Analysis of the Bending Behaviors of U-Bend 316L Stainless Steel as a Teaching Material for Medical Implant Application

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ABSTRACT

The present paper deals with modifications to the bending behaviors of U-bend 316L stainless steel as a teaching implant material after the performance of a two-step cold forming process. The thickness of the 2.0 mm steel was reduced within the range of 10% to 50% using cold rolling process. The steel was then plastically deformed using a bending jig into a U-bend shape, with a final curvature radius of about 5.0 mm, by means of a bending process. This process was conducted according to a 3-point bend testing technique at a constant speed of 1.0 mm/min using a tensile machine in order to analyze the flexural strength of the U-bend steels. The resultant curvature of the steels were measured using a profile projector whereas spring back and strain effects were calculated through analytical approach. The findings revealed that the cold-rolled U-bend steel exhibited higher flexural strength compared to the U-bend steel without cold rolling process. Under cold-rolled conditions, a higher percentage of thickness reduction resulted in a greater increase in flexural strength. This increase was strongly influenced by internal stresses, resulting in greater spring back and strain effects.

Keywords: Bending behavior; Cold forming process; U-bend 316L stainless steel; Medical implant

INTRODUCTION

Bending is a common mechanical process in metal forming in almost all steelmaking industries. Generally, metal forming is a secondary process which is carried out using additional tools or machines at sufficient pressure and speed during the operating process to produce curved products or components. The size and thickness of the metal are two main factors to be considered in order to achieve better formed products. Any dimensional changes are normally done before the bending by means of other processes such as rolling, forging and drawing. Another factor is the type of metallic material, which is important for applications where safety is of prime concern, for example, the use of metal in the construction of medical products such as implants and instruments. This application requires the selection of suitable materials in the design stage and a higher precision tool during the manufacturing process. 316L stainless steel has reportedly become the dominant material to be used in this particular application (Asri et al., 2017, Chew et al., 2012 and Wong & Bronzino, 2007). The 316L grade not only has excellent resistance to corrosion, but also has better formability in the cold forming environment.

In this application, manufacturers have fabricated medical implant products made of 316L stainless steel using several codes, standards and specifications, as required by the customers, or by referring to the standards of other well-recognized organizations such as ISO and ASTM. The products, either in a flat or curved shape, are available in different sizes and thicknesses. These dimensional variations refer to the type of forming techniques performed within the manufacturing process. In general, cutting, forming and other alternative machining processes are used during fabrication of 316L stainless steel and other metal-based medical devices (Bombac et al., 2007). For medical implants used in orthopaedic applications, the flat products are fabricated using a common

mechanical process, such as rolling, forging and wire drawing. These cover numerous types of surgical 316L grade fixation plates and nail implants with various thicknesses and sizes. The curved products, which include semi- or quarter-tubular plates, are normally fabricated by the bending process. The more complicated products, such as hip and femoral implants in variable shapes and sizes, are generally fabricated using a casting process.

