Iranian Journal of Materials Forming 9 (2) (2022) 4-13

Online ISSN: 2383-0042

Iranian Journal of Materials Forming

Journal Homepage: http://ijmf.shirazu.ac.ir

Research Article

A Study of the Effects of Grain Size, Sheet Thickness and Punch Radii on Springback in Copper Sheets

M.J. Lorestani and A. Adelkhani*

Department of Mechanical Engineering, Kermanshah Branch, Islamic Azad University, Kermanshah, Iran

ARTICLE INFO

Article history:

Received 16 December 2021
Reviewed 1 February 2022
Revised 17 February 2022
Accepted 17 February 2022

Keywords:

Grain size
Thickness
Springback
Annealing temperature

ABSTRACT

Sheet metal forming is one of the most common manufacturing processes in the production of many mechanical components and auto parts. Therefore, accurate investigation of the effects of important parameters in the sheet metal forming process is of primary importance for engineers and designers. In the present study, the effects of grain size, punch radii, and sheet thickness on the springback in the W-shaped bending dies are evaluated. The investigated metal sheets are composed of pure copper with three thicknesses of 0.1, 0.3, and 0.5 mm. In this research, the annealing heat treatment process is conducted for 60 minutes at 500, 750, and 900 degrees on the Celsius scale to study the grain size in copper specimens, then the recovery process is performed at ambient temperature. The experimental results revealed that the rise of annealing temperature results in the significant variations of metallographic structure and grain size. According to the results, for a constant thickness, the mechanical properties changed by increasing the annealing temperature. As the grain size increased, the elongation and yield strength decreased. With a constant annealing temperature, the yield strength and elongation fell with a decrease in thickness. However, in both cases Young's modulus does not change much. The results also indicated that by increasing the thickness of the sheet under the same conditions of grain size, the springback angle decreased as well, so that the springback angle minimized through selecting the radii of 0.3 mm for the punch. Additionally, it was concluded that the springback angle can be minimized with a decrease in t/d ratio for a constant sheet thickness. Based on these results, a multiple-choice regression model has been employed that the average error of this model for springback prediction was 8.08%.

1. Introduction

Since most automotive bodies are developed by forming processes, one of the methods of producing these bodies is through the bending process on a macro scale [1]. The springback is a vital subject in bending and other processes and affects the final shape and accuracy [2]. The prediction of springback of sheet metal is a conflict in the metal forming process [3]. In fact, sheet metal forming is a method used to convert flat metal sheets into the desired shape without breakage or intense localized thinning of the metal sheet. Bending is one of the processes of sheet metal forming that is primarily present in forming methods. One of the applications of

* Corresponding author
E-mail address: a.adelkhani@iauksh.ac.ir (A. Adelkhani)
https://doi.org/10.22099/IJMF.2022.42544.1205

this process is to create curvature in metal sheets or to convert them into U or V-shaped or in some cases circular C-beams [1-4]. The more important springback parameters are the Young's modulus, material property, tools radius, and the blank holder force [5]. In order to predict springback, it is necessary to accurately determine the distribution of internal yield stress, which is extremely demanding and requires complex cyclic loading, while numerical simulation can be a convenient and easy solution to solve this problem. The bending process is influenced by various parameters, including sheet thickness, friction, and the mechanical properties of the material. Not to mention, springback has been studied through numerical and experimental methods applied by many researchers. For example, an experimental and FEM study on bending angles, punch radii and different holding times effects in the V-bending process was established by Şen and Taşdemir [6]. In another research, the factors affecting springback in sheet metal bending were studied [7]. Numerical methods have been applied to study the effects of various parameters, such as the clearance between the punch and die, friction coefficient, punch speed and sheet thickness, on springback in U-shaped dies [8-11]. Mkaddem and Saidan showed that the reduction of the die radius dropped springback [12]. Moreover, the accuracy of springback prediction is greatly influenced by Young's modulus and yield stress, and the effects of Young's modulus and other parameters on springback have been investigated in numerous studies [13]. For example, Panti et al. [14], Jiang et al. [15], and Mori et al. [16] reported that a rise in yield stress led to a rise in springback. In metal engineering, an increase in the elastic modulus led to a decrease in the springback [17, 18]. Studies showed that a decrease in the size of specimens leads to a decline in flow stress and a rise in friction. In micro-bending, the grain size ratio (D) and sheet thickness (T) are two key factors in the springback [10]. Liu et al. [19], investigated the size effect on springback of sheet metal foils in micro-bending. His results showed that by increasing grain size, springback increased as well [19]. In another study performed by Serkan et al. [20], it was revealed that a rise in the sheet thickness reduced springback. Springback can also be reduced through the friction between the surface of the sheet and the die. A parametric study on the bending accuracy in micro-W-bending was studied by Liu et al. [21]. They concluded that, the foil thickness had the highest influence on springback [21]. Springback should be determined to increase the accuracy of the final product [22]. The mechanical properties of the material changes with mechanical work [23]. Based on the researchers' studies, a myriad of studies has been conducted on the effects of specimen size, grain size and punch dimensions on springback, but so far, no research has been performed on the interaction of different parameters on springback in W-shaped dies of pure copper. Much research has been done on the copper sheet in the form of U, V, and L shapes. Additionally, in this research, a multi-choice regression model has been utilized. The springback can be measured based on this equation.

