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EVALUATION OF THE EFFECTS OF LOCAL HEATING ON SPRINGBACK BEHAVIOUR FOR AHSS DOCOL 1400 SHEET METAL

Summary

In this study, the impacts of the heating temperature and bending angle on springback were experimentally examined in the V-bending of Docol 1400 steel sheets. The bending angle (30°, 60°, 90° and 120°) and the temperature (Room Temperature-RT, 200°C, 300°C, 400°C, 500°C, 600°C) of the bending zone were determined as the variable experimental parameters. The springback was measured using a coordinate measuring machine (CMM). The springback was observed to decrease by 7.7% on average between RT and 200 ºC, to increase by 8% between 200 ºC and 300 ºC and by 18% between 300 ºC and 600 ºC. The material data used in the analyses were attained from the tensile test results conducted at different temperatures. The analysis shows that the springback values decreased linearly at elevated temperatures. It was seen that the mechanical properties of the material decreased within the temperature range of RT to 600ºC in the heated bending zone.

Key words: *springback, V-bending, Docol 1400, bending angle, hardness*

1. Introduction

The use of advanced high-strength steel (AHSS) sheets has recently been increasing, especially in the automotive sector. AHSS materials reduce vehicle weight, fuel consumption, and carbon emissions since they provide opportunities for using thinner sheets in production. AHSS sheet materials are deemed the basic materials for future applications in the automotive sector. For this reason, the importance of advanced high-strength steel sheets is growing. AHSS materials include general types such as dual-phase (DP), transformation-induced plasticity (TRIP), complex phase (CP) and martensitic steels (MART). In contrast to cold formable single-phase steels, the mechanical properties of AHSS steels are affected by many factors such as phase composition, phase distribution, volume ratio, dimension and morphology of the phase compounds in the general microstructure [1-2]. DP sheets are steel with low carbon content and contain ferrite and martensitic phases in their microstructure. DP steels are produced by cooling hypoeutectoid steels from any temperature within the A1-A3 temperature range (Ferrite + austenite zone) in the Fe-C balance diagram at a speed at which a partial austenite structure could turn into a martensite one. While the ferrite phase occurring in the material during cooling provides DP steels with excellent ductility, the martensite phase determines the strength of the steel [3-5]. The higher the volume ratio of the martensitic phase, the higher the strength of the steels. While an increase in the volume ratio of the martensitic phase increases the yield and tensile strengths, it reduces uniform elongation [6]. Besides, increasing the material strength with the second phase or the strength depending on the martensitic volume ratio in dual-phase materials leads to a lowering of the elastic anisotropy of the material [8]. The deformation occurring in the material's microstructure could also be determined using the representative volume element method with finite element software items. The deformation relationship among the phases can be detected using the materials' geometrical models and the mechanical properties of the phases in these software items [9-10].

It is well known that temperature affects the mechanical properties and formability behaviour of metallic materials. Young's Modulus, yield strength and ultimate tensile strength decrease depending on the increasing temperature. Total elongation increases in proportion to the increase in the forming temperature, and uniform elongation decreases slightly. The existing carbides in the tempered matrix continue to grow with the increase of temperature, and new carbides emerge at the grain boundaries [11-13]. Dynamic strain aging, dynamic recovery and dynamic recrystallisation that occur during the forming cause the material to show complex behaviour at increasing temperatures [14-15].

There are many different methods for the forming of sheet metal. The quality of formability mainly depends on the forming methods and parameters applied [16]. One of these methods is the bending process which is the forming process conducted to give a shape to and strengthen the cut part of the sheet metal materials. The tensile value applied to the material during bending exceeds the yield strength, but it remains under the ultimate tensile strength boundary. When the force applied to the material is removed, the material tries to return to its former state due to the elastic tensions and opens backwards by stretching back a little, a phenomenon called springback. Thinner sheet materials with higher strength used in sheet metal forming tend to increase their springback due to the high strength properties. Compensating for springback by trial and error at the manufacturing stage is exceptionally costly. Therefore, it is essential to determine the amount of springback previously and optimise the forming sets depending on the used materials and the applied forming process.