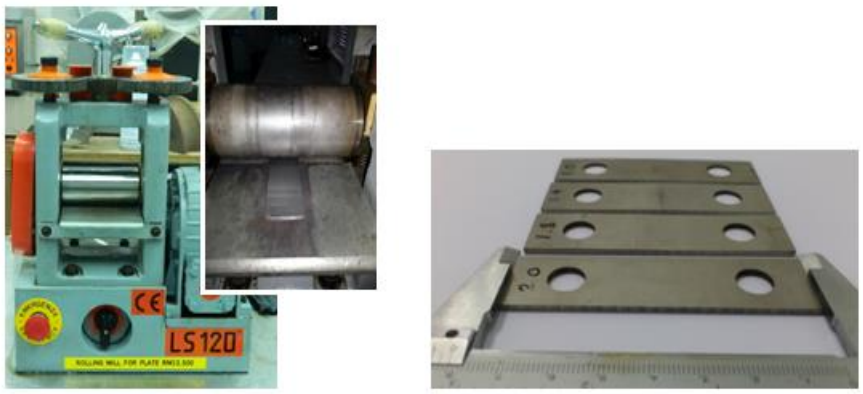
Extensive researches have been carried out on deformed 316L steel in cold-rolled conditions, with a few researches having been carried out on the bending conditions. For cold-rolled steel, past researches investigated the relationship between the process, microstructure and properties (Wang et al., 2018, Hou et al., 2013 and Silva et al., 2011); and on improving the structures and properties using additional surface and heat treatments (Eskandari et al., 2013 and Kumar et al., 2011). For bent steel, previous researches investigated elas-tic bending with a small deflection. These studies covered the evaluation of bending behaviors and stress, and the distribution of strain using analyses, simulations or experiments, either individually or in combination (Quach et al., 2004 and Tan et al., 1994). Similar approaches were also used for steels with large deflections, such as C-rings, V-bends and U-bends. These bent shapes are prepared according to the recommendations of the organizational standard. The U-bend is the more difficult one among the bent shapes because of the unknown stress conditions (Sedricks and Syrett, 1990). From the literature review, researches have been conducted on U-bend alloys, but these have focused more on the evaluation of the stress corrosion cracking (SCC) behavior, rather than on the influence of the forming process on the mechanical and microstructure evolution (Prosek et al., 2009).

Therefore, this study emphasized the modification of the bending behaviors of the mechanically-treated U-bend 316L stainless steel. The deformed steel, with a reduction in the variable thickness, was prepared earlier using two step-cold forming process. The spring back and the strain condition of the deformed steel were also experimentally investigated.

METHODOLOGY

This study used the 316L stainless steel in its as-received condition in the sheet metal roll with an initial thickness of 2.0 mm. The steel was cut into 85.0 mm x 25.0 mm pieces, before being labelled as cold-rolled specimens. The cold-rolled specimens were prepared using a LS120 motorized single rolling mill as shown in Figure 1 (a). The specimens were prepared with thicknesses of 2.0, 1.8, 1.4, and 1.0 mm, corresponding to thickness reductions of 0%, 10%, 30%, and 50%, respectively with the final dimensions being 80.0 mm x 20.0 mm. Two holes, with a diameter of 10.0 mm, were also made on both sides of the specimens as shown in Figure 1 (b). A set of three specimens was used for each particular thickness reduction.

Figure 1: (a) Cold rolling process and (b) a set of the specimen with the two holes on both side



(a) (b)

The bending process was carried out according to the ASTM G 30-97, using a two-stage stressing procedure (ASTM G 30, 1997). In the first stage, the bending process was done through a 3-point bending test with a support span of 20.0 mm. The test was carried out using a flexural loading mode to analyze the flexural strength (σ_f) of the U-bend specimens. The sequence of the 3-point bending test is shown in Figure 2. The test was performed at room temperature using a bending jig that was attached to a servo-hydraulic Instron 8802 tensile

machine system with a capacity of 250 kN. The jig was locally fabricated with a bend radius of about 4.5 mm. The test was conducted at a slow strain rate of 1.0 mm/min. Prior the test, the specimen with a dimension of 80.0 x 20.0 mm was placed in the specimen holder of the bottom jig. It was marked at the centre, 40.0 mm from both ends to obtain a symmetrical U-bend shape. Three repeated tests were conducted on each specimen, and the average strength was calculated from the results. The second stage of the bending process was performed by manually subjecting the specimen to stress until the U-bend shape was finally obtained. A set of the specimens after the unbending are shown in Figure 3.