2. Materials and Methods

2.1. ABAQUS simulation and stretching test

Numerical simulation is widely used in the engineering field. ABAQUS is a powerful finite element software for modeling homogeneous and heterogeneous materials [1]. In this investigation, the ABAQUS software was used for result validation [11]. In this study, the die was fixed, and the punch moved in the direction of the vertical axis. Given that the size of the element and its type directly affects the results, the elements of type SR4 were used in this study. A dynamic explicit model with an analysis time of 0.01 was considered (Fig. 1). The relationship between stress and strain is one of the important parameters in a computer simulation. For this purpose, samples, before and after annealing, were prepared according to ASTM E8 standard. The true stress-strain curves of the annealed pure copper are shown in Fig. 2. The metal sheet under study was made of pure copper [1] in three thicknesses of 0.1, 0.3, and 0.5 mm and dimensions of 16 mm×12 mm [10]. To study the mechanical properties of copper

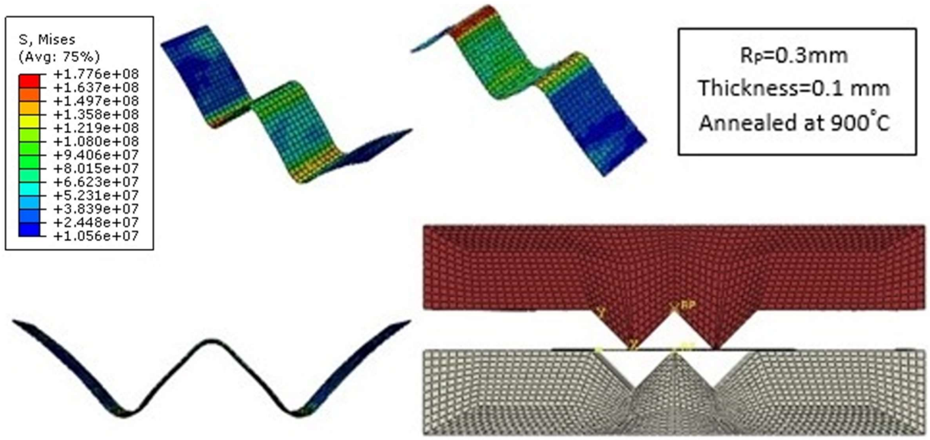

Fig. 1. The specimen simulation.

sheets, the uniaxial tensile test was employed. Young's modulus and Poisson's ratio were adjusted to 104 and 0.28, respectively [24].

First, according to the ASTM E8 standard (see Fig. 2 and Table 1), a sample was prepared, and the dummy sample was then subjected to a tensile speed of 0.01 mm/min until the breakage and tearing of the specimen, and the force-displacement data was recorded by the computer throughout the process [10, 21]. Fig. 2 illustrates the effect of specimen grain size and thickness on the stress-strain curves for the specimens. It is observed that the yield strength and elongation gradually decrease with a decrease in thickness, while Young's modulus experiences a minor decline. When there are several grains in the thickness direction, the yield strength is strongly influenced by the surface grain weakening effect. As for the interactive specimen geometrical effect and grain size effect on the mechanical properties of the copper sheets, the yield strength is observed to decrease by increasing the grain size.

2.2. Heat treatment

The most commonly used heat operation for steel alloys is annealing, and the goal is to achieve a completely