Springback behaviours have begun to be examined in the literature at the stage of the forming of AHSS steel sheet materials that are becoming widely used in industrial applications via bending. However, there are still many steel material types that must be investigated within the AHSS steel group. Lim et al. examined the springback behaviours in high-strength steels depending on time. Springback change depending on time not observed in traditional steels was seen in all tested high-strength steels. Springback of AHSS, depending on time, is approximately as much as one-third of aluminium alloys [17]. Yanagimoto and Oyamada examined the springback behaviours of high-strength steels under hot forming conditions. It was found that a sudden decrease occurred in the springback of steel sheets in the isothermal V-bending process conducted at a temperature of approximately 750 K, and this decrease stems from the temporary creep deformation at high temperature [18]. Öztürk et al. examined the springback behaviour of DP600 sheet material during warm forming. The material was seen to show complex behaviours in different directions and at different temperatures. While springback increased within the rolling direction at 200 °C, springback values decreased with an increase in temperature in other directions [19]. Karaağaç et al. experimentally examined the impacts of the sectional heating process and bending parameters at different temperatures on the formability and springback behaviour in the V-bending of galvanised DP600 sheet material. They stated that the springback angle increased as the heating temperature rose from room temperature to 200 °C, decreased as the temperature increased from 200 °C to 400 °C and increased again when the temperature increased from 400 °C to 500 °C.

Docol 1400 steel from AHSS steel types belongs to materials of a martensitic structure. The martensitic structure of the material limits the formability of these sheet materials at room temperature and causes the forming of defects such as cracking and fracture at high bending angles. Therefore, the temperature is generally used to increase the formability of forming AHSS sheet materials. However, heating the whole die or sheet material causes very high energy consumption and a decrease in the superior properties of the material. As a result of the literature review, it has been determined that there are insufficient studies on the effect of temperature on the formability of Docol 1400 steel with V-bending and on the determination of springback behaviour. Therefore, in this study, the formability of the V-bending process at different die angles and in springback behaviours were experimentally examined. The heating process was only applied to the bending zone to analyse the Docol 1400 sheet material's formability without harming its mechanical properties. In addition, bending analyses were carried out under the same conditions as the experiments. Finally, the changes caused by the heating in the bending zone were also examined in the material's microstructure.

2. Experiments

2.1 Sheet Material

Docol 1400 sheet material of 1.5 mm thickness used in the experimental studies was prepared by cutting in dimensions of 40x20 mm in a way that the long side would be in the rolling direction. The chemical composition of the sheet material used is given in Table 1.

Table 1 Chemical composition of the Docol 1400 material (wt.-%)

C	Si	Mn	P	S	Al	Nb	Ti	Cr	V	B	Ca	N	Fe
0.179	0.16	1.20	0.0104	0.0044	0.041	0.0018	0.033	0.026	0.018	0.0010	0.0019	0.0074	Bal

2.2 The Experimental Setup

The experimental studies were conducted in an electronically controlled experiment device whose punch speed, bending force and ironing period could be controlled. The experiment apparatus consists of the die group containing a mechanical unit, electric unit, electronic control and data collection unit, hydraulic unit, V die, punch and load-cell. The general appearance of the experimental apparatus is shown in Fig. 1.

Fig. 1 General appearance of the experiment apparatus

Sheet samples were subjected to a V-bending process at angles of 30°, 60°, 90° and 120°. In the V-bending processes, the sheet material was placed between a die and a punch with radii Rp = 4 mm. In the process, the aim was that as the punch was moved downwards, the sheet material would be bent qua elastic-plastic. Before bending, the bending zone was heated using a resistor rod controlled by a proportional-integral-derivative controller (PID) on the heating board, and a thermal camera monitored the heating process. As the material reached the desired temperature, the bending process was carried out by taking the resistor rod from the sheet material. By performing these steps, V-bending processes were repeated twice at each bending angle at temperatures of RT, 200°C, 300°C, 400°C, 500°C and 600°C. Thermal camera images are given in Fig. 2.