Figure 2: Sequence of 3-point bending test at (a) initial insertion setup, (b) apply the bending load, (c) release of the load and (d) specimen's removal from the jig

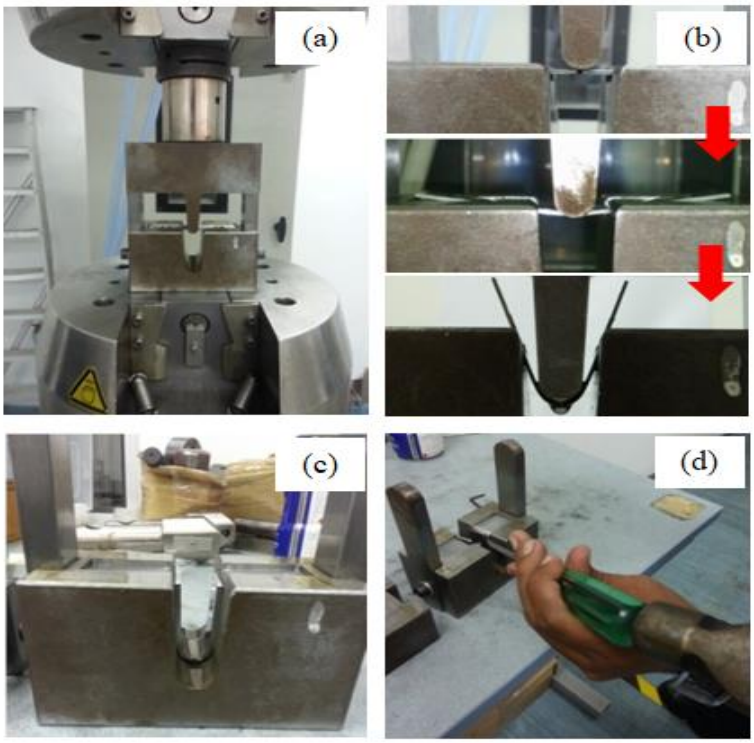


Figure 3: The specimens after unbending. Note that U-bend specimens with a thickness reduction of 0, 10, 30 and 50% are shown from left to right



The resulting curvatures after the unbending of all the U-bend specimens were measured using a DS600 profile projector, as shown in Figure 4. The equipment was equipped with a Digital Readout (DRO) system, and the final displacement (D), the radius of curvature (R), and the bend angle (α) were measured at the 2, 5 and 4 points, respectively. The sequences of the curvature measurement are shown in Figure 5.

Figure 4: DS600 profile projector including its main components

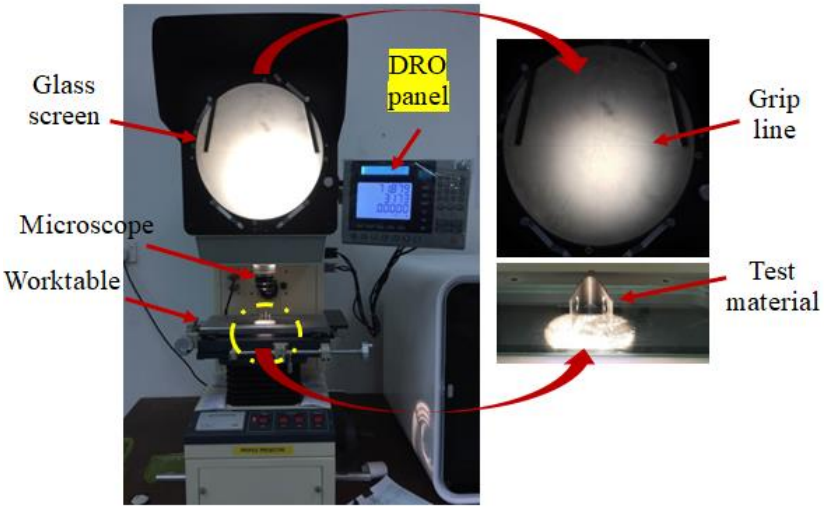
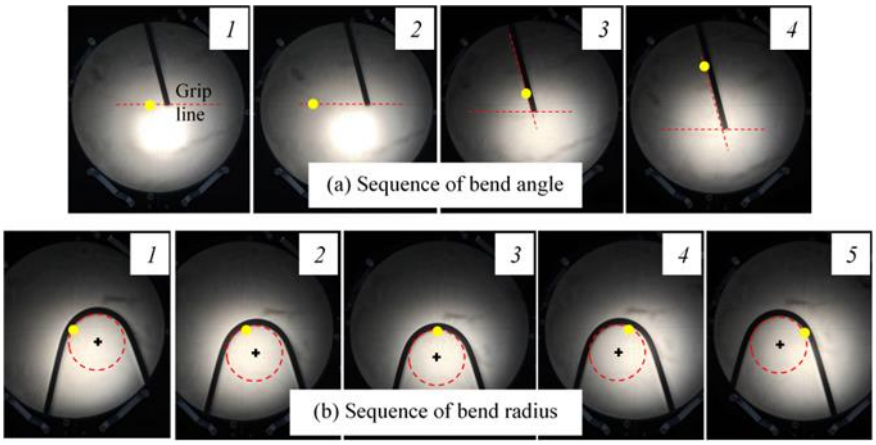
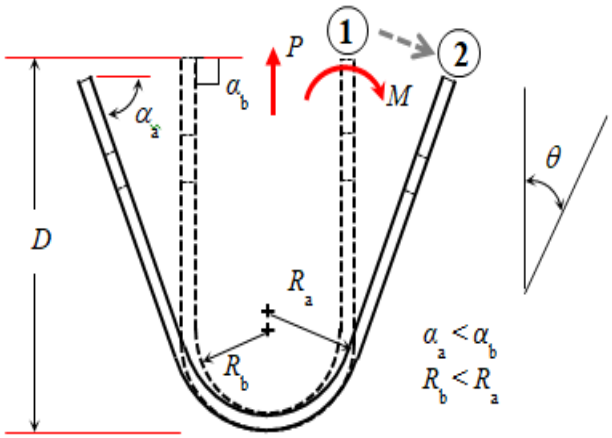