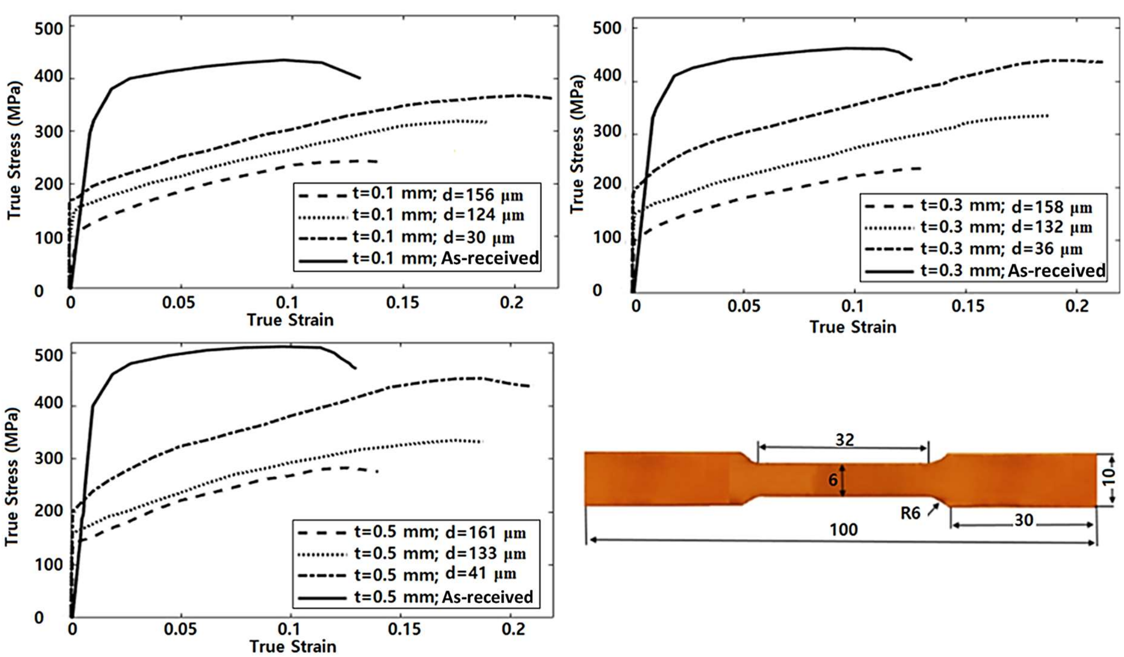

Fig. 2. The stress-strain curves for a thickness of 0.1, 0.3 and 0.5 mm based on tensile test.

Table 1. The yield Stress and UTS for various thickness of copper sheets at received, 500, 750 and 900°C

t (mm)	Temperature (°C)	Yield Stress (MPa)	UTS (MPa)
0.1	As-received	302 (±10.5)	455 (±9.4)
0.1	500	173 (±4.9)	340 (±9.3)
0.1	750	127 (±6.1)	275 (±8.9)
0.1	900	103 (±7.7)	200 (±7.8)
0.3	As-received	310 (±9.1)	450 (±5.0)
0.3	500	204 (±3.2)	400 (±4.1)
0.3	750	135 (±6.1)	295 (±6.5)
0.3	900	110 (±6.2)	215 (±5.6)
0.5	As-received	390 (±7.3)	500 (±6.6)
0.5	500	210 (±8.3)	415 (±4.6)
0.5	750	154 (±6.3)	310 (±2.7)
0.5	900	130 (±4.3)	234 (±3.7)

homogeneous and stable metallurgical structure (usually ferrite or pearlite) and free from tension, cold working, and separation effects. It should be noted that the annealed parts are usually more flexible and have the least solidity. Annealing occurs during three stages of recovery, recrystallization, and grain growth. In the present research, the pure copper blanks with the thicknesses of 0.1, 0.3 and, 0.5 mm were annealed at 500, 750, and 900°C. Moreover, given the furnace temperature, the copper specimens were exposed to annealing at a constant temperature for 60 min [25, 26].

An electric furnace with a thermal precision of ±2°C was used. Thereafter, the furnace was turned off and the specimens were left to cool down outside the furnace. In addition, the metallographic tests were conducted to determine the grain size after the heat treatment. The samples were polished in a solution of 5 g $FeCl_3$, 15 ml HCl and 85 ml H_2O for 10 s [10]. After heat treatment and the removal of the samples from the furnace, the samples were allowed to be cooled down to the ambient temperature, then they were cut according to ASTM D6287-17 standard. The grain size was evaluated by an optical microscope (Neophot 32, Germany). ASTM E112 standard was used to measure the mean grain size (Fig. 3). Table 2 shows the mean grain size, thickness, and the ratio of primary thickness to the grain size (t/d), under

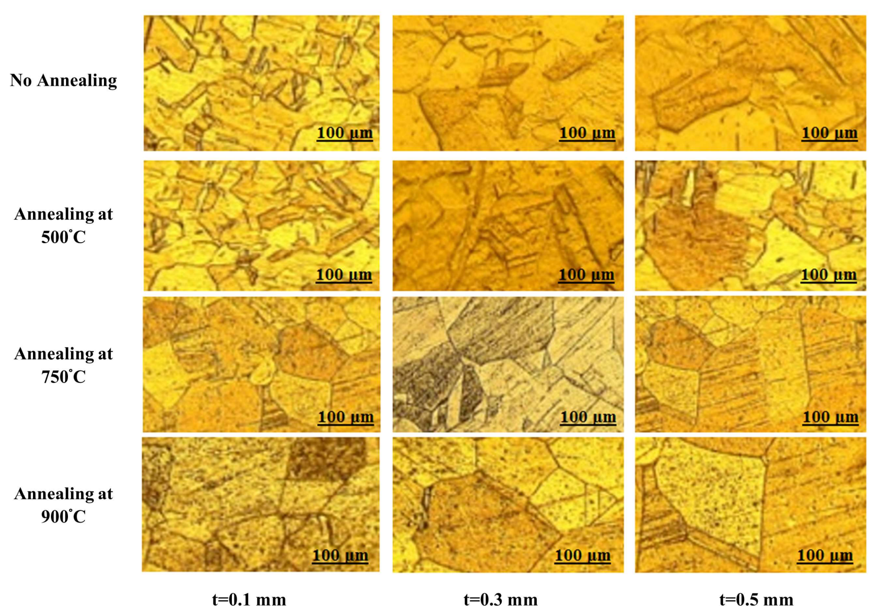

Fig. 3. Specimens microstructure based on different thickness and annealing circumstance.