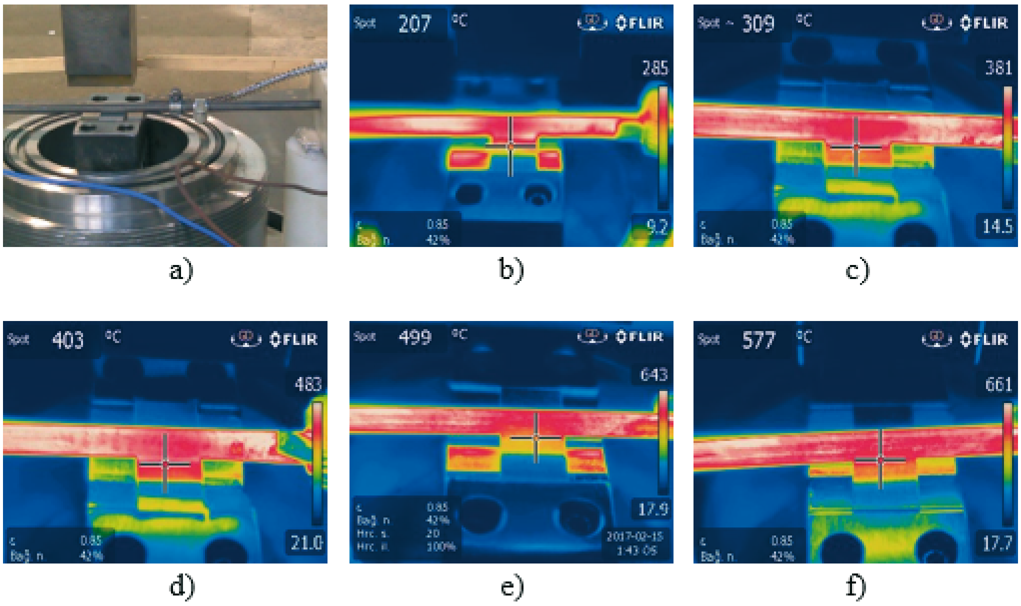

Fig. 2 Temperature control with thermal camera a) RT, b) 200, c) 300, d) 400, e) 500, f) 600°C

As a result of all the experiments, the samples' springback angles were measured with the help of a computed coordinate measuring machine (CMM). First, the experiment samples were placed on a sheet plate in the springback measurement processes, and care was taken not to distort the bending angle during the placement process. The measuring machine probe was touched at three different points on the bending surfaces, and a plane was formed on both surfaces. The angle between the two planes was calculated, and the springback value was attained according to the bending angle.

An optical microscope was used to determine the impact of temperature on the material's structure, and the relation between this impact and springback and the material structure imaging was established. Forming, sanding, polishing, etching and microscope examination were conducted for this process. First, the samples were cut with the help of an abrasive disc-cutting device and prepared in the measurements that could fit in the hot bakelite device. The hot forming process was performed under a load of 50 kN and at a temperature of 200°C. Afterwards, the sanding and polishing stages took place. After six sanding processes, a smooth surface without scratches was attained by using a thinner abradant than the one used previously. At the last stage, 2% nital etchant was dripped on the formed and polished samples, and it was cleaned with the help of alcohol after keeping it waiting for almost 10 s and made ready for examination in an optical microscope.

3. Modelling of the numerical analysis

Using Deform software, bending and springback analyses were carried out with the finite element method, the elastoplastic behaviour law, and based on the yield function type using the Von-Mises criterion. Under these conditions, the mesh structure was created by the software. The geometric model was designed in the SolidWorks program and imported to Deform. The relationships to contact between the tangential and normal surfaces for a friction factor typical of Docol 1400 were determined. The mesh in Deform was defined only for the sheet material. The die and punch were assumed to be rigid bodies. The mesh of the sheet material contains 3000 tetragonal elements. The boundary conditions were defined where the die was fully fixed.

