Characterization of Microstructure and Bending Response of Sheet Material: Influence of Thickness

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ABSTRACT

Bending process is one of the most significant fields of application of sheet metal die. In the bending process, it is quite vital that the product should have the desired angle. Furthermore, in order to obtain the desired angle in the bent parts, spring-go and spring-back amounts must be known. In this study, 30^{o}, 60^{o} and 90^{o} bending processes were applied to the S235JR (1.0038) sheet metal having 3, 4, 5 and 6 mm thicknesses. These materials were bent in three forms as heat-untreated, normalized, and tempered. In addition, the bending process was carried out by making the punch waited on the material for 30 seconds (30 s-punch-wait bending) and by removing the punch without waiting (direct bending). As a result of the experiments it was determined that while the amount of spring-go increased in the 30^{o} bending process depending on the thickness of the material, it decreased in the 60^{o} and 90^{o} applications. It was also determined that the amount of spring-go in 30 s punch-wait bending process was less than that of the direct bending process. Finally, the effects on the bending process and deformation of heat treatment were revealed by micro-structural characterization.

1. Introduction

Identical parts which should be produced in great numbers and in mass-production are usually produced by using sheet metals or plastic injection mold depending on the usage area. Sheet metal die has a great significance in low-cost production of the products which are manufactured from sheet metal and used for several purposes in daily life and industry, because by means of sheet metal dies, the pieces can be produced in desired shapes and sizes in mass-production without chip removing. For instance, bending dies are used to produce chassis, crankshafts, dumps, axle sleeves in automotive industry; machine frames, commercial fans, wagons in machine industry, roofs, bridges, and beams in steel constructions.

When bending process is applied, compressive and tensile stress occur in the inner and outer surfaces of the material, respectively (Fig. 1) and, as a result, inner surface shortens and outer surface elongates. When the tensile strength is greater than the compressive stresses, spring-go occurrs [1].

When the force which is applied on the sheet

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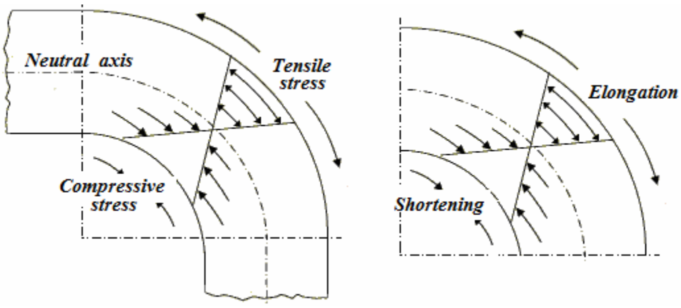


Fig. 1. Compressive and tensile stresses occuring during the bending process

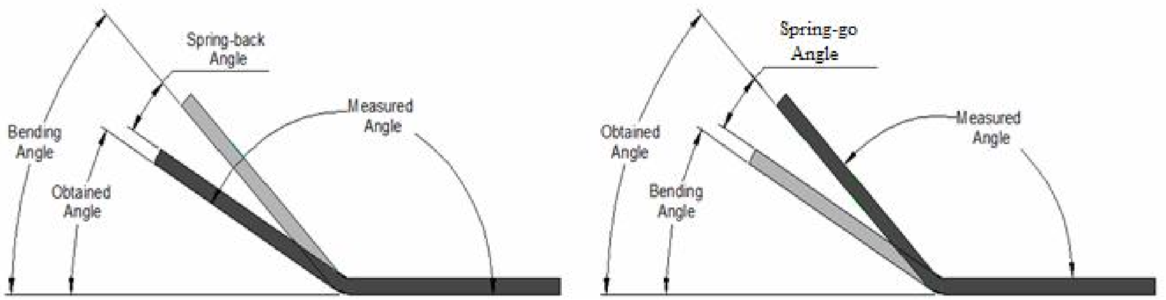


Fig. 2. Determination of spring-go and spring-back

material is removed, a backward motion occurs due to elastic stress, which causes a little bit spring-back in the sheet (Fig. 2a). Obtaining a larger angle than expected in the sheet material is called spring-go (Fig. 2b).

