand deformation in some cases. This is one of the most important advantages of severe plastic deformation compared to other conventional methods to increase strength.

3. Severe plastic deformation methods for tubes

As mentioned before, products with plastic deformation are extensively used in various fields and this usage is increasing. Tubes are one of the most widely used parts in the industry and due to strengthening different parts of a structure, improving the strength of all parts according to the reinforced parts is necessary. Therefore, given the widespread use of tubes in many machines and mechanisms, improving the mechanical properties of tubes is important. A variety of methods have been proposed for this purpose. All proposed methods have advantages and disadvantages and a there is a continuous research and development to improve them. In the next section the most common methods of plastic deformation in tubes is discussed.

a. High-pressure tube twisting

With the introduction of high-pressure tube twisting a new step was taken towards producing the ultra-fine-grained tubes. This process is schematically shown in Fig.1. In this method first the tube with the average radius r and the thickness t is placed within a rigid disk.

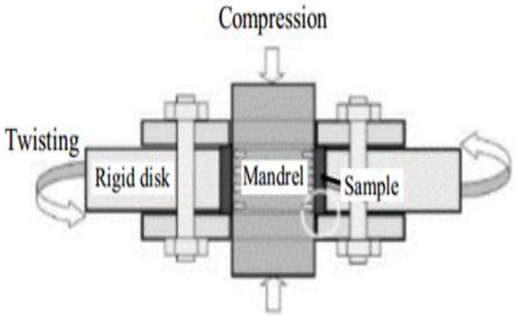

Fig.1 Schematic vertical section of the experimental /high-pressure tube twisting [5

A mandrel is located in a tube. The tube is under the axial pressure during the process and due to the lateral expansion of the mandrel the inner and outer walls of the tube between the disk and mandrel is completely bounded. In these circumstances the tube is placed under a large hydrostatic pressure. By twisting the rigid disk up to the angle β, the shear strain applied to the tube with low thickness can be calculated by the Eq. (1).

(1)

The average shear strain is the tube with the inner radius a and the outer radius b can be obtained by the Eq. (2).

(2)

Analyzing the tested aluminum tubes indicate the change in the orientation of grains along the application of shear strain. Vertical force exerted on mandrel does not have any effect on the flow of matter and the flow of material is controlled by the shear component of the applied stress. By increasing the amount of shear strain, the material strength is increased and its ductility is slightly reduced [20]. One of the reasons for increasing strength in this process is the increase in dislocation density within grains, high-angle grain boundary orientation towards the applied shear force and the formation of new grains in the previous coarse grains [21, 22]. One of the disadvantages of this method is the different applied shear as the result of twisted disc inside and outside the tube. As this difference is increased at different parts, the material grain size and microstructure is more heterogeneous and tube properties will not be homogeneous in different parts [23]. Fig.2 indicates that the initial size of the grains in the microstructure of the material before the process was 24 micrometers which is reduced to 0.4 micrometers after applying the average strain of 8 [20].

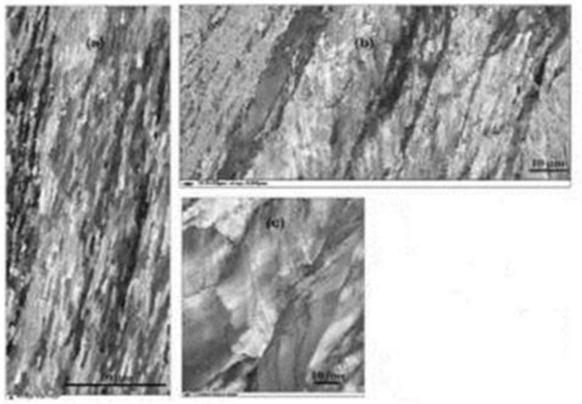

Fig. 2 Micrographs obtained by EBSD from different points on tube thickness (a) near the inner surface, (b) in the middle, (c) near the outer surface [20]

The required pressure for mandrel expansion, providing hydrostatic pressure and force required for twisting tube applied by a rigid disc have led to large force requirement in this method.

b. Accumulative spin-bonding (ASB) [6]