In contrast, the punch displacement was in the vertical axis, leading to the sheet material's symmetric bending. The analyses were repeated by changing the die and punch angles. The punch velocity was set to 10 mm/s in all analyses. To perform Deform analyses, the material properties of Docol 1400 were obtained from the tensile test results. The tensile tests were performed at a 1.0 s–1 strain rate to transfer the sheet material data to the finite element software. Tensile test samples were prepared by cutting within the rolling direction. The results of the tensile test conducted for Docol 1400 material at RT, 200°C, 300°C, 400°C, 500°C and 600°C are given in Fig. 3.

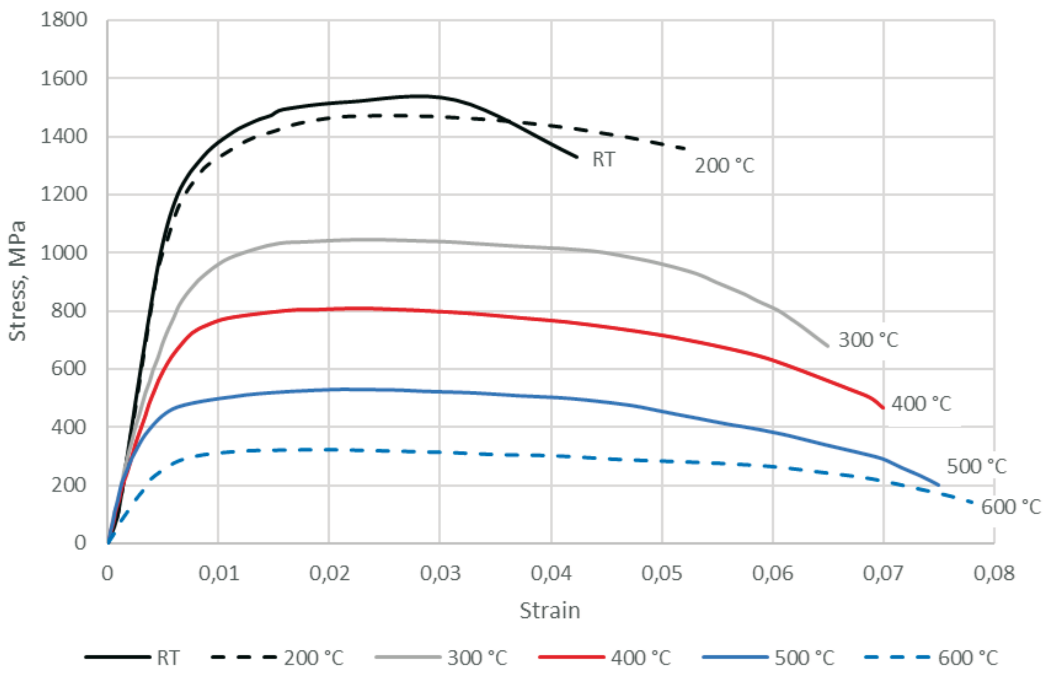

Fig. 3 Stress-Strain curves of the Docol 1400 sheet material at different temperatures

Friction tests were performed under 1 MPa, 2.5 MPa, 5 MPa, 10 MPa, 15 MPa pressures, and 0.3 m/s speed to determine the coefficient of friction. Since lubrication was not used in the experimental study, friction tests were carried out under dry conditions at RT. Every test value was obtained by using an average of three friction tests. Finite element analyses were done by changing the die and punch angles so that the sheet material could be bent at 30°, 60°, 90° and 120°. Springback analyses were also conducted after carrying out the bending analyses at the specified angles. Fig. 4 shows a schematic display of the die design formed for V-bending analyses. The forming parameters used in the experimental studies and analyses are given in Table 2.