A great number of studies have been carried out on spring-back and spring-go. Bakhshi-Jooybari et al. [2] studied the spring-back and spring-go of the CK67 steel sheet in V-die and U-die bending processes. Sheet anisotropy and punch tip radius on the spring-back/go in V and U die bending processes of the CK67 steel sheet by cutting it with 0°, 45° and 90° rolling directions have been realized. The results of the experiments were also compared with those of the finite element simulations. Ragai et al. have studied the effect of sheet thickness, sheet anisotropy, material property, friction coefficient, punch-tip, and size on spring-back and spring-go [3]. Branko et al. have studied spring-back and spring-go which occurred as a result of the bending of the St1403 sheet material in the V-bending die by using the finite element method (FEM) [4]. Thipprakmas used the coined-bead method in the V bending process and analyzed the amount of spring-go and spring-back by using FEM [5]. Imai et al. have some studies which have taken the material properties into consideration in the V-bending dies [6]. Li et al. have simulated the effect of material thickness on spring-back and spring-go in the V-bending die [7]. Thipprakmas et al. [8–11] investigated the spring-back and spring-go phenomena, as well as the effects of punch height and the ratio of punch to workpiece length on the V-bending process using the finite element method and Taguchi technique. Panthi et al. [12] studied the spring-back prediction of sheet metal bending process by using FEM.

It is not only the occurrence of spring-back but also the occurrence of spring-go that has effect on the bending angle. In recent years, the spring-go has also been conducted to understand the bending feature as well as to achieve the accuracy of the bending angle. Dilipak et al. [13] used S235JR (1.0038) materials having a thickness of 4 mm were bent with 90º punches having 5 different tip radii. The bending process was carried out by making the punch waited on the material for 30 s (30 s waiting bending) and by removing the punch without waiting (direct bending). Specimens were prepared in three forms as non-heat-treated, normalized and tempered. Ozdemir and Dilipak used S235JR materials which were cold, normalized and tempered (10 and 30 min.), bent for 90º bending process. Materials

Table 1. Chemical composition of the sheet material in weight percentage

C	Si	Mn	P	S	Mg	Cr	Co	Ni	Mo	Cu	Ti
0.059	0.263	0.702	0.017	0.004	0.0005	0.021	0.007	0.037	0.005	0.06	0.002

Table 2. HRB hardness values and tempering durations of the S235JR (1.0038) sheet materials

		Without deformation zone			*Deformation zone*		
Sheet Thickness (mm)	Tempering Duration (min)	Heat-untreated	Normalizing Process	Tempering Process	Heat-untreated	Normalizing Process	Tempering Process
3	7	165.6	140.3	154.3	182.7	168.7	182
4	10	167.3	143.1	155.7	183	153	160
5	12	183.7	145.7	166.3	210	162.3	180.7
6	14	188.2	152.3	172.1	196	168.3	186.7

with 4 mm thickness were bent with 6 mm punch radius. At the end of the experiments, when tempering time of the S235JR sheet metal increased, the ideal bending angle was obtained [14].

In this study, in parallel with previous studies in literature, the amounts of spring-go were examined. During this study, the amount of spring-go which occurred as a result of the bending of the materials with different thickness was determined. Furthermore, we also studied the effect of heat-untreatment, normalizing and tempering, which were applied to the materials, on spring-go.

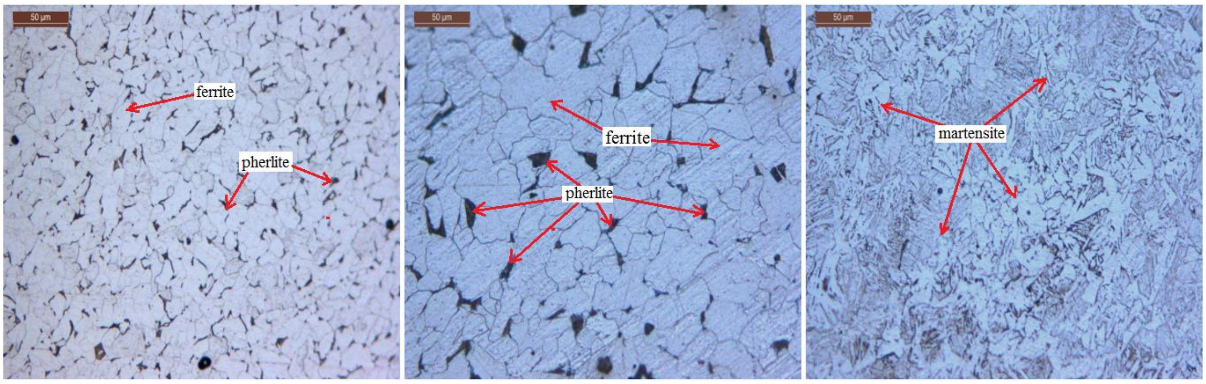
2. Experimental

Material properties and bending parameters (material properties, sheet anizotropy, bend angle and bend curvature, bending force, and process parameters etc.) are the factors which make the estimation of spring-back and spring-go difficult [15-18]. In this study, the materials with 3, 4, 5 and 6 mm thicknesses and with 30x60 mm dimensions were prepared by cutting with hydraulic shear. The chemical composition of the material in weight was given in Table 1.