Accumulative spin-bonding (ASB) such as accumulative roll bonding (ARB) which is used to connect two sheets with different alloys, is applied to connect two tubes to each other. In this method two tubes that the diameter of one of them is larger than the other one are fit in each other and a mandrel passes through them. mandrel and tubes are located in the chuck lathe and the spinner is fit into the place and with the Mandrel and tube’s rotation, the spinner moves along the axis of the tubes and in contact with the tubes and connects the tubes by applying pressure and creating plastic strain. In this process, applying plastic strain to the material leads to fine-grained structure. Fig. 3 shows the process schematically. The outer tube is in direct contact with the spinner has more reduced thickness. One of the important points in this method is the lack using tubes with identical size because the tubes should fit in each other before starting the process. And to repeat the process the measurements should be such that the process could be repeated for several times.

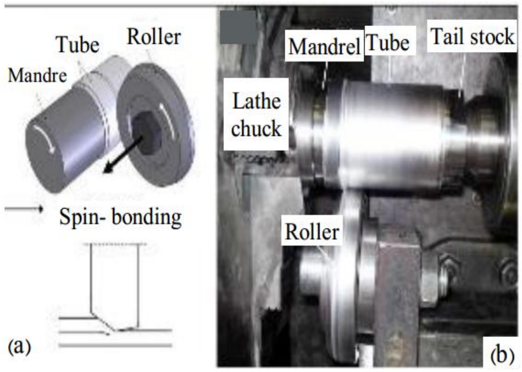

Fig 3 (a) Schematic illustration of the spin-bonding and (b) tube spinning set up used for spin-bonding on lathe [6[

c.Tube Channel Pressing (TCP)

This process involves a cylindrical channel in which a bottleneck is located with a less diameter. The mandrel is also located inside the tube the diameter of which is proportional to the inner diameter of the tube. In the bottleneck the mandrel diameter is reduced such as that of the bottleneck so that the tube thickness remains constant at all stages of the process. Accordingly using a tube-shaped mandrel a tube is pressed into the channel from the top. The tube diameter is reduced by reaching the bottleneck and returns to normal state after passing it. As the material passes through this bottleneck a severe plastic strain is applied to the material. This process is shown in Fig.4.

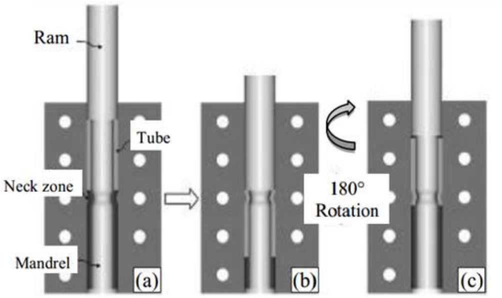

Fig4. Tube Channel Pressing (TCP) [7]

Since this mechanism creates more accumulative strain and has simpler and more uniform performance, it is more practical than other mechanisms [24]. The introduced approach has been successfully carried out for the aluminum alloy 1050 up to 5 replications and the results indicate that the yield and final strength of the tubes in this way is nearly double the strength of the annealed tubes [7]. The micro-structural analyses revealed good modification of granulation in this method. The grain size of the annealed specimen is about 1000 microns while it is about 200 microns in the specimen that has experienced this method 5 times. As can be seen in Fig.5 the aluminum6061 specimen as the output of this process the graining is based on the intersection of shear bands as follows [25].

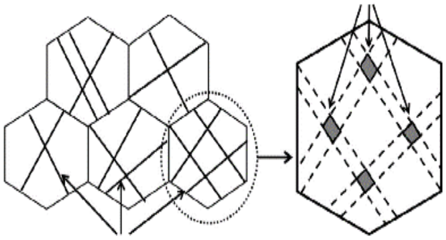

Fig.5 Schematic illustration of IMSB mechanism [25]

d. Tubular Channel Angular Pressing (TCAP) [8]

Given that the shear strain plays the most important role in the establishment of microstructure in materials, the main purpose of tubular channel angular pressing is to apply shear strain in the material. As can be seen in Figure 6 the tube enters a mold that has a triangular-shaped groove. The tube passes through the mold and the triangular groove under the pressure of the cylindrical mandrel. When passing through the triangular groove the tube is subject to severe plastic strain in three areas. After applying this process once on the AZ91 alloy, analyzing the grain structure shows that the average grain size is reduced from 150 microns to 1.5 microns. The tube hardness increases from 51 to 78 Vickers.