Table 2. The Effect of temperature on Grain Size in different thickness

	Stage 1			Stage 2			Stage 3			Stage 4		
Annealing conditions	Without Annealing			500°C			750°C			900°C		
Thickness or t (mm)	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
Grain size or d (µm)	11	18	20	30	36	41	124	132	133	156	158	161
t/d	9	16.7	25	3.4	8.3	12	0.81	2.3	3.8	0.64	1.9	3.1

different temperatures. The specimens were tested by a 60-tons tensile testing machine (SANTAM, Iran). Furthermore, given the bending nature on small scales, the dimensions of the die were set on a millimeter scale. To examine the effects of process parameters, the punch radius (R_p) was set at 0.3, 0.5 and 0.8 mm, and the external radius of the die (R_d) was set at 0.4 mm [9]. Additionally, the clearance between the punch and matrix was set at the thickness of the copper sheet divided by 2. The punch and the die with external dimensions of 35 mm×20 mm and 30 mm were built (Fig. 4). Moreover, to increase the precision of machining, the clearance between the punch and die was considered, as well. The punch and die required for micro-bending process should be made of cost-effective materials that have relatively high strength and good machining capacity. Therefore, the steel VCN 150 was selected in the present study. Fig. 5 shows the length and width of copper specimens in the present study, with the of dimensions 16 mm×12 mm.

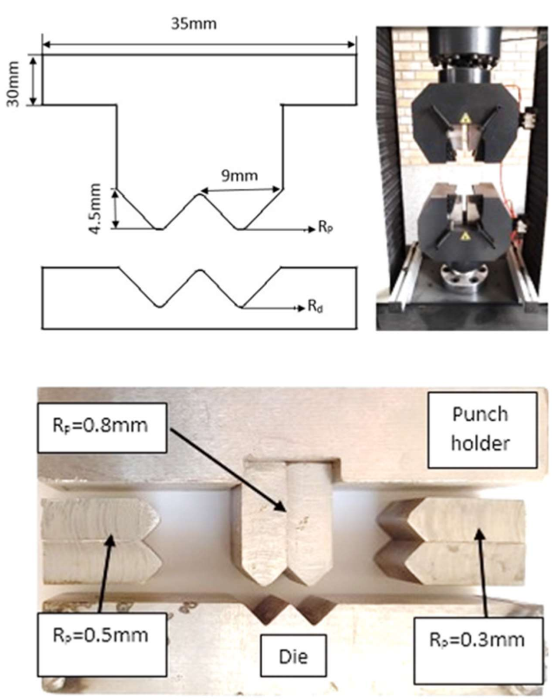

Fig. 4. The components of the die built and applied in the present study.

3. Results and Discussion

3.1. The thermal cycles effects on the grain size

In Table 2, the effects of thermal cycling on the behavior of grain size are shown. As can be seen, an excessive increase in the temperature of annealing cycle negatively affects the crystalline structure and grain size. Based on Fig. 5, when the metal is heated to half the melting point, recrystallization occurs and the grain boundaries are displaced. As a result, the seeds appear with new sizes. The cooling method and its speed were two other major parameters that influenced the final size of grains. Different cooling speeds result in changes in the microstructure, grain size, intermetallic phases, and their mechanical properties. In the metals deformation process at low temperatures (environment temperature), the density of misalignments increases, with the accumulation of misalignments behind the grain boundaries, strength and yield stress increase and flexibility decreases. In the present study, the cooling was carried out at ambient temperature. The size of grain decreases with a fall in annealing temperatures and the specimen thickness. Based on the result of this investigation and literature review, by increasing the annealing temperature the copper grains become larger and the seeds tend to grow and subsequently the strength will decrease [26].

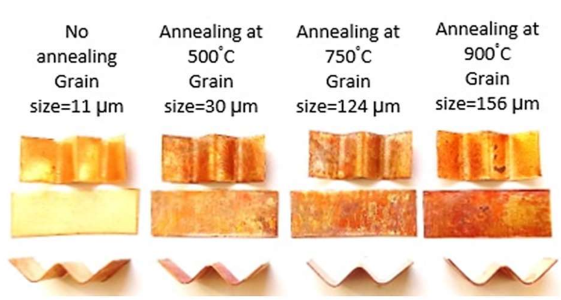

Fig. 5. W-bending for R_P=0.8 mm and thickness of 0.1 mm.