The experimental specimens were prepared in dimension of 30x60 mm depending on their thickness by cutting in the rolling direction (0^o) with hydraulic shear. The burrs formed during the cutting process were removed.

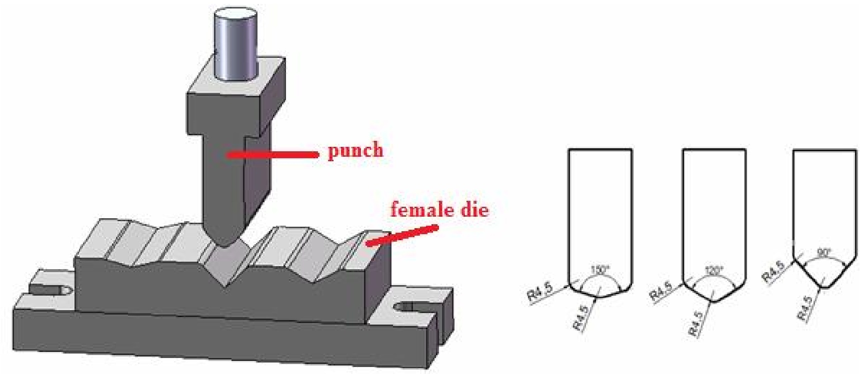
The sheet materials were heated up to 920^{o}C in normalization process, which is one of the heat treatment methods, and then they were left to air cooling [19]. The materials, however, were heated up to 880^{o}C in the second process called tempering and dipped into 20-40^{o}C distilled water. Since tempering causes cracks in the completely cooled quenched materials, we placed the materials into the furnace for the tempering process when their temperature was about 60-80^{o}C. The specimens were waited in 400^{o}C furnaces depending on their thickness and their tempering durations, as shown in Table 2. Afterwards, they were taken out of the furnace and left to cooling. When the specimens were cooled to room temperature, they were exposed to the bending process. In the hardness tests of experiment samples, macro hardness measurements were conducted with INSTRON WOLPERT DIATESTOR 75551 device by using 0,500g load. HRB hardness parameters of without deformation and deformation zones of the materials are shown in Table 2.

At room temperature, plastic deformation applied to materials of different thickness causes the deformation of of the crystals and grain boundary. Therefore, the grains are elongated in the direction of forming. As a result of the bending process elongations occur in the structures of materials. With the increasing amount of deformation dislocation density increases as well. For density increase dislocation movement complicates, hardness



a b c

Fig. 3. Microstructural images ofthe pre-bending process experiment specimens; a) heat-untreated, b) normalized, c) tempered



a. Bending-die **b. 30°, 60° and 90°bending punches**

Fig. 4. The bending die and bending punches used in the experimental study

and strength of the material increases [20,21]. With the increase in the amount of deformation, increase of hardness values are shown in Table 2.

The microstructure images of the materials that were prepared with 3, 4, 5 and 6mm thicknesses of heat-untreated, normalized and tempered samples before the bending process are shown in Fig. 3.

Male punch and female die of the bending-die used in the study were made out of the AISI 1390 spring steel in CNC vertical processing center. There might be cracks in the bending-die materials because of the impact. Therefore, in order to avoid the stress in microstructure of the die-material, tempering process was applied. Fig. 4a shows the bending-die and Fig. 4b shows the bending punches. The punch-tip angles were set as 4.5 mm.