Figure 5: Sequence of the measurement of (a) bend angle using angle method and (b) bend radius using circle method for the U-bend specimen after unbending



The geometry of the sheet specimens during the bending process and the parameters used in determining the spring back and strain effects are shown in Figure 6. All measurements were taken three times for each specimen to ensure consistency and repeatability. During the process, the legs of the U-bend specimens moved spontaneously to their maximum distance from position 1 to 2 after the release of the load, P. The bending behaviors of the U-bend specimens were predicted according to the measurement of the resulting curvature in combination with the bending equations.

Figure 6: Geometry of the specimen sheets



For the rectangular sheet metal, the bending stress (σB) and strain (εB) were measured using a bending equation:

$$\sigma_B = \frac{3PL}{2bh^2} \quad (1)$$

$$\varepsilon_B = \frac{6Dh}{L^2} \quad (2)$$

where P is equal to a bending load (N), L is equal to the support span (mm), b is equal to the width of the specimen (mm), h is equal to the thickness of the specimen (mm) and D is equal to the maximum deflection of the centre of the specimen (mm). The equation, which was already stored in the tensile machine, was applied within the 3-point bending test.

Another term used for the U-bend metal was the total strain outside the bend (ε), which was estimated using equation (ASTM G 30):

$$\varepsilon = \frac{h}{2R} \quad (3)$$

where h is equal to the thickness of the specimen (mm) and R is equal to the radius of curvature (mm).

From the literature, this is a reliable equation with regard to the U-bend shape. The strains were analysed according to the position at the maximum deflection before and after unbending, and were referred to as ε_b and ε_a, respectively. In Figure 5, these conditions were referred to as position 1 and 2, respectively.

The percentage of strain changes were then calculated using the equation:

$$\Delta\varepsilon = \left(\frac{\varepsilon_a - \varepsilon_b}{\varepsilon_a}\right) \times 100\% \quad (4)$$

where the limit of strain of the U-bend specimen at the position before and after the unbending was then estimated.