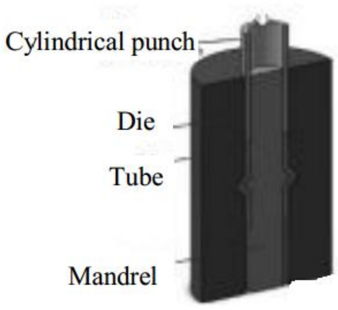

Fig.6 (a) Schematic of TCAP and (b) experimental setup

e.Parallel tubular channel angular pressing (PTCAP) [9]

As schematically shown in Fig.7 this method has two steps. In the first step the tube is extruded by the cylindrical mandrel into the cylindrical angular channel with two shear coaxial areas and the initial diameter is increased to its maximum value. In the second step the tube is again extruded by the second mandrel into the angular channel parallel to the shear zones and the pipe section return to its initial size. This method is successfully tested on the pure copper tube.

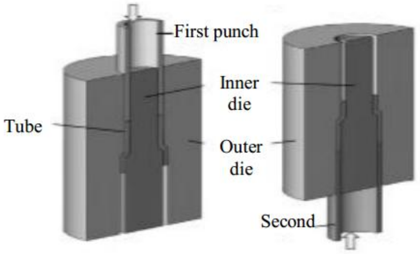

Fig.7 different steps of PTCAP

Finite element analysis indicates that the strain applied on the tubes in this method has a very good homogeneity compared to the tubular channel angular pressing. Therefore the mechanical properties of the tube such as hardness are expected to be more homogeneous [27]. The advantages of this method are an increase in hardness and the same relative hardness along the tubes. This method requires less applied force than most methods. According to calculations this method requires about 60% less energy than the tube channel pressing [9]. The analysis of applying this method on pure copper research results indicate that after one step, fine-grained materials can be seen in the structure that have intertwined dislocations. In the second step the grains are stretched and density of dislocations within them is reduced [28]. In the second step and applying more plastic deformation the stretched grains disappear and the coaxial grains with the average size of 150nm are formed by dynamic restoration. Thus a completely homogeneous microstructure is created. By increasing the number of replications the dislocation density is reduced in the grains [26]. Assessment of changes in the mechanical properties in different directions indicates a strong anisotropy in the ultrafine grained specimens. Although in this technique the strength and stiffness are increased in both circumferential and axial directions, generally the strength of the material in the circumferential direction is greater than the axial direction [29].

f. Cyclic flaring and sinking (CFS) [10]

This method is similar to parallel tubular channel angular pressing method. As it can be seen in Fig.8 first the tube is extruded to the angular cylindrical channel by a cylindrical mandrel with two shear areas and the tube diameter increases to reach the maximum level. Then the new tube is extruded into the same channel so that the tube section returns to the original value. If the outer mold and mandrel are removed in the first and second stages, the friction is reduced. In this case performing the process periodically with high frequency will increase the applied strain and improve grading.

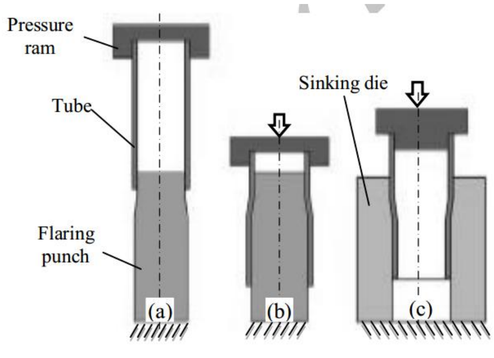

Fig. 8 Schematic of CFS process (a) initial state, (b) the flaring (first half-cycles) and (c) the sinking (second half-cycles) [10]