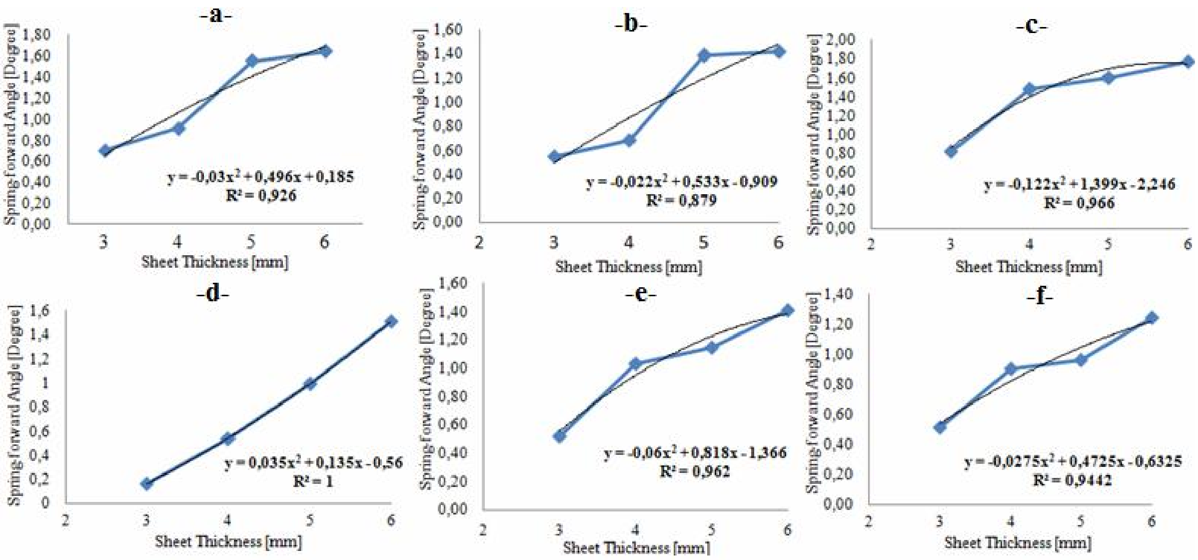
The pieces obtained from the bending process were measured using a protractor and then each piece was measured sensitively by using 1 minute sensitive profilometer. By this way measurement errors were minimized and reliability of the results was ensured.

In the experiment series, 720 sheet materials with 30x60mm dimensions were bent by heat-untreating, normalizing and tempering. The bending parameters are shown in Table 3. Each experiment was repeated 10 times and the results of the experiments were compared to each other. Furthermore, the spring-go diagrams of heat-untreated, normalized and tempered sheet metals in direct bending and 30 s punch-wait bending processes were created. Experiments were made at free bending force and 25 m/min punch drop speed.

In order for investigating the changes in the deformation zones pre and post bending process, respectively, sanding, polishing and etching process were applied. % 5 Nital solution (5ml HNO_3, 95 ml H_2O) was used as an etchant. Later, microstructure observations

Table 3. The bending parameters used in the experimental study

Sheet thickness S, mm	Bending Method																	
	Heat-untreated						Normalized						Tempered					
	Direct			30 s punch wait			Direct			30 s punch wait			Direct			30 s punch wait		
	Bending Angle (Degree)																	
	30°	60°	90°	30°	60°	90°	30°	60°	90°	30°	60°	90°	30°	60°	90°	30°	60°	90°
3, 4, 5, 6																		



(a) Heat-untreated, direct bending (b) Heat-untreated, 30 s punch-wait bending (c) Normalized, direct bending (d) Normalized, 30 s punch-wait bending (e) Tempered, direct bending (f) Tempered, 30 s punch- wait bending

Fig. 5. The diagrams showing the spring-go amounts obtained from the 30° bending process and the obtained polynomial curve equations

were carried out with Leica optical microscope.

