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مناقشة حول العودة الرجعية للصفيحة ذات الطبقتين من النحاس و الفولاذ المقاوم للصدأ التي ينتجها اللحام الإنفجاري خلال عملية التقويس بشكل حرف U

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الخلاصة

تمّ إنتاج الورقة ذات طبقتين من النحاس النقي التجاري- الفولاذ المقاوم للصدأ 304 في هذه الدراسة مع إستخدام طريقة اللحام الإنفجاري و تمّ تشكيله في شكل التقويس بشكل حرف U. فتمّ في هذه الدراسة إنجاز التحليل على أساس القوّة وكذلك التدقيق في اثر المعايير لشعاع رأس القضيب، سماكة الصفيحة، معامل الاحتكاك و الخواص الميكانيكية على العودة الرجعية للصفيحة ذات الطبقتين مستخدماً الطرق المختبرية و محاكاة العنصر المحدود. النتائج في هذه الدراسة دلّت على أنّه بواسطة زيادة المقاومة و معاير المرونة الطولي للمادة، زيادة سماكة الصفحية، زيادة معامل الإحتكاك و إخفاض الشعاع لرأس القضيب؛ يخفض كمّيّة و مقدار العودة الرجعية. علاوةً على هذا، فتأثير خواص الفولاذ الميكانيكية و أثر زيادة سماكته على إنخفاض العودة الرجعية في الصفيحة ذات الطبقتين يكون أكثراً من النحاس.

Investigation of springback of two-layer metallic sheet produced by explosive welding in U-die bending process

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ABSTRACT

In the present study, the two-layer sheet made of commercially pure copper (CP-Cu) and 304 stainless steel (SS-304) was fabricated by using explosive welding process and then was formed in U-shape bending process. In the study, the load was analyzed and effect of parameters such as punch tip radius, sheet thickness, friction coefficient, and mechanical properties on spring back of the two-layer sheet was investigated using experiments and finite element simulation. The results of this research show that, by increasing the strength and modulus of elasticity of material, thickness of sheet, the friction coefficient between die wall and sheet and reducing the punch tip radius, the spring back amount of sheet decreases. Moreover, the effect of mechanical properties of steel and increasing its thickness on the spring back reduction is more than the copper in two-layer metallic sheet.

Keywords: Explosive welding; finite element simulation; springback; two-layer metallic sheet; U-shape bending.

INTRODUCTION

In metallic sheet forming industry, especially in the sheet bending process, “springback” phenomenon plays a significant role and there is a major concern that such phenomenon may cause geometric and dimensional inaccuracies. Springback is caused by the elastic recovery of the material during the unloading in bending process which leads to the geometric changes of the products. The springback phenomenon directly affects the bend angle and the bend curvature. Also, under certain conditions, it is possible that the final bend angle be lower than the intended one, which is called as “springgo” or “springforward” phenomenon (Kalpakjian & Schmid, 2006). The springback/springgo amount is influenced by various parameters such as the tool shape and dimensions, the contact friction condition, the material properties, sheet anisotropy and the sheet thickness (Ragai et al., 2005).

There have been many studies on the springback phenomenon of one-layer sheets and the effect of various parameters on it in different forming processes, especially the bending procedure. Phanitwong & Thipprakmas (2016), proposed a new factor for achieving the bend angle in wiping die bending process more accurately. Using finite element simulation and experimental methods, they revealed that in contrast with the previous theories, the springback factor does not only depend on the die radius and work-piece thickness; and the bend angle is also an effective parameter. Choi

& Huh (2014), studied the effect of punch speed on the springback of steel in U-shape die. Their research showed that by increasing the punch speed, the springback is also increased. In order to eliminate the springback effect in U-shape die, a new method was proposed by Lawanwomg et al. (2014). They considerably reduced the springback by designing a special punch and by applying an additional bend to the sheet during the forming, and by using finite element simulation and experimental tests, showed that by applying negative bending moment, the springgo amount can be reduced. Davoodi & Zareh-Desari (2014), also investigated the forming parameters influencing the springback in multi-point forming process through numerical and experimental methods. The aluminum sheet springback amount in L-shape bending process was determined by Dilip Kumar et al. (2014) and through experimental tests, the effect of clearance between the punch and the die on springback amount was studied. Baseri et al. (2011), using the results of experimental tests, proposed the FLBP (Fuzzy Learning Back-Propagation) algorithm for predicting the springback phenomenon in V-shape die. Bakhshi-Jooybari et al. (2009), studied the effects of significant parameters on the springback in U-die and V-die bending of CK67 anisotropic steel sheet using experimental and numerical methods. Thipprakmas & Rojananan (2008), studied springback and springgo phenomena in V-shape bending process using finite element method. The effect of sheet anisotropy on the sheet springback in U-shape bending process was investigated by Gomes et al. (2005). Tekıner (2004), investigated the effect of bend angle on the springback phenomenon of various materials with various thickness in V-shape die. The effect of some crucial factors on the accuracy and efficiency of simulation was investigated by Xu et al. (2004). Moon et al. (2003), experimentally examined the effect of hot die and cold punch combination on the springback reduction of aluminum sheet. Cho et al. (2003), conducted a numerical study on the effects of some parameters such as the punch and die tip radius, clearance between the punch and die and the friction coefficient on the springback phenomenon in U-shape bending process. Papeleux & Ponthot (2002), investigated the effect of blank-holder force and friction coefficient on the springback phenomenon in U-shape bending process. Li et al. (2002), showed that the accuracy of springback simulation is directly influenced by the material hardening model.