It is found that, in the case of constant sheet thickness, with increasing grain size, elongation and yield strength decreased. Moreover, a slightly lesser Young's modulus was observed when the grain size grew larger at constant thickness. The reason contributing to this effect is that the surface grains have fewer constraints compared to the inner ones, thus they present relatively lower flow stress. For a given sheet thickness, the proportion of surface grains increases when the average grain size grows larger, leading to a decrease in the flow stress.

3.2. The punch radius's effects on springback behavior

To study the effects of punch radius on springback behavior in copper sheets, the results were examined for the same grain sizes. Fig. 6 displays the annealed specimens in thicknesses of 0.5 mm and three punch radii at 500, 750, and 900°C. As can be seen, when the punch radius increases, the residual stresses are distributed in a larger area and the springback increases because of an increase in the deformed region. In other words, the material flow zone decreased in the plastic area with the decrease of the punch radius, and the accumulation of residual stresses occurred in a small area of the sheet, thereby leading to a decrease in springback. The results demonstrated that this was the lowest springback for the 0.3 mm punch radius (Fig. 7). This is in agreement with the experimental results obtained by Liu et al. [10].

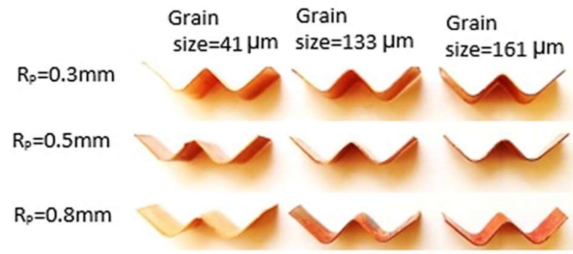

Fig. 6. The results of experimental bending for thickness of 0.5 mm.

3.3. The effects of thickness and grain size of the copper sheet on springback behavior

Material thickness has a major influence on springback [27]. In Fig. 7 and Fig. 8 the effects of thickness of the copper sheet on springback behavior are shown for various punch radii. As can be seen, the springback angle has been reduced by increasing the thickness of the sheet. On the other hand, it can be observed that with the rise in the t/d ratio, the springback angle has been decreased because in the same forming angle and thickness conditions, the plastic deformation

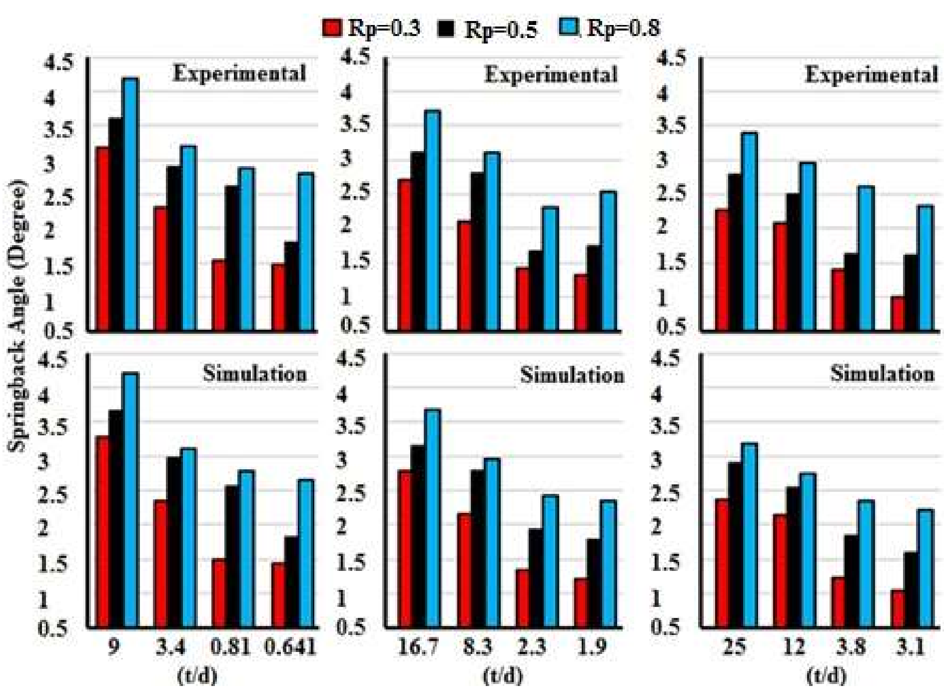

Fig. 7. The effects of thickness, grain size and punch radius on springback angle.