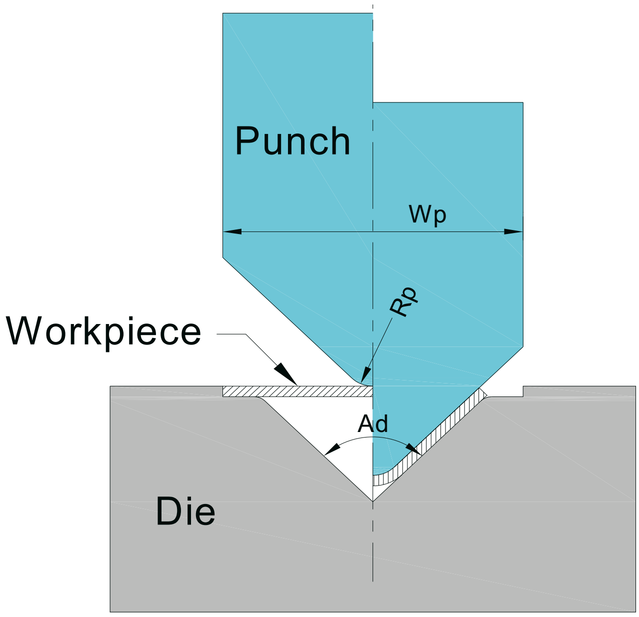

Fig. 4 Schematic display of the V-bending process

Table 2 Forming parameters

PARAMETERS	VALUE
Blank Material/Thickness	Docol 1400 / 1.5 mm
Blank dimensions	40 x 20 mm
Punch Width (W_p)	40 mm
Punch Radius (R_d)	4 mm
Bending Depth (H)	Varied
Temperature	RT, 200°C, 300°C, 400°C, 500°C, 600°C
Die Angle (A_d)	60°, 90°, 120°, 150°
Bending Angle	180 - A_d
Punch velocity (V)	10 mm/s
Coefficient of Friction (CoF)	0.1

4. Results and Discussion

The obtained experimental and analysis results were assessed regarding the impacts of the forming angle and zonally applied heating temperature on springback behaviour. By keeping other zones away from the heat during the forming of the sheet material, the mechanical properties of the materials in these regions remained unchanged.

4.1 The Impact of Temperature on the Amount of Springback

The conducted experimental study and analysis results show that the springback values occurring after the forming of the sheet material at increasing temperatures generally tend to decrease. It is known that the warm and hot forming of sheet materials reduces the amount of springback [19-20]. The relation of the temperature and springback obtained from the experimental studies and analyses is comparatively given in Fig. 5.