Furthermore, the spring back phenomenon was estimated from the resultant curvature of the U-bend sheet material. It referred to the spring back ratio (K_S), using the equation (Dieter, 1988):

$$K_s = \frac{\alpha_a}{\alpha_b} \quad (5)$$

Another formula for the KS is:

$$K_s = \frac{\left(2R_b/h\right)+1}{\left(2R_a/h\right)+1} \quad (6)$$

Equation (6) can be written as:

$$R_b = \frac{h\left\{\left[K_s\left(2\frac{R_a}{h}\right)+1\right]-1\right\}}{2} \quad (7)$$

in order to calculate the radius of curvature before unbending. With reference to equations (5) to (7), α_b is the bend angle (°) of the specimen before unbending, α_a is the bend angle after unbending, and R_b and R_a are equal

to the radius of curvature (mm) before and after unbending, respectively. In addition, the spring back angle (θ) was measured from the differentiation of the bend angle before and after unbending.

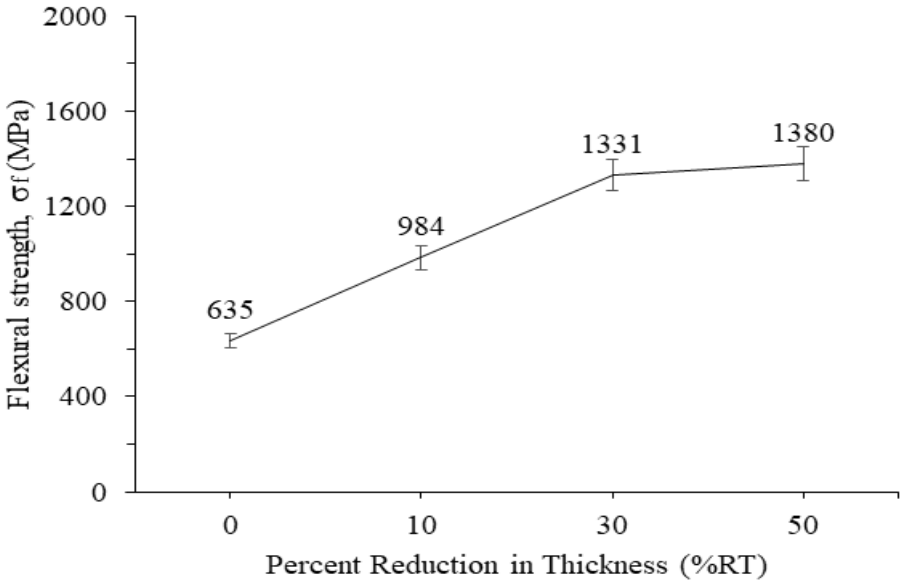
RESULTS AND DISCUSSION

Bending properties

The average flexural strength (σ_f) of the U-bend 316L stainless steel are shown in Figure 7. There was a significant increase in the flexural strength of the U-bend 316L stainless steel which had previously undergone the cold rolling process. The strength was increased from 984 MPa to 1380 MPa for the steel with 10% to 50% thickness reduction. Also, the strength becomes closer for both U-bend 316L stainless steels after heavy deformation (greater than 30%). As comparison, the specimens without cold rolling process, where the value was 635 MPa. The fast increment of the flexural strength was mostly due to the influence of the grain modification mainly by cold rolling. The extensive thickness reduction increased the number of surface defects such as dislocations and twins.

Another important factor which influenced the rapid increment of the strength was the formation of residual stress. During the forming operation, the steel was deformed with twice the plastic deformation, starting with the rolling and then, the bending process. In the rolling process, the steel contained high compressive residual stresses at the surface and a tensile residual stress at the centre. In the bending process, the stresses were simplified as tensile stress near the concave surface and compressive stress near the inside surface, while at the centre, the steel contained both tensile and compressive residual stresses. Thus, the two-step forming process greatly affected the strength of the U-bend steel by producing greater residual stresses.

Figure 7: Flexural strength of U-bend 316L stainless steel



Therefore, it can be summarized that the type of metal forming process highly affected the bending properties of the deformed steel. The cold rolling extensively modified the internal structure as well as generated a higher residual stress, which led to a greater increase in the bending properties.