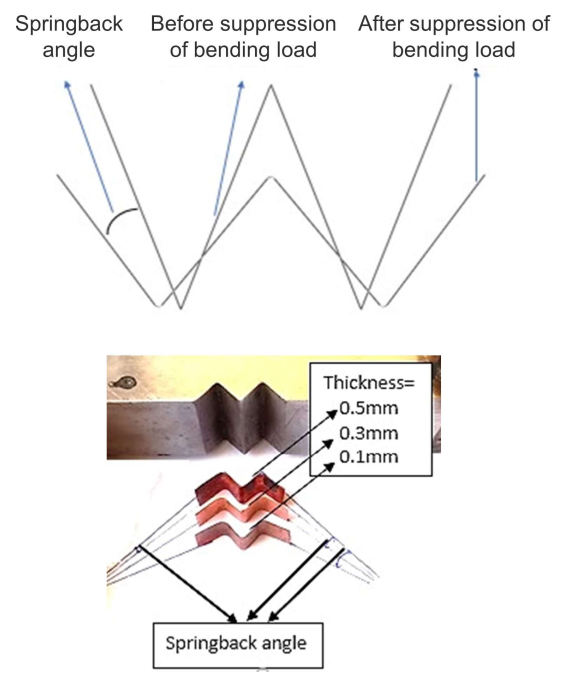

Fig. 8. The effects of thickness on springback angle when the punch radius is 0.8 mm and 500°C annealing temperature.

area is larger, which requires a large forming force, thus resisting the springback behavior. In other words, by increasing the thickness, the moment of inertia of the rectangular area of specimens increases, and the stress of the bending area decreases.

One of the important factors in the study of springback behavior on a micro scale is the ratio of primary thickness to the grain size (t/d) [7]. However, the smallest springback angle was for a thickness of 0.5 mm and a grain size of 161 µm at a temperature of 900°C. Thus, it can be concluded that temperature selection is a necessary element in studying springback behavior on a micro scale. In Table 2, the t/d ratio measured at about 9.0 for a thickness of 0.1 mm and a grain size of 11 µm, which is relatively large and consistent with the classic bending theories for metal sheet forming. However, with a decrease in the t/d ratio, the springback angle has decreased as well. Furthermore, this ratio measured 0.64 for a thickness of 0.1 mm and a grain size of 156 µm. Therefore, it is concluded that the factor of grain size has significant effects on springback angle, and it is the t/d ratio that affects it. These results are consistent with that of Wang's [26].

3.4. Simulation results

Validation results were carried out based on software simulations which were in good agreement with the experimental results. For constant thickness, the springback decreased by increasing the grain size and, in the case of fixed annealing temperatures, it decreased by increasing the t/d ratio (Fig. 7). Increasing the punch radius also increased the springback. Due to the fact that the difference in the annealing temperature of the specimens results in the variation of grain size, and subsequently the stress-strain curves, in this paper, the real stress-strain data obtained by the experimental tests were precisely imported in ABAQUS. Therefore, the accurate material behavior for the corresponding analysis could be considered by this finite element tool. Please note that for the simulation all the settings of analysis were similar except for the mentioned stress-strain curves of each specimen. Table 3 shows the numerical values of Fig. 7 (numerical values of experimental and simulated tests and error values). In fact, the error values demonstrate the difference between experimental tests and simulation results. It can be noted that the average errors for the punch radii of 0.3, 0.5, and 0.8 mm are 4.26%, 3.34%, and 5.19%, respectively. Therefore, the numerical simulation and experimental results correlate well and are in good agreement.

3.5. Regression model

In this study, the role of the springback and its corresponding effect has been scrutinized. It is seen that the variation of the springback is attributed to some parameters including punch radii, sheet thickness and grain size. Furthermore, to prognosticate the springback, the multi-choice regression model has been utilized based on MATLAB 2015 software. The input numbers are the mentioned parameters such as punch radii, sheet thickness, and grain size, and the outcome is the springback, thereby Eq. (1) has been calculated. It should be mentioned that the correlation coefficient is 0.9216 (R^2=0.9216).

$$SP = 2.06754 \times R_p - 0.5358 \times t - 1.2578 \times \log(d) + 3.7575 \quad (1)$$

Table 3. Comparison between experimental with numerical results (Sim=Simulation, and Exp=Experimental)

t/d	R_p=0.3		Error (%)	R_p=0.5		Error (%)	R_p=0.8		Error (%)
	Exp	Sim		Exp	Sim		Exp	Sim	
9	3.2	3.3	3.0	3.6	3.6	0.0	4.2	4.2	0.0
3.4	2.3	2.3	0.0	2.9	3.0	3.3	3.2	3.1	3.1
0.81	1.5	1.5	0.0	2.6	2.6	0.0	2.9	2.8	3.4
0.64	1.5	1.4	6.7	1.8	1.8	0.0	2.8	2.6	7.1
16.7	2.7	2.8	3.6	3.1	3.1	0.0	3.7	3.7	0.0
8.3	2.1	2.2	4.5	2.8	2.8	0.0	3.1	3	3.2
2.3	1.4	1.3	7.1	1.7	1.9	10.5	2.3	2.4	4.2
1.9	1.3	1.2	7.7	1.7	1.8	5.6	2.5	2.3	8.0
25	2.3	2.4	4.2	2.8	2.9	3.4	3.4	3.2	5.9
12	2.1	2.1	0	2.5	2.5	0.0	3	2.7	10.0
3.8	1.4	1.2	14.3	1.6	1.8	11.1	2.62	2.3	12.2
3.1	1	1.0	0	1.6	1.5	6.2	2.32	2.2	5.2
	Mean Error		4.26			3.34			5.19