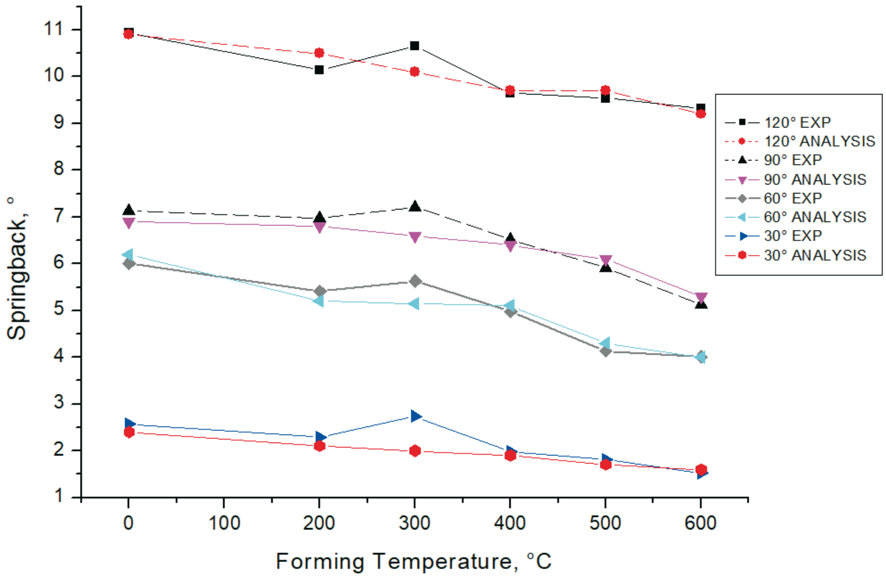

Fig. 5 Relation between Springback and temperature

A decrease in the springback is expected in the event of an increase in formability. A decrease was observed in the springback at all bending angles when the forming temperature increased from room temperature to 200°C. The increasing temperature in the bending zone also reduces the hardness of the material. This decrease in the hardness of the material (Fig. 8) causes a decrease in the springback angle. In contrast, an increase was observed in the springback when the forming temperature increased from 200°C to 300°C. The reason for this is that the carbon elements rapidly expand in this temperature range, locking the dislocations and raising the yield limit of the material. Since this situation, also called dynamic strain aging, increases the bending zone's hardness, it was observed that the springback increased at this temperature range. The graphs also support the dynamic strain aging occurring in this zone due to the experimental studies and the hardness measurement experiments taken from the material bending zone. Tempering temperature is within the range of 300°C-700°C in high-strength steel like Docol 1400. In this value range, it is expected that the material will gain ductility and have a low hardness value and a low amount of springback due to the softening of the martensite with annealing. It can be seen that these data obtained from the experiments are compatible with the literature review [15, 19, 20].

The springback values attained from the analysis show that springback decreased with the increasing temperature. Although the experimental and analysis results show remarkable similarity, an increase in the springback observed in experimental studies at 300°C was not seen in the analyses.

4.2 The Impact of the Forming Angle on the Springback Angle

The forming angle is an important parameter affecting springback in bending processes. Springback stems from the unequal tension distribution in the thickness section of the material. During the bending process, compressive stress occurs on the internal surface where the punch contacts the sheet material and tensile stress occurs at the external surface. Depending on this, the stresses occurring during the forming increase. The amount of springback is determined by the magnitude of the bending moment distribution. The bending moment in the sheet material increases with the increasing bend angle, which causes more springback in the sheet metal after the bending process [20]. Therefore, the amount of springback increases with the increase in the applied forming angle. When the forming angle grows, the moment of flexion and the area affecting the forming also increase. It was observed that springback grew because the increase in the die angle heightened the stresses formed in the bending processes. The amount of springback showed a similar increase at all temperature values depending on the forming angle. Each 30°C increase in the forming angle caused an increase of 2.741º on average in the amount of springback. The forming angle-springback relation attained experimentally at different temperature values is given in Fig. 6.

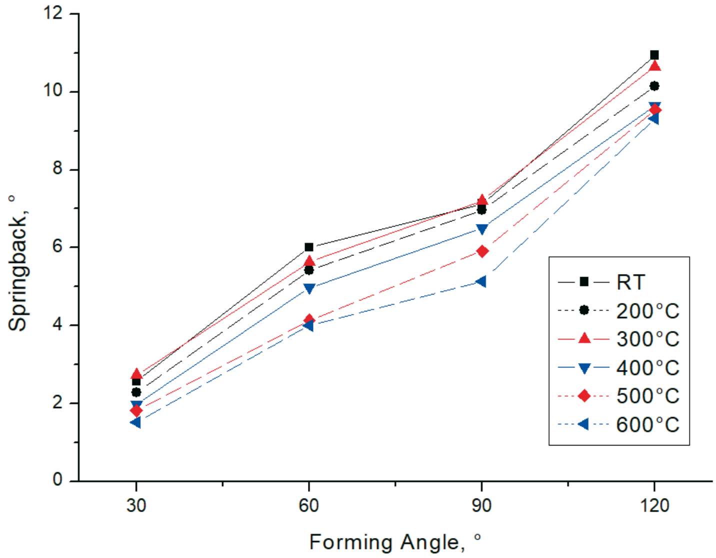

Fig. 6 Forming angle-springback relation

4.3 Microstructure Analysis and Hardness Measurement Results

The impacts of the forming temperature on the microstructure of the sheet material were analysed in terms of the changes in the martensitic phase in the area exposed to heat and the hardness changes. For this purpose, the microstructure images of the experimental samples were attained with an optical microscope, and hardness measurement was measured at the bending zone. The internal structure images attained from the examination conducted in the optical microscope are given in Fig. 7.