Spring back

Spring back is another characteristic of bending which normally occurs in curved shape materials. According to the principles of metallurgy, spring back is defined as a dimensional change in the formed metal after the load or pressure of the forming tool has been released (Dieter, 1988). It is also known as an elastic recovery produced by changes in the strain of the formed metal before and after the release of the load. The U-bend specimens shown in Figure 3 were firmly produced by spring back. Generally, there are certain factors such as the elastic

modulus, yield strength, thickness and bend radius that influence the amount of spring back that occurs in any bent material (Gedeon, 2009). The material with a higher strength and lower elastic modulus will have a greater range of elastic to plastic strain, and exhibit more spring back. Also, the thinner and larger bend radius of the sheet metal will increase the spring back. In the present study, the modulus had no influence on the spring back, the reason being that a similar sheet metal of 316L stainless steel was used. As mentioned in a previous study, the elastic modulus of the steel was shown to have an identical value to the steel in the cold-rolled state (Mohamad et al., 2015).

Another factor that may influence the spring back is the type of cold forming process, since the U-bend steels were previously prepared through two different processes. As shown in Figure 7, the steel with the cold rolling process showed an increase in flexural strength from 984 MPa to 1380 MPa. Thus, the cold rolling process produced a higher strength, which led to a greater spring back. Tan et al. (1994) studied the stresses in the bending of the sheet metal with a small deflection using an analytical approach, and they came to the conclusion that the stress after unbending was the sum of the stress before unbending and the elastic spring back stress, and it could be expressed as $\sigma a = \sigma_b + \Delta\sigma$. In the present study, the relationship was used as general guide in order to hypothesize the stress condition in the U-bend steel with the two-step forming process.

A further analysis was done based on the resulting curvature before and after the unbending, including the bend radius. Generally, the greater the spring back, the lesserthe α_a and K_S, and the higher the θ and R_a, with both legs of the U-bend steel moving away from each other. The bend angle before unbending, α_b of all the specimens was 90°, where both the legs were kept parallel.

Table 1 shows the resulting curvature of all the U-bend specimens. The measurements represent the mean values obtained from three specimens.The U-bend steel without the cold rolling process had a curvature, R_a of 5.00 mm and α_a of 85.13°. The difference between the bend angle before and after the unbending, or spring back angle, θ was 4.87°, which means that the steel had a lower spring back compared to the other mechanically treated steels.

Table 1: Resulting curvature and its related parameters in the U-bend 316L stainless steel

Sample description	**Percent reduction in thickness, %RT**	**Bend angle after unbending, αa (°)**	**Radius of curvature after unbending, Ra (mm)**	**Spring back ratio, Ks**	**Radius of curvature before unbending , Rb (mm)**	**Spring back angle, θ (°)**
U-bend without cold rolling	0	85.13±0.30	5.00±0.05	0.9459±0.003	4.68±0.07	4.87±0.30
U-bend with cold rolling	10	81.16±0.41	5.22±0.03	0.9018±0.005	4.62±0.05	8.84±0.41
	30	74.69±0.73	5.48±0.02	0.8299±0.008	4.43±0.05	15.31±0.73
	50	66.22±1.66	5.74±0.04	0.7357±0.018	4.09±0.09	23.78±1.66

A higher spring back was obtained in the U-bend steel with the cold rolling process. This could be clearly seen from the rapid increment of the R_a and α_a, where both parameters were changed from 4% (5.22 mm) to 15% (5.74 mm) and from 5% (81.16°) to 22% (66.22°), respectively for the steel with a cold reduction within the range of 10% to 50%. In other words, the higher the cold reduction, the higher the spring back that occurred. These modifications may also have generated a large amount of residual stress, which rose higher for the steel with exten-sive cold reduction. Therefore, the spring back occurred with greater elastic stress.

From the analysis, it can be summarized that the U-bend steel with the mechanical treatment had a greater effect on the spring back. This can be simplified as: cold rolling process > as-received. This was because the cold-rolling process produced enhanced grain hardening and developed a relatively higher amount of residual stress,

which led to a greater spring back. Also, it showed a good agreement with the preliminary statement that the strength, thickness and resultant curvature influence the spring back.