“Explosive welding (EXW)” is one of the joining methods. This process is categorized as a solid state welding process. In this method, two metallic sheets are joined together using controlled explosive detonation on the surface of metal (Gülenç et al., 2016). During the collision, due to the production of a high velocity jet caused by explosion, any impurities are removed off the metal surface. By the intense collision of the flyer plate with the base plate, a strong bonding is created in the interface surface of the metals. Since the metal plates are joined together in an internal point under a very high pressure; a considerable local plastic deformation is created in the interface surface. Consequently, the metals with the metallurgical bonding are joined together stronger than the parent metals and make a two-layer sheet (Findik, 2011).

Similar and dissimilar materials with various properties such as different thickness, dimensions and mechanical-thermal properties can be perfectly joined by explosive welding (Mynors & Zhang, 2002; Findik, 2011). Since the high strength is one of the main advantages of explosive welding process, a lot of joining procedures have been conducted by this method in order to investigate the mechanical-metallurgical properties, and also to analyze the microstructure, stress and the effective parameters on the joining procedure (Mousavi et al., 2008). The joining of copper-copper (Rybin et al., 2014), steel-stainless steel (Habib et al., 2015), low carbon steel-middle carbon steel (Borchers et al., 2016), copper-aluminum (Honarpisheh et al., 2012), tantalum-low carbon steel (Kosec et al., 2003), copper-low carbon steel (Raghukandan, 2003), aluminum-titanium (Kahraman et al., 2007), aluminum-steel (Li et al., 2015), 304 stainless steel-titanium (Mousavi & Sartangi, 2009) copper-steel (Bina et al., 2013), titanium-magnesium (Habib et al., 2015), tungsten-ferritic steel (Mori et al., 2014), etc. have been operationally reported so far.

Since springback of multi-layer sheets produced by explosive welding has not been investigated so far, in the present study, by manufacturing a two-layer commercially pure copper-304 stainless steel or Cu-SS sheet through explosive welding method, its springback amount has been studied in U-shape die bending under different conditions such as variable punch tip radius, variable sheet thickness, various friction conditions and different mechanical properties by two experimental and finite element simulation methods.

MATERIALS AND EXPERIMENTAL PROCEDURE

Materials

In the present study, two sheets of 304 stainless steel (SS-304), and commercially pure copper (CP-Cu) were used for joining via the explosive welding procedure. The chemical composition of these two materials obtained by using emission spectroscopy method was shown in Tables 1 and 2. In order to prevent the anisotropic effects on the experimental results, both pure copper and SS-304 sheets, were annealed before applying explosive welding process. The pure copper was heated to 600 °C for an hour and was cooled in the off-furnace. The SS-304 was also put in the furnace with 1050 °C temperature for an hour, and in order to prevent surface oxidation, controlled argon atmosphere was applied upon it.

Table 1. Chemical composition of 304 stainless steel (%wt).

Fe (Base)	Cr	Ni	Mn	Si	C	P	S
70.6	19.5	9.2	1.8	0.78	0.078	0.032	0.026

Table 2. Chemical composition of commercial pure copper (%wt).

Cu (Base)	Fe	Zn	Cd	Pb	Ag	Si
99.95	0.029	0.023	0.009	0.007	0.004	0.002

Explosive welding

Metallic sheets of CP-Cu and SS-304, in proper dimensions cutting and underwent explosive welding after cleaning the surface and sanding the interface surfaces with the sand paper No.600. The explosive powder was AMATOL with 14-17 mm thickness, 0.8 g/cm3 density, and mean detonation velocity of 2500 m/s (Honarpisheh et al., 2012). Also, in order to start and making sure of the proper explosion operation, C4 detonator was used. For doing the explosive welding of the Cu-SS two-layer, firstly the copper plate was put on a concrete block as the fixed plate or base, and then the steel plate was placed on the base plate as the flyer plate, with a certain distance by wooden legs. After being prepared and balanced, the detonation materials were poured into a completely dry wooden box, and then it was put on the flyer plate. Figure 1, shows the schematic view of the plate array before the explosion and also the way an explosive welding procedure is done.