It was observed in the microstructure examinations that the sharp martensitic structure started to soften together with the impact of tempering as the temperature increased. No change was detected in the grain structure of the material at the temperatures of RT and 200º, but the grain structures and grain boundaries started to grow at a temperature of 200º. The decrease in strength depending on the increase in temperature observed in the mechanical tests also clearly reveals this situation. Tempering becomes very slow, and the mechanical properties decrease less when the temperature is below 250ºC in the martensitic steels containing 0.2 or less carbon [13, 21]. It was also observed in the experimental studies that mechanical properties start to decrease as of 300ºC in the bending zone (Fig. 1 to Fig. 8). However, it was seen in the mechanical tests that the mechanical strengths of the material remained the same without any change in the zones not exposed to heat. This situation is an essential advantage in using the material without losing its properties after forming. The material strength decreases at temperatures above 350 ºC since the carbide grains in the material structure start to roughen [13]. It was also observed in the experimental studies that the springback values (Fig. 5) started to decrease from 300ºC. In the experimental studies, it was noted that the springback value decreased because the hardness of the material only in the bending zone started to decrease.

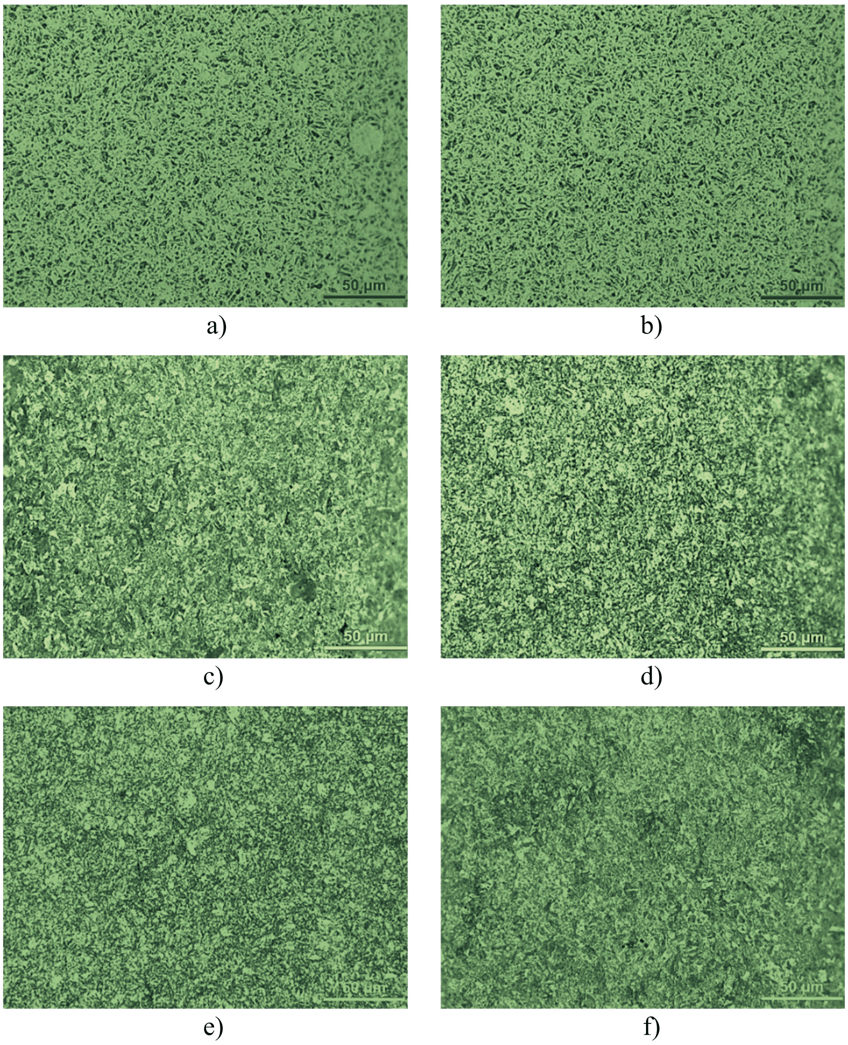

Fig. 7 Bending zone microstructure images of the sheet material at different temperatures a) RT, b) 200°C, c) 300°C, d) 400°C, e) 500°C, f) 600°C