By applying this process on aluminum tube1050 the yield level became 165 and the ultimate strength increased to 173 MPa. The maximum replication of this procedure leads to the formation of grain boundaries with higher angle and increases aluminum strength [30, 31]. This method also increases the hardness of the material so that the tube hardness is 23 Vickers before the test and then it reaches 38 Vickers after10 replications. Firming grain boundaries with high angle from applying severe plastic stress can increase the hardness of the material [32]. This method is only for the channel angles to more than 150 degrees because at lower angles plastic strain is not applied appropriately due to the lack of hydrostatic pressure on the outer surface of the tubes. After applying one cycle of the process the average grain size is reduced from 68 to 1 micron. In severe plastic deformation methods a large part of energy is used to overcome the friction. In the CFS method the amount of friction is reduced because the contact surfaces are reduced. Another advantage of this method is the reduced cost of molds and the lack of need for high power equipment. On the other hand applying strain gradually creates strain uniformity and thus uniform mechanical properties along the tube [10].

g. Tube cyclic expansion-extrusion (TCEE) [11]

Tube cyclic expansion-extrusion method is shown in Fig.9. In this method curved cavities are created around the severe plastic deformation areas such that first some curves are created on some mandrels. Then the tube is located between the mandrel and mold and it is pressed and after expansion of the cavity the tube is forced into it and the material become micro structured by cyclic expansion-extrusion of the tube.

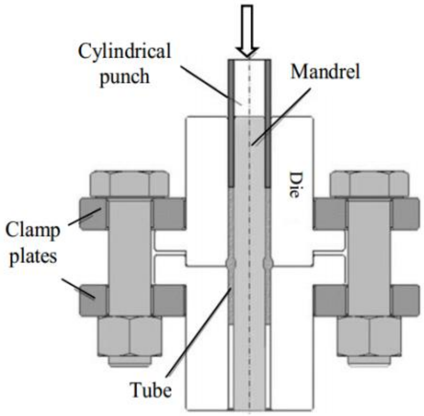

Fig 9- Schematic of TCEE [11]

After implementing two cycles on the magnesium tube with alloy AZ91 the material gradation was reduced from 150 micrometers to 1 micrometer [33]. The initial grain orientation relative to the adjacent grains affects the grain refinement [27] also by performing two cycles, the yield stress was increased by 2.9 times and the tensile strength was increased by 2.6 times. In this method tube formation also improves. This is one of the important advantages of this approach. Expensive equipment to create pressure behind the tube is one of the main disadvantages of this method [11].

h. Tube Cyclic Extrusion-Compression (TCEC) [11, 12]

This method can be done in two ways and does not require pressure behind the tube. In the first type (Fig.10 – a) the tube is located between the mandrel and inhibitor chamber from top to down that it has low looseness. So the tube is located in a place with constant volume and plastic deformation is quite manageable. Mandrel is passed through the tube by a ridge and the plastic strain is applied. In the second type (Fig.10 – b) the tube is moved by the up and down inhibitor and a ridge is created on the chamber. In this case the chamber is fixed and the tube moves. After crossing the ridge the tube is subject to plastic strain. In each cycle of this process a relatively high plastic strain is applied that will modify graining. This method has been applied on the tubes with three different materials: aluminum 1050, Magnesium AZ91 and pure copper CU [34].

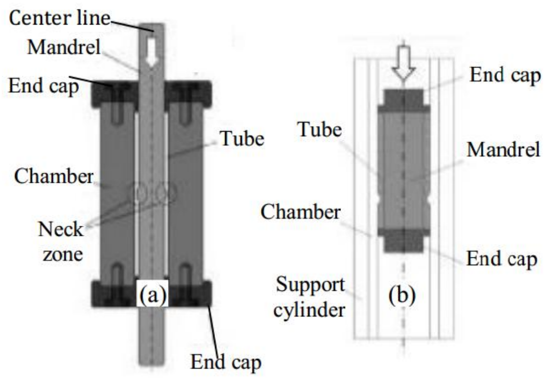

Fig.10 Schematic of TCEC (a) first Executive Style /[11] and (b) second Executive Style [12

By several iterations of this method on aluminum 1050 in addition to increased strength of the material, the non- uniform length change increases which could be due to reduced grain size and increased sensitivity to the rain rate [35, 36]. Several iterations of this method on pure copper have led to significant decrease in grain size but it has reduced material ductility slightly [37].

i. Repetitive tube expansion and shrinking (RTES)[13]

This method is composed of two half cycles. In the first part the tube is located in the mold and pressed under the punch pressure and it is converted into a tube with a greater diameter by passing through the groove. In the second part the tube with expanded diameter is again located in another mold and passes through the mold's groove by punch pressure and returns to the original diameter. As it can be seen in Fig.11 by the flow of the metal in the opposite direction of the punch movement a severe deformation is applied to the tube per cycle. By repeating this process it is possible to apply a severe plastic strain to the material and make the crystal structure of the metal micro structured.