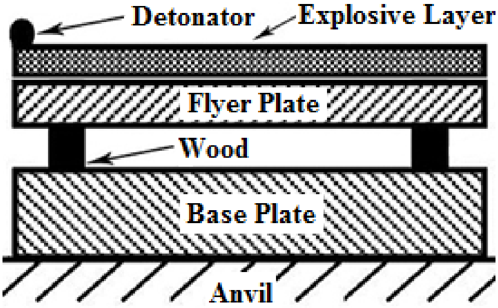

Fig. 1. Schematic view of two-layer explosive welding.

Cu-SS two-layer sheets were manufactured in different thicknesses of copper and steel and then in order to do the U-shape die bending, these two-layer sheets with different thicknesses were cut in rectangular dimensions of 30×80 mm. In Figure 2, a schematic view of Cu-SS two-layer sheet and dimensional parameters has been shown. t_{Cu}, t_{St}, L and b are copper thickness, steel thickness, length sheet and width of the sheet, respectively. Real illustration of Cu-SS two-layer sheet produced by explosive welding and microscopic image of the thickness of it show in Figure 3.

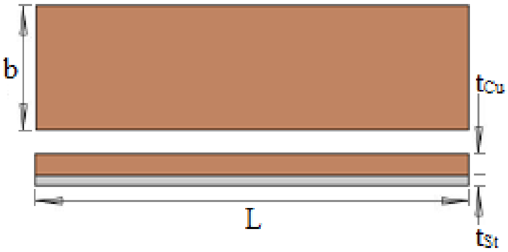

Fig. 2. Schematic view of Cu-SS two-layer and its dimensional parameters.

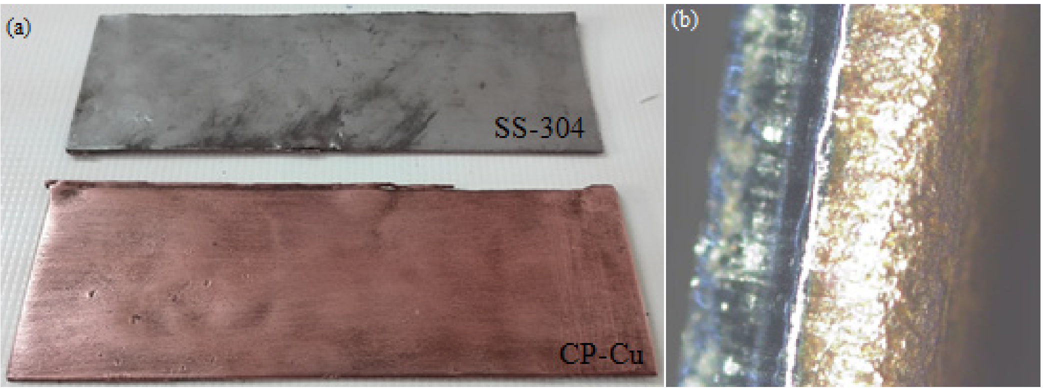

Fig. 3. (a) Real view of Cu-SS two-layer sheet after explosive welding process,
(b) Microscopic image of the thickness of Cu-SS two-layer sheet.

U-shape bending

The U-shape bending tool setup includes die, blank-holder and punch. These components are made of DIN 1.2080 cold work tool steel and are hardened up to 57 Rockwell C. Figure 4 shows the schematic and real view of the used U-shape die and its dimensional parameters. In order to investigate the dimensional effects of the punch and the sheet on the springback amount, the two-layer sheet thickness (t) and the variable punch tip radius (r) were considered. Hence, in order to do sheet bending in different thicknesses, punches with various widths (d) were used. Die tip radius (R) was considered constant. This parameter helps the material to flow easily during the bending process. The dimensions of the die, punch, and the two-layer sheet have been presented in Table 3.