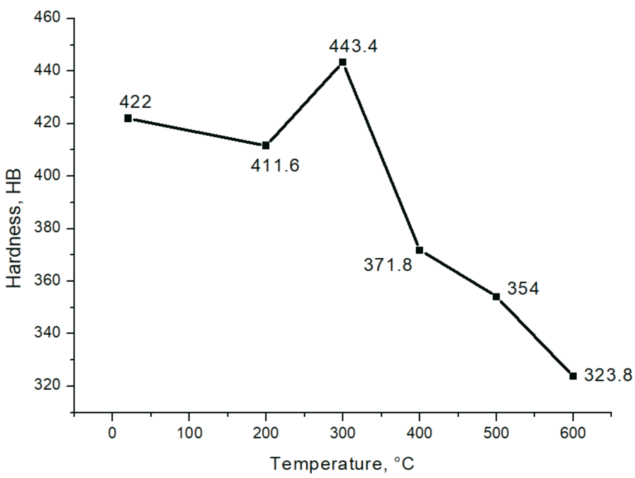

Fig. 8 Hardness measurement results of Docol 1400 sheet material bending zone

The temperature-material hardness relation obtained as a result of the Brinell hardness measurement tested using a carbide ball of 2.5 mm diameter, and 31.25 kg-f is shown in Fig. 8. According to the results of the hardness measurement taken from the heated bending zones, it can be seen that the increase in temperature reduced the hardness of the material. However, it was observed that the hardness values attained from the samples tested at 300°C were higher than the hardness values of the samples tested at other temperatures. Therefore, the material hardness is understood to have increased at this temperature. This situation showed that the dynamic strain aging was realised within the range of 200°C to 300°C for Docol 1400 material. It was determined as a result of the conducted experimental studies that springback and hardness values increased and decreased in the same ranges. The increased ductility in the material's structure due to the tempering is typical. This situation revealed the relationship between hardness, microstructure, and the amount of springback and supported the literature review.

5. Conclusions

In this study, the springback behaviour of the Docol 1400 sheet material frequently used in automotive and aviation industries in the V-bending process was experimentally examined by the local heating of only the bending zone. Bending analyses were also carried out by using Deform software. The obtained results are itemised below:

1- On average, a decrease of 7.7% was observed in the experimental studies in the amount of springback between RT and 200°C. The material hardness decreased from 422 HB to 411.6 HB at these temperatures.

2- The material hardness increased to 443.4 HB, the forming temperature from 200°C to 300 °C, and the amount of springback increased by 8% on average. These data show that dynamic strain aging occurred between 200 °C and 300 °C for Docol 1400 sheet material.

3- The springback decreased between the values of RT and 200°C, increased between 200°C and 300°C and decreased again after 300°C. Besides, hardness values decreased depending on the increasing temperature after 300°C.

4- The decrease in mechanical properties is low, and no apparent change exists in the microstructure due to the slowness of tempering at temperatures of 200°C and below. However, the material's mechanical properties decreased only at the limited heated zone due to the softening of the martensite because of tempering at temperatures above 400°C and due to the growth of the carbides and grain boundaries in the microstructure.

5- The material's mechanical properties were not changed in other zones not exposed to heat.

6- It was determined that each 30°C increase in the bending angle increases by 2.741° on average in the amount of springback.

7- It was also seen in the finite element method analyses that the increasing temperature and forming angle values reduce the springback.

8- The finite element analyses and experimental results show significant similarity. Using finite element analyses for estimating springback in the bending processes of Docol 1400 sheet material is a convenient method.

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