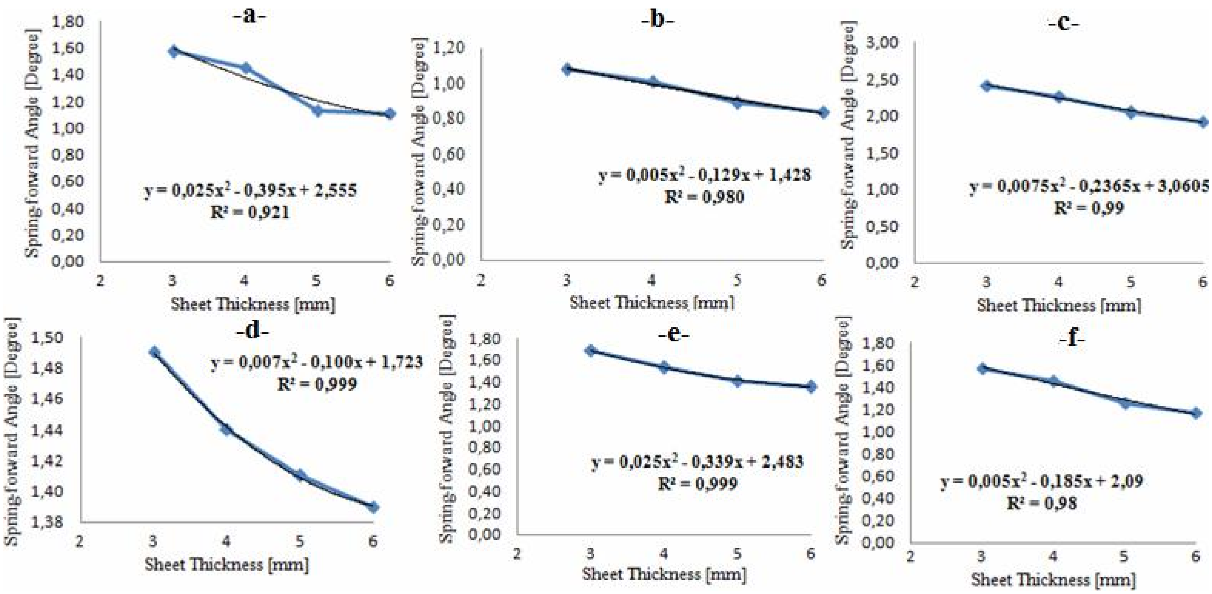
3. Result and discussion

3. 1. The 30° bending experiments

The results obtained from the 30° bending process of 3, 4, 5 and 6mm-thick experiment specimens are shown in diagrams in Fig. 5.

During the forming process applied on the sheet materials, when the load was removed from the material the bending angle of the sheet material increased and, as a result, certain amount of spring-go occurred. Fig. 5 shows that the thicker was the material, the greater spring-go amount was obtained. The lowest spring-go amount was measured as 0.16° in the 30 s punch-wait bending process of the 3mm-thick normalized sheet material (Fig. 5d). The highest spring-go amount was measured as 1.77° in direct bending process of the 6mm-thick normalized sheet material (Fig. 5c).

The lowest amount of spring-go was obtained in 30 s punch-wait bending process of the normalized material (Fig. 5d). The greatest amount of spring-go, however, was obtained in direct bending process of the normalized material. As for the material hardness, it was determined that the hardness of the normalized materials decreased (Table 2). When this material which had the lowest hardness value of all the experiment specimens was bent with 30 s punch-wait bending method, it was detected to have an effect on homogenous distribution of the load applied to punch contact area and homogeneity of the residual stress depending on the waiting duration. Therefore, the material, whose internal stress decreased, was thought to remain in the angle which was near to the bending angle. Whereas, when the



(a) Heat-untreated, direct bending (b) Heat-untreated, 30 s punch-wait bending (c) Normalized, direct bending

(d) Normalized, 30 s punch-wait bending (e) Tempered, direct bending (f) Tempered, 30 s punch- wait bending

Fig. 6. The diagrams and polynamial curve equations showing the spring-go amounts obtained from the 60° bending process

normalized material was exposed to direct bending, the material in which plastic deformation occurred had a bit more deformation following the force removal and this caused some increase in spring-go.

There was no significant statistical difference between the results of direct bending and 30 s punch-wait processes of the tempered and heat-untreated materials (Fig. 5e and 5f). We observed homogenously-distributed, tough and relatively ductile material properties in tempered materials due to microstructure transformation, which was a classical stress relieving and tempering behavior [20].

The materials whose toughness increased due to tempering were observed to have a smaller amount of spring-go compared to the unprocessed materials. When compared to the 30 s punch-wait bending process, direct bending process had greater amount of spring-go proportionally, depending on the material thickness.