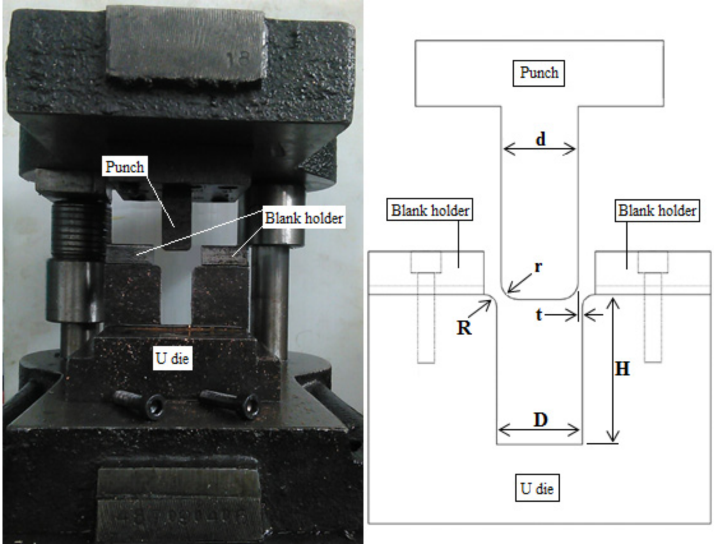

Fig. 4. Real and schematic view of U-shape bending die with dimensional parameters.

Table 3. Dimensions of the die, the punch and the two-layer sheet.

Parameters	Dimension (mm)		
t_{Cu}	0.8	1	1.2
t_{St}	0.3	0.5	0.7
$t = t_{Cu} + 0.3$ $t = t_{St} + 0.8$	1.1	1.3	1.5
r	2	4	6
d	17.8	17.4	17
D	20		
H	35		
R	3		
L	80		
b	30		

The bending of the two-layer sheets was performed at room temperature (25 °C), by a hydraulic press and with the nominal force of 200 tons, with the constant ram speed of 0.65 mm/s. After putting the sample on the die, under the blank-holder and lubricating all the surfaces using MoS_2, bending process is performed in two stages. In the first stage which is called "loading", the punch is moved 35 mm downward and the intended bend is created on the sheet. In the second stage, which is named "unloading", the punch goes upward completely out of the die, during which, a little bend recovery occurs -called "springback"- on the sheet, due to the material elastic properties. In order to determine the bend angle after the unloading, the Baty R14 optical profile projector was used. Figure 5a shows a view of the Cu-SS two-layer sheet undergone explosive welding before and after the bending process. The springback angle is also shown in U-shape bending, schematically in Figure 5b.

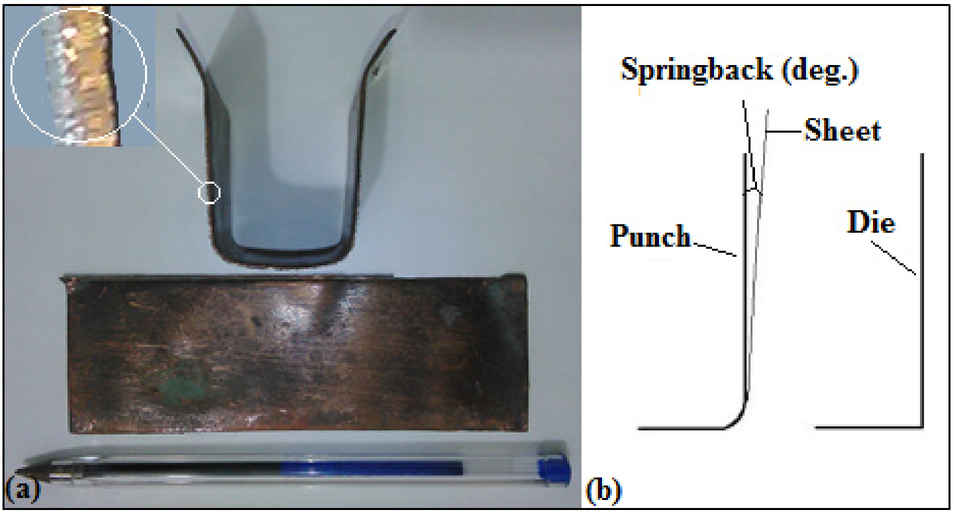

Fig. 5. (a) Cu-SS two-layer sheet bonded with explosive welding before and after the bending process; (b) Schematic view of the springback angle in U-shape bending.

Experimental tests

In this study, sheet tensile test was used under the standard of ASTM E 8M-00, in order to evaluate the elastic-plastic properties of the CP-Cu and SS-304 under annealed condition; in such a way that the standard samples with effective width of 12.5 mm were cut and they were put to tensile test using Zwick- Z250 universal testing machine with strain rate of 0.001 s^{-1} (Shaeri et al., 2013). Figure 6 and Table 4, in order show the resulting engineering stress-strain curves, and also the materials mechanical properties such as yield strength, ultimate strength, elongation and Holloman Equation $(\sigma = k\,\varepsilon^n)$.