Strain effects

The bending process with a large deflection on the steel also generates some amount of strain. From the book of Material Science, the deformation by this forming process produces some fraction of energy, which is stored in the metal as strain energy (Callister, 2007). The existing energy around the newly-created dislocation is associated with tensile, compressive and shear zones. As stated in the preceding section, for curved steel, the strain at the concave surface was in high tension compared to the compression on the inside surface. The strain had been predicted based on the total strain (ε) outside the bend of the steel. The effect of the cold forming process on the strain condition of the U-bend steel is shown in Table 2. The average values of the three identical specimens were obtained before and after the unbending. The percentage of strain change (Δε) in all the specimens are also indicated in the table.

The results show that there was a small difference in the strain condition, although the U-bend steel with variations in the thickness reduction had been prepared using cold rolling process. However, all the U-bend steels showed a similar trend, where ε was reduced with a thickness reduction for both positions before and after the unbending. The values most likely depended on the geometrical changes to the steel as, according to eq. (3), the strain is directly proportional to the thickness of the metal. In other words, it appears that the forming processes had no influence or less influence on the strain produced in the steel.

Table 2: Strain condition of U-bend 316L stainless steel

Sample description	**Percent reduction in thickness, %RT**	**Total strain after unbending, ε_a (mm)**	**Total strain before unbending, ε_b (mm)**	**Percentage of strain changes, Δε (%)**
U-bend without cold rolling	0	0.1999±0.0020	0.2138±0.0031	6.50
U-bend with cold rolling	10	0.1724±0.0008	0.1949±0.0021	11.54
	30	0.1277±0.0004	0.1581±0.0018	19.23
	50	0.0871±0.0006	0.1222±0.0026	28.72

The effects of the processes could be seen in the measurement of the strain changes. The U-bend steel without any mechanical treatment showed a low Δε of less than 7%. A linear increment was observed for the steel with the cold rolling process within the range of 11% to 28%, respectively. The steel in the cold-rolled state had already generated such strain energy before undergoing the bending process. These fractions of energy became higher for the steel with an extensive cold reduction of up to 50%. The strain energy was only produced after the bending operation. Thus, it can be stated that the steel with the greater change in strain had a higher mechanical effect.

Futhermore, the strain condition of all the U-bend steels revealed a similar pattern, as follows: for all the U-bend steels, total strain after unbending, ε_a is less than total strain before unbending, ε_b. The reduction in the strain was mostly due to the release of the strain energy. The steel specimens were plastically deformed to the U-bend shape using a bending load at a slow speed 1.0 mm/min. At the position before unbend-ing, the grain structures had been modified by generating some fraction of strain energy. After unbending, the spring back occurred with a "free" loading mode, where both legs of the U-bend were quickly turned back to the previous path. The elastic deformation after unbending would probably have released some energy in the steel with the cold-rolled effect.

From the analysis, the strain condition of the U-bend steel had been correctly predicted using a combination of analytical and experimental data obtained from the measurement of the resulting curvature. The results of the

analysis showed that the equations are not only valid for the condition before and after the unbending, but may also apply to the steel with the influence of the cold rolling process. The analysis was carried out by estimating the total strain outside the bend and not the specific local strains produced at the tensile or compressive surfaces during the plastic deformation. Thus, it would be fair to state that the amount of strain was mainly influenced by the spring back, which varied according to the percentage of thickness reduction after cold rolling process.

CONCLUSION

This study attempted to look at the bending behavior of the U-bend 316L stainless steel as a teaching material for medical implant application. The bending characteristics after the formation of the U-bend structure were determined analytically and experimentally. From the analysis of the deformed steel, it was concluded that:

1. The 3-point bending test showed that the U-bend steel with cold rolling had a greater effect on the bending properties than the U-bend steel without cold rolling process. The higher percentage of thickness reduction caused a greater increment in flexural strength.

2. The relationship between the spring back and strain behavior of the deformed steel was established using the resulting curvature and the related bending equation. The spring back effects were greater for the U-bend steel with the cold rolling process. This phenomenon also contributed to the changes in the strain.

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