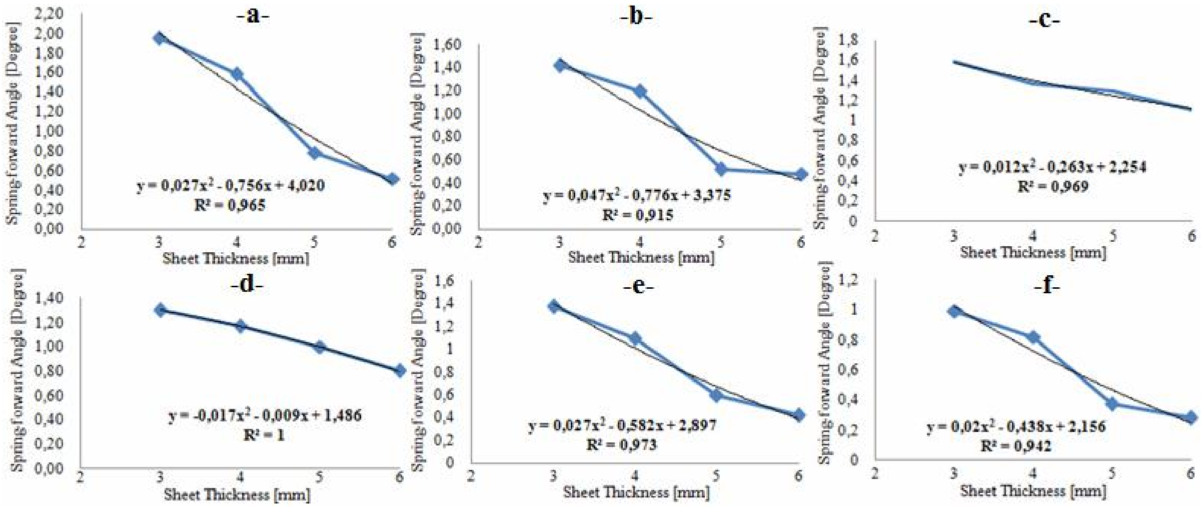
3. 2. The 60° bending process experiments

The results obtained from the 60° bending process of the specimens are shown in the diagrams in Fig. 6.

In the 60° bending process, it was observed that the greater was the thickness of the material, the less amount of spring-go did we obtain (Fig. 6). When the results were assessed according to the bending parameters, it was clear that the best result was obtained in the heat-untreated, 30 s punch-wait bending process of the materials (Fig. 6b). The lowest amount of spring-go was measured as 0.84° in the 30 s wait bending process of the 6mm-thick heat-untreatedsheet material (Fig. 6b). The greatest amount of spring-go was measured as 2.41° in direct bending process of the 3mm-thick normalized sheet material (Fig. 6c).

As a result of the measurements, it was determined that hardness values of the normalized materials were lower than that of the heat-untreated and tempered materials. It was thought that due to having low hardness value, normalized sheet materials had greater amount of spring-go in the bending processes. That punch was waited on the material for 30 s during the bending process caused plastic deformation in the bending area of the material. Since the internal stress, which has an effect on spring-go, was distributed due to plastic deformation caused by punch-wait, spring-go amount decreased.

When their hardness values were compared, it



(a) Heat-untreated, direct bending (b) Heat-untreated, 30 s punch-wait bending (c) Normalized, direct bending (d) Normalized, 30 s punch-wait bending (e) Tempered, direct bending (f) Tempered, 30 s punch- wait bending

Fig. 7. The diagrams and polynomial curve equations showing the spring-go amounts obtained from the 90^{o} bending process

was observed that the hardness value of the tempered sheet-materials was slightly lower than that of the heat-untreated sheet materials. Furthermore, greater amount of spring-go was observed in the bending process of the tempered sheet materials when compared to the heat-untreated sheet materials. Tempering treatment not only increases the machinability of the materials, but it also increases ductility and toughness of steel by removing the stress occurring in microstructure of materials. Although tempering increases the ductility of steel, it causes decrease in its hardness and strength [21]. Punch-wait process decreases the internal stress in microstructure of the materials.

3. 3. The 90^{o} bending process experiments

The spring-go diagrams obtained from the 90^{o} bending process of the specimens are shown in Fig. 7.

As can be seen from the diagram in Fig. 7, the thicker was the material, the lower the amount of spring-go was in the 90^{o} bending process. When diagrams are viewed, it can be understood that the lowest amount of spring-go was measured as 0.28^{o} in 30 s punch-wait bending process of the 6mm-thick tempered sheet material (Fig. 7f). The greatest amount of spring-go was measured as 1.95^{o} in direct bending of the 3 mm heat-untreated sheet material (Fig. 7c).

As can be seen from Fig. 7, the greatest amount of spring-go was observed in direct bending process of normalized sheet materials. Since normalizing process decreased the hardness of the materials, they had greater amount of spring-go (Fig. 7c and 7d). Since punch-waiting on materials during the bending process decreased the stress in the microstructure of the materials, we obtained lower amount of spring-go. In heat treatments, depending on temperature and duration of the treatment and atmosphere control, decarburization might frequently occur in the materials. Depending on its cross-section and surface area, it is possible to notice decarburization in S235JR sheet material, too. However, it might be caused by some other factors because there is no available microstructure-carbon relation research. The hardness level of the heat-untreated sheet material did not reach the expected level after conventional normalizing. It was thought that the change in hardness values could have shown the difference of normalizing process if a complete-tempering had been applied to the material.