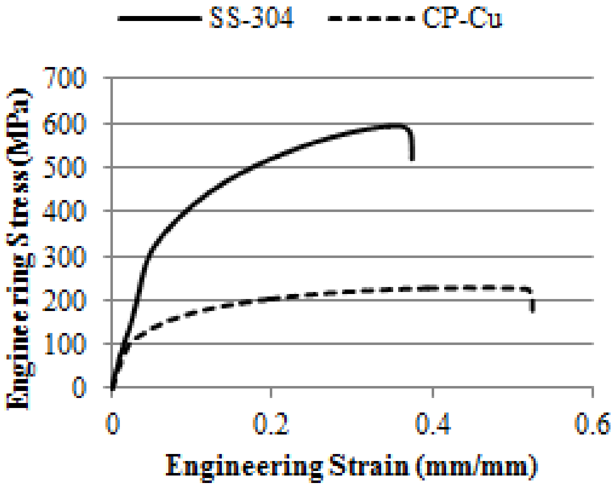

Fig. 6. Twin tunnel's stress distribution

Table 4. Yield and ultimate strength, elongation and Holloman equation of the annealed CP-Cu and SS-304.

Material	Strength (MPa)		Elongation (%)	Holloman Equation $(\sigma = k\,\varepsilon^n)$	
	Yield	Ultimate		k (MPa)	n
CP-Cu	113	227	52.5	286	0.233
SS 304	294	593	37.5	866	0.326

FINITE ELEMENT SIMULATION

In order to determine the amount of springback of the Cu-SS two-layer sheet under various conditions, the finite element software of Abaqus/CAE 6.12-1 was used. The U-shape die, punch and blank-holder were modeled as the analytical rigid elements and of R3D4 (A 4-node 3-D bilinear rigid quadrilateral) type and the two-layer sheets were modeled as deformable and of C3D8R (An 8-node linear brick, reduced integration, hourglass control), according to the dimensions presented in Table 3. Figure 7, reveals a view of the configuration of the U-shape bending process parts including the die, blank-holder, punch and the two-layer sheet in the software interface, before and after the bending process.

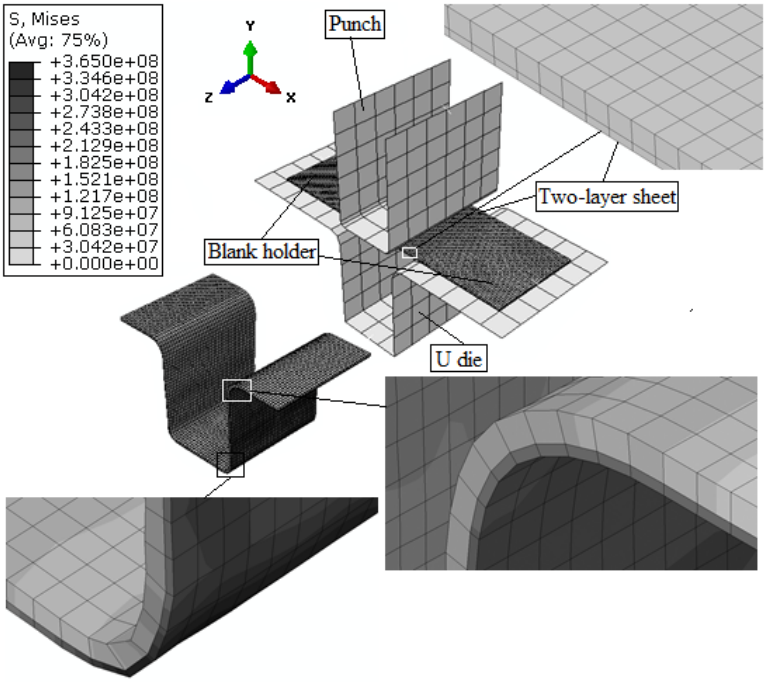

Fig. 7. A view of configuration of the U-shape bending process parts in the software interface, before and after the bending process.

Holloman stress-strain equation ($\sigma = k\ \varepsilon^{n}$) is inserted into the software, was obtained by fitting the power function to the plastic region of the engineering stress-strain curve as obvious from Table 4, Equations σ (MPa) = 286 $\varepsilon^{0.233}$ and σ (MPa) = 866 $\varepsilon^{0.326}$, expressed the Holloman equation for annealed CP-Cu and SS-304, respectively. Young's modulus, density and Poisson's ratio of the CP-Cu were considered as 110 GPa, 8500 kg/m^3 and 0.34 and for SS-304, these amounts were 193 GPa, 7800 kg/m^3 and 0.29, respectively. Approximate friction coefficient of 0.1 (Bakhshi-Jooybari et al., 2009; Shaeri et al., 2013) was used for all the surfaces. Due to the high strength of the Cu-SS bonded by the explosive welding, the two-layer sheet in the software interface was modeled as a sheet with the total thickness of the two welded metals, namely (t), and by partitioning it into two sheets with thickness of copper (t_{Cu}) and steel (t_{St}), the elastic-plastic properties of each material was applied to each partition. In order to conduct the finite element simulation similar to the experimental test, the die and the two blank-holders were fixed to all degrees of freedom and the sample was assembled under the blank-holder. With the punch movement with the speed of 0.65 mm/s according to the experimental condition, the sample is formed in the U-shape bending process. To obtain accurate simulation results, by eliminating the dependence of the results on the number of elements of the two-layer sheet, the optimum number of elements of the sheet was determined according to mesh sensitivity and by comparing the resulting numerical force with the amounts obtained from the experiments, the simulation results were trusted. In order to determine the number of elements of the die, blank-holder and the punch due to rigidity, default amounts were used, trusting the software. The number of optimum elements in the two-layer sheets with different thicknesses and also the number of the default elements of the die, the blank-holder and the punch were presented in Table 5. The purpose of using finite element simulation in this study, is to determine the springback amount of the two-layer sheets of Cu-SS under different dimensional conditions of punch tip radius and two-layer sheet thicknesses.