Fig. 9 shows the correlation between the actual and predicted values in the regression model. The result shows that the proposed model has good accuracy for predicting springback. In order to evaluate the extracted regression model, for eight different samples, springback was performed experimentally. Samples included 0.4 mm and 0.8 mm thick, sheets annealed at 600°C and 830°C. SEM imaging was performed on the annealed specimens to determine the grain size and two punch radii of 0.7 and 1 mm were used (Fig. 10). Table 4 presents the springback values for the samples as experimental and predicted by the regression model. The results of evaluating the regression model using experimental data showed that the average error of the model for estimating the springback is 8.08%.

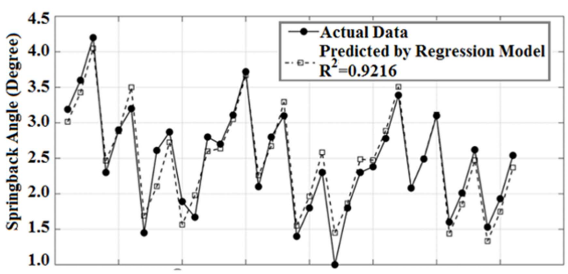

Fig. 9. Correlation between actual and predicted values by regression model.

Table 4. Springback comparison between results of formula prediction (Pre) and experimental (Exp)

R_P (mm)	t (mm)	T (°C)	d (μm)	Springback (Degree)		Error (%)
				Exp	Pre	
1	0.4	600	100	3.19	3.09512	2.97
1	0.8	600	140	2.71	2.697	0.48
1	0.4	830	145	2.63	2.892151	9.06
1	0.8	830	172	2.43	2.584552	5.98
0.7	0.4	600	100	2.32	2.474858	6.25
0.7	0.8	600	140	1.71	2.076738	17.66
0.7	0.4	830	145	1.84	2.271889	19.01
0.7	0.8	830	172	2.03	1.96429	3.23
Mean Error						**8.08**

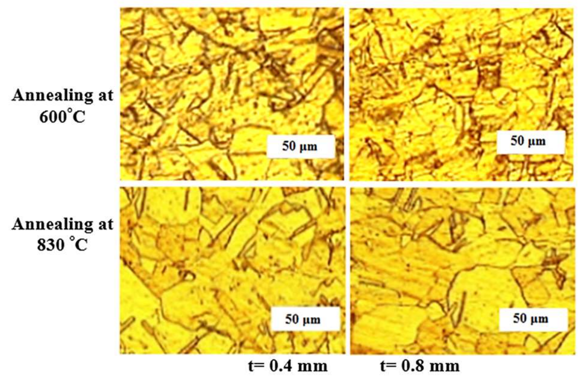

Fig. 10. Specimens microstructure for 0.4 mm and 0.8 mm thick sheets, annealed at 600°C and 830°C.

4. Conclusion

- According to the results of the heat treatment cycle, the grain size increased with increasing the annealing temperature, leading to a decrease in the mechanical properties of the sheet such as the yield strength, and ultimate strength.
- The springback decreased with an increase in the sheet thickness and annealing temperature and increased in return for the rise in punch radii.
- The comparison of simulation and experimental results showed that the mean error values of 4.26%, 3.34%, and 5.19% for the punch radii of 0.3, 0.5, and 0.8 mm were negligible, and the results of numerical simulations match well with the experimental tests.
- Based on the mentioned results, a mathematical

formula was obtained to predict springback. This mathematical relationship for the prediction of springback based on the punch radii, grain size, and thickness can be used efficiently to avoid costly experimental tests.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of Interests

The authors have no conflict of interests to declare.

5. References

[1] A. Adelkhani, H. Ebrahim, M.M. attar, The experimental and numerical study of the effects of welding angle on forming multilayered sheets in U-bending operations, *Journal of Mechanical Science and Technology*, 34(1) (2020) 239-244.

[2] H. Hou, G. Zhao, L. Chen, H. Li, Springback behavior and a new chord modulus model of copper alloy during severe plastic compressive deformation, *Journal of Materials Processing Technology*, 290 (2021) 116974.

[3] P. Hetz, S. Suttner, M. Merklein, Investigation of the springback behaviour of high-strength aluminium alloys based on cross profile deep drawing tests, *Procedia Manufacturing*, 47 (2020) 1223-1229.

[4] M. Cheraghi, A. Adelkhani, M.M. Attar, The experimental and numerical study of the effects of holding force and die radius on springback in a stretch bending test, *Iranian Journal of Materials Forming*, 8 (2) (2021) 35-43.

[5] S. Jadhav, M. Schoiswohl, B. Buchmayr, Applications of finite element simulation in the development of advanced sheet metal forming processes, BHM *Berg-und Hüttenmännische Monatshefte*, 163(3) (2018), 109-118.