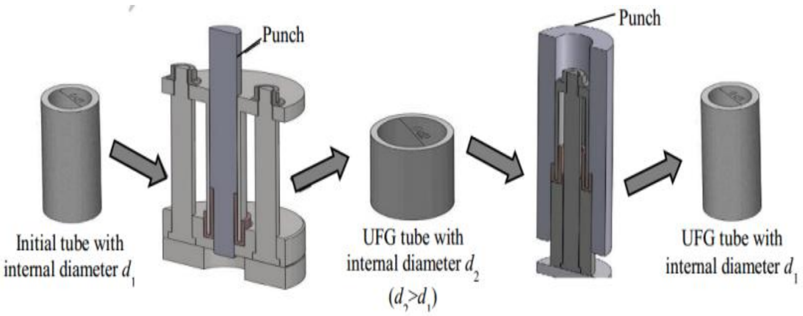

Fig 11.Schematic of RTES [38]

The highest strain applied to the material in this process is the shear strain. By increasing the number of iterations in this method, the created microstructure will be more uniform. By studying the tube's hardness it becomes clear that hardness is not uniform throughout the thickness of the tube. The greatest hardness is associated with the inner surfaces of the tube. Hardness is reduced by moving from the inner surface of the tube to the outer surface. Tube hardness is appropriate in terms of uniformity in both circumferential and axial directions [39]. This method presents significant results in terms of creating microstructure in alloy AZ91 so that by performing this process in the tubes made of this alloy just once, the average grain size is reduced from 150 micrometers to 700 nm. Performing this procedure on the aluminum alloy Al 1050 reduced the average grain size from 45 micrometers to 320 nm. By performing this process on the pure copper the average grain size below 100 nm is obtained [13, 40]. The stress-strain curves of aluminum Al 1050 after a half cycle and a full cycle of this process versus the annealed alloy is presented in Fig.12. As the Figure suggests, the tensile strength of the material increases the strength of the material by applying a half cycle compared to the annealing method.

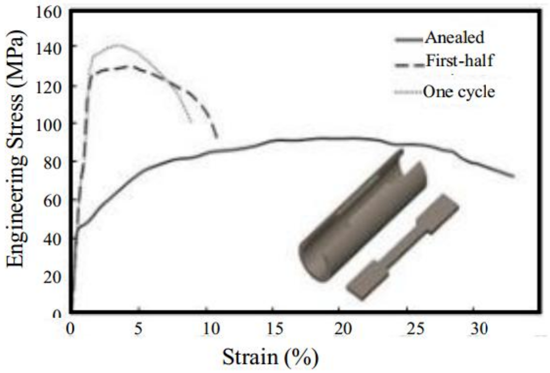

Fig12. Stress-strain curves obtained from the tensile tests [38].

4. Conclusion

Tubes are among the most important parts used in industry, thus increase strength and improving their mechanical properties is considered. Severe plastic deformation method is a new method that improved the material’s mechanical properties by micro structuring the crystal lattice of a metal. Various methods have been developed to manufacture such tubes in different sizes required by the industry. Each method has advantages and disadvantages that encourage researchers to develop and refine existing methods and develop new approaches. Some of the most important limitations of these methods are the tubes’ size, the time required for manufacture and the needed equipment and molds. Some of these methods can be used for the manufacture of tubes in various sizes by they require expensive molds and equipment with the potential to apply very high forces. Some methods have higher rate of production but they less improve the mechanical properties of the material. Some methods lead to the manufacture of relatively homogeneous tubes with good mechanical properties but in some methods this improvement in properties is just achieved in some aspects. In the end it cannot be claimed that what has been discussed contains all methods used for manufacturing tubes because every day new and developed methods are devised to meet the needs and shortcomings.

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