Table 5. The number of default elements for the die, punch, blank-holder and optimum elements for two-layer sheets.

Parts	No. of Elements		
Two-Layer Sheet	**t = 1.1 mm**	**t = 1.3 mm**	**t = 1.5 mm**
	9600	11704	13254
U-Die	150		
Punch	96		
Blank-Holder	24		

RESULTS AND DISCUSSION

Force analysis

Figure 8 demonstrates the maximum experimental force and the change procedure of the loads applied on the punch during the two-layer sheet bending process of Cu-SS, resulting from the finite element simulation. The thicknesses of copper, steel and the punch tip radius are in order 0.8, 0.3 and 4 mm. The force in the bending process in each instant consisted of the sum of the force needed to deform the sheet in bending and the force needed to overcome the friction force between the die and the sheet. The bending process involves two stages of loading and unloading. In loading stage or in area (i), with the downward movement of the punch, at first the force needed for deformation of the sheet is imposed on the punch, and then the friction force between the die internal wall and the sheet surface increases instantly. Therefore, the force in loading stage has an increasing trend. The unloading stage involves two areas of (ii) and (iii). In area (ii), by the upward movement of the punch, suddenly the deformation force is unloaded from the punch, so a sudden reduction is observed in this area in Figure 8. In area (iii), by the upward and instant movement of the punch, the contact surface between the punch and the sheet is reduced and gradually the punch force decreases. Hence, the gradual reduction with a mild slope in stage (iii), is related to the instant reduction of the friction force. In Figure 8, the maximum experimental force was presented where we can see an acceptable agreement between the experimental results and finite element simulation.

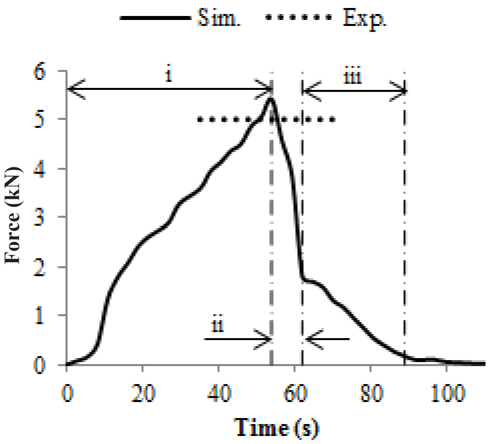

Fig. 8. The diagram of force-time in U-shape bending process.

Trusting the simulation results, the effect of punch tip radius and sheet thickness was investigated on the forming load amount, using experimental and simulation methods. The bending force amounts in Table 6, were presented for different conditions.

Table 6. Bending force amounts in different conditions.

Thickness (mm)		**Forming Force (kN)**					
		Experimental results			**Simulation results**		
t_{Cu}	**t_{St}**	**r = 2**	**r = 4**	**r = 6**	**r = 2**	**r = 4**	**r = 6**
0.8	0.3	-	5	-	5.9	5.4	5
0.8	0.5	6.5	6	5.3	6.7	6.2	5.7
0.8	0.7	-	6.4	-	7.6	6.9	6.1
1	0.3	5.9	5.4	5.1	6.2	5.7	5.3
1.2	0.3	-	5.6	-	6.5	5.9	5.7

In Figure 9, the effect of punch tip radius was shown on the bending force in two-layer sheet thickness of 1.3 mm. As it can be seen, by increasing the punch tip radius due to the deformation force reduction caused by bending, the needed force for the bending process also decreases. There is good agreement between the values obtained by simulation and experiment.