The best result (the lowest amount of spring-go) in the 90^{o} bending process experiments was obtained in the 30 s punch-wait bending process of tempered sheet materials (Fig. 7f). Since ductility and toughness of the materials increased during the tempering process, spring-go amount decreased. When punch is waited on the materials, plastic deformation occurs in the bending area and internal stress in microstructure of the material is distributed, which is thought to decrease the amount of spring-go of the materials.

Polynomial curve equations of the spring-go amounts obtained have been shown in Fig. 5-7 for sheet metal thickness in the experiments. Also, finding the spring-go values is fairly easy for sheet metal thickness at the intermediate values and test values (above or below). For example, the spring-go value (by means of graphic or calculated) can be found for the bending process without waiting in 90º punch of the S235JR steel material at the 2 mm-thick tempered sample. For calculating the spring-go value of the 2mm-thick sheet material the following polynomial curve equation was used.

$y = 0{,}0275x^2 - 0{,}5825x + 2{,}8975$

$y = 0{,}0275x(2^2) – 0, 5825x (2) + 2{,}8975$

$y= 1{,}8425^{o}$

During bending processes, for determining the bending angle of the punch which will be manufactured, the amount of spring-go should be taken into consideration. For example, in order to bend the specimens of 2 mm in thickness with 90º tempered immediate removal bending method, the spring-go value is taken as 1,8425º. The bending angle and the punch angle value is calculated as follows:

Punch angle＝desired angle＋amount of spring-go＝90º+1,8425º=91,8425º

3. 3. 1. Micro structural changes during deformation

Due to more deformations according to the bending processes in 30° and 60°, the micro-structural investigations were carried out in the 90° bending process. The micro-structural images of the deformation zones are shown in Fig. 8. The micro-structural variations appeared in deformation zones depending on the bending parameters were investigated on the heat-untreated, normalized and tempered material.

Because of having a specific crystal structure and formability of materials of metal character, the dislocation movement and density in sutructure is quite important in terms of materials deformation [22]. In this context, depending on the increase in the sheet material thickness as a result of the bending process, the stress field to bring about the dislocations collapsed in the grain boundaries increases and deformation becomes difficult. Fig. 8 show that decrease in the amount of spring-go was determined as the thickness of the sheet material.

The changes in the grain structure as a result of bending and deformation were determined especially in the heat-untreated sheet metals (a, d, g, j). Formation of a finer ferrite-pearlite structure was shown by normalizing heat treatment (b, e, h, k). It was not observed the grain orientation depending on deformation in the micro-structural images of samples under normalization in comparison with other samples. [23]. The micro-structural images of elimination of internal tensions and reduces brittleness of martensite by quenching in microstructure of material after tempering process are shown in Fig. 8; c, f, i and l. It was formed to homogenization lack of secondary processing activity in the internal stresses with an alternative slip planes and other operations introduced by micro-structural homogeneity in all the tempered materials. This uniformity provides equal distribution of all zones of deformation depending on the load applied to the material. Therefore, the amount of spring-go in the tempered material was determined to be less than heat-untreated and normalized material.

4. Conclusion

The results obtained are given below depending on the bending angles and heat treatments applied to the materials.

While the results obtained with the 60º and 90º bending angles showed parallelism, they had an inverse proportion with the results of 30º bending angles.

One of the significant deductions we made is that material thickness is a significant factor.