[6] N. Şen, V. Taşdemir, Experimental and numerical investigation of the springback behaviour of CP800 sheet after the V-bending process, *Ironmaking & Steelmaking*, 48(7) (2021) 811-818.

[7] S.B. Chikalthankar, G.D. Belurkar, V.M. Nandedkar, Factors affecting on springback in sheet metal bending: a review, *International Journal of Engineering and Advanced Technology*, 3(4) (2014) 247-251.

[8] M.K. Choi, H. Huh, Effect of punch speed on amount of springback in U-bending process of auto-body steel sheets, *Procedia Engineering*, 81 (2014) 963-968.

[9] O. El Fakir, L. Wang, D. Balint, J.P. Dear, J. Lin, T.A. Dean, Numerical study of the solution heat treatment, forming, and in-die quenching (HFQ) process on AA5754, *International Journal of Machine Tools and Manufacture*, 87 (2014) 39-48.

[10] X, Liu, S. Zhao, Y. Qin, C. Wang, W.A. Wan-Nawang, Size effects on the springback of CuZn37 brass foils in tension and micro W-bending, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 232(14) (2018) 2439-2448.

[11] W. Phanitwong, A. Sontamino, S. Thipprakmas, Effects of part geometry on spring-back/spring-go feature in U-bending process, In *Key Engineering Materials*, 549 (2013) 100-107.

[12] A. Mkaddem, D. Saidane, Experimental approach and RSM procedure on the examination of springback in wiping-die bending process, *Journal of Materials Processing Technology*, 189(1-3) (2007) 325-333.

[13] D. Hakan, Ö. Mustafa, S. Murat, Effects of material properties and punch tip radius on spring-forward in 90 V bending processes, *Journal of Iron and Steel Research International*, 20(10) (2013) 64-69.

[14] [14] S.K. Panthi, N. Ramakrishnan, M. Ahmed, S.S. Singh, M.D. Goel, Finite element analysis of sheet metal bending process to predict the springback, *Materials & Design*, 31(2) (2010) 657-662.

[15] Z.Q. Jiang, H. Yang, M. Zhan, X.D. Xu, G.J. Li, Coupling effects of material properties and the bending angle on the springback angle of a titanium alloy tube during numerically controlled bending, *Materials & Design*, 31(4) (2010) 2001-2010.

[16] K. Mori, K. Aktia, Y. Abe, Springback behavior in bending of ultra-high-strength steel sheets using CNC servo press, *International Journal of Machine Tools and Manufacture*, 47(2) (2007) 321-325.

[17] X. Li, Y. Yang, Y. Wang, J. Bao, S. Li, Effect of the material-hardening mode on the springback simulation accuracy of V-free bending, *Journal of Materials Processing Technology*, 123(2) (2002) 209-211.

[18] H. Y. Yu, Variation of elastic modulus during plastic deformation and its influence on springback, *Material & Design*, 30(3) (2009) 846-850.

[19] J.G. Liu, M.W. Fu, J. Lu, W.L. Chan, Influence of size effect on the springback of sheet metal foils in micro-bending, *Computational Materials Science*, 50(9) (2011) 2604-2614.

[20] S. Toros, S. Kilic, F. Ozturk, The effect of material thickness and deformation speed on springback behavior for DP600 steel, *Advanced Materials Research*, 264 (2011) 636-645.

[21] X. Liu, S. Zhao, Y. Qin, J. Zhao, W.A. Wan-Nawang, A parametric study on the bending accuracy in micro W-bending using Taguchi method, *Measurement*, 100 (2017) 233-242.

[22] Z. Tekıner, An experimental study on the examination of springback of sheet metals with several thicknesses and properties in bending dies, *Journal of Materials Processing Technology*, 145(1) (2004) 109-117.

[23] M. Sabzi, & M. Farzam, Hadfield manganese austenitic steel: a review of manufacturing processes and properties, *Materials Research Express*, 6(10) (2019) 1065c2.

[24] X. Ha, M.G. Oliveira, A. Andrade-Campos, P.Y. Manach, & S. Thuillier, Prediction of coupled 2D and 3D effects in springback of copper alloys after deep drawing, *International Journal of Material Forming*, 14(5) (2021) 1171-1187.

[25] A.A. Suvorova, I.V. Danilov, G.M. Kalinin, A.B. Korostelev, Heat treatment effects on the microstructure and properties of Cu–Cr–Zr alloy used for the ITER blanket components, *Nuclear Materials and Energy*, 15 (2018) 80-84.

[26] J. Wang, M. Fu, J. Ran, Analysis of the size effect on springback behavior in micro-scaled U-bending process of sheet metals, *Advanced Engineering Materials*, 16(4) (2014) 421-432.

[27] S. Thipprakmas, W. Phanitwong, Process parameter design of spring-back and spring-go in V-bending process using Taguchi technique, *Materials & Design*, 32(8-9) (2011) 4430-4436.