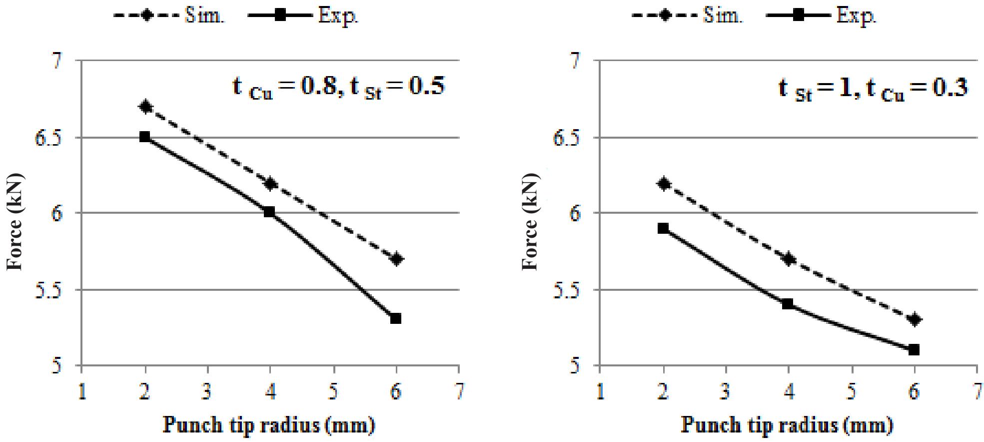

Fig. 9. Experimental results and simulation of the punch tip radius effect on bending force.

In Figure 10, the effect of two-layer sheet thickness on the forming force was studied using experimental and finite element simulation. As it is obvious, by considering the copper and steel thickness as constant values of 0.8 and 0.3 mm, and also by keeping the punch tip radius constant at 4 mm, the effect of sheet thickness on the forming load was investigated. The results show that by increasing the sheet thickness, the bending force increases as expected. Obviously, the effect of the steel thickness on the bending force is more than that of the copper which is due to the higher strength of steel compared to copper. In these results, also there is an acceptable agreement among the experimental and simulation results.

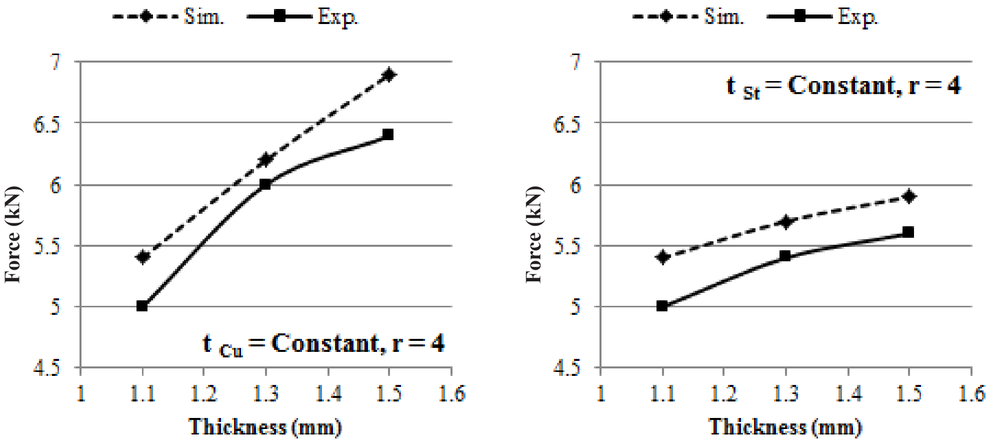

Fig. 10. Experimental and simulation results of the effect of two-layer sheet thickness on bending force.

In Figure 11, the effect of punch tip radius on the forming force for bending was presented. These results which are merely obtained out of the finite elements simulation were calculated in different radii just in case of considering the thickness of steel and copper as constant amounts. The results show that by increasing the punch tip radius in various thicknesses, the bending force is reduced which is caused by the lower deformation of the bent region in larger radii.

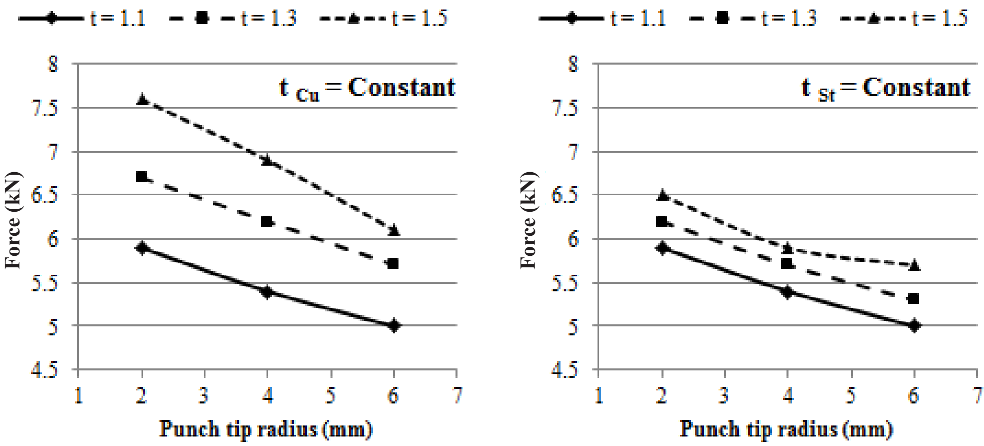

Fig. 11. Simulation results of effect of punch tip radius in various thicknesses on bending force.