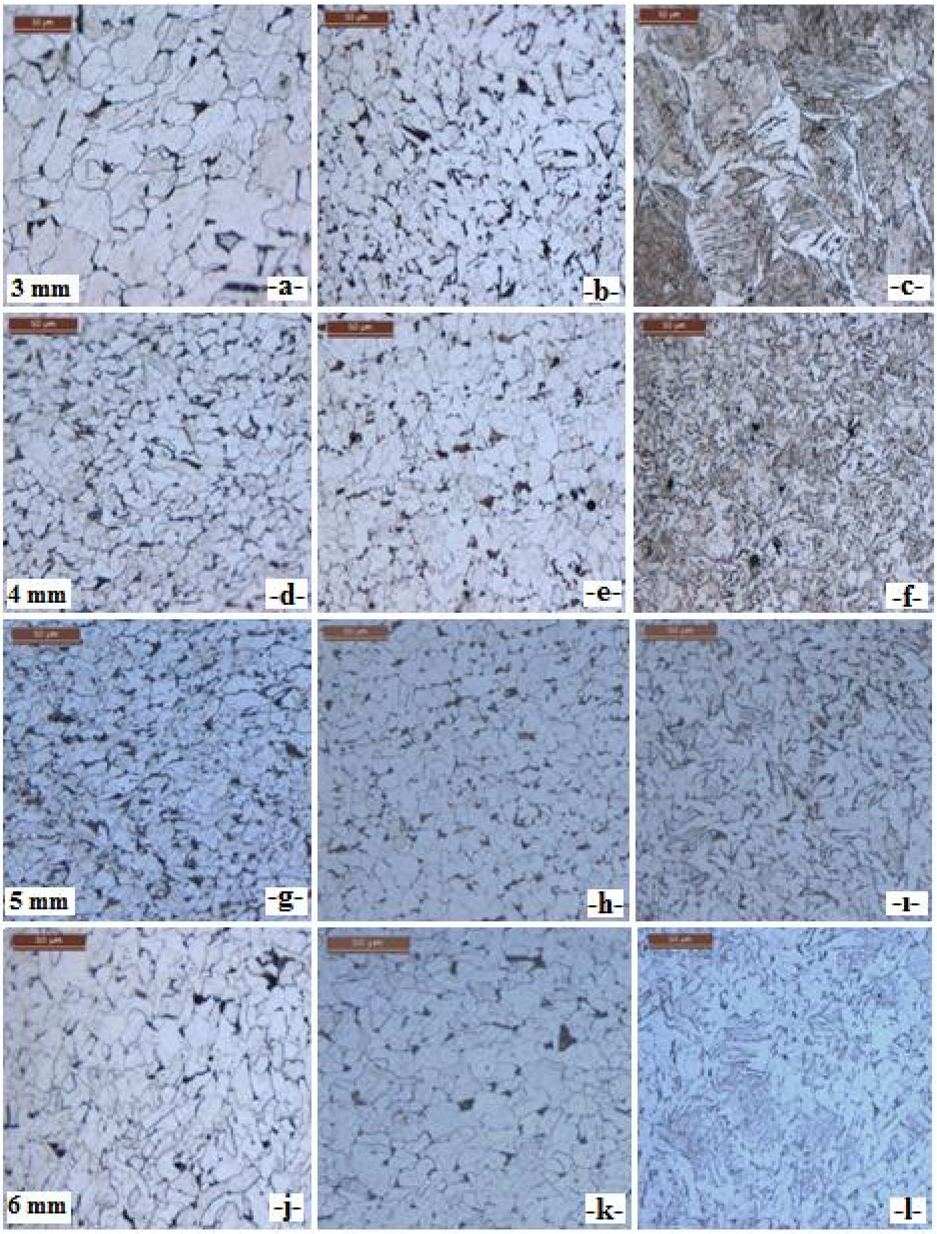


Fig. 8. Microstructural images of deformation zones after the bending process of the materials with 3, 4, 5 and 6mm thicknesses; (a,d,g,j) heat-untreated, (b,e,h,k) normalized and (c,f,i,l) tempered

While the amount of spring-go increased as we used thicker materials in the 30^o bending process, the situation was reverse in the 60^o and 90^o bending processes.

In general, the amount of spring-go was lower in the 30 s punch-wait bending processes compared to direct bending processes.

It was also concluded that while the normalizing in the 30^o bending process was suitable for relatively thinner sheet materials (3mm and 4mm), it was not so effective in relatively thicker materials (5 and 6mm).

We determined that the tempering treatment applied to 5 and 6mm sheet materials in 30 s punch-wait bending process decreased the amount of spring-go.

We also determined that spring-go amount was a significant parameter in the 30 s punch-wait 30^o bending process compared to the 60^o and 90^o bending processes.

It was concluded that normalizing and tempering treatments increased the spring-go amount in the 60^{o} bending process.

We determined that in the 90^{o} bending process as the thickness of the materials increased, the tempering treatment decreased the amount of spring-go. In 90^{o}, direct and 30 s punch-wait bending processes, the greatest amount of spring-go was observed in the normalized materials but the lowest amount of spring-go was observed in the tempered sheet-materials.

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