Figure 12, demonstrates the simulation results of sheet thickness effect on the bending force in different punch tip radii. As it is obvious from the results and as it was predictable, by increasing the sheet thickness, the bending force increases and the effect of the steel thickness on the forming load is more than that of the copper which is due to the higher strength of steel compared to copper.

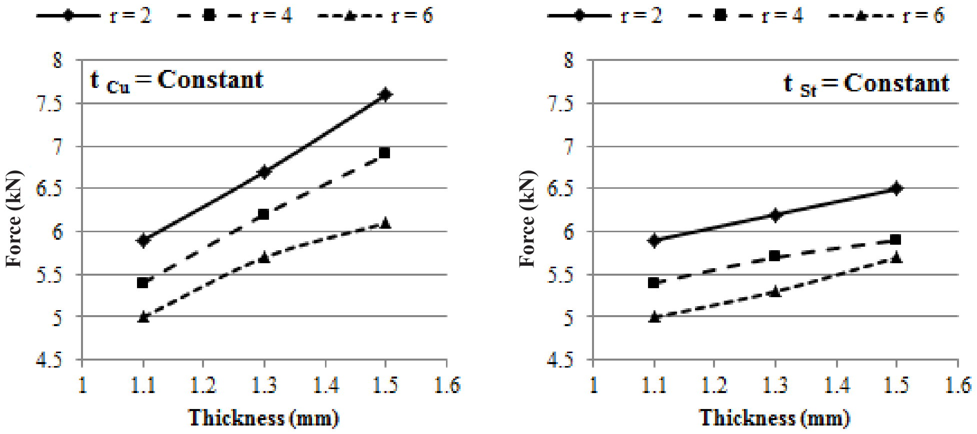

Fig. 12. Simulation results of the two-layer sheet thickness effect on bending force in different punch tip radii.

The effect of materials mechanical properties on springback

Figure 13 reveals the effect of two materials with different strengths and Young's modulus on the springback amount in U-shape die. As the finite element simulation results show, by increasing the sheet thickness, the springback reduces and also by separately comparing the sheet springback of one-layer steel and copper, one can conclude that the springback amount of the steel sheet is less than that of the copper sheet, which is due to the different strengths and modulus of elasticity of these materials (Nanu & Brabie, 2011). By increasing the strength and modulus of elasticity the needed energy for elastic recovery increases and consequently, the springback amount decreases (Li et al., 2002; Ragai et al., 2005).

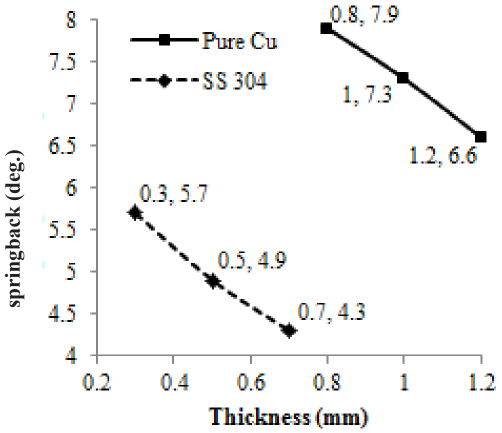

Fig. 13. The effect of material type in the various thicknesses on springback amounts.

The effect of punch tip radius on springback

The springback amounts out of finite element simulation and experimental tests are presented in Table 7 for different thicknesses and punch tip radii.

Table 7. Springback amounts in different conditions.

Thickness (mm)		Springback (deg.)					
		Experimental results			Simulation results		
t_{Cu}	t_{St}	r = 2	r = 4	r = 6	r = 2	r = 4	r = 6
0.8	0.3	-	4.9	-	4.4	5.1	5.9
0.8	0.5	3.6	4.4	5.2	3.8	4.6	5.3
0.8	0.7	-	3.8	-	3.5	4.1	5.1
1	0.3	4.2	4.8	5.4	4.3	5	5.7
1.2	0.3	-	4.6	-	4.1	4.9	5.5

The effect of punch tip radius on springback amount of two-layer Cu-SS sheet is demonstrated in Figure 14, using the results of finite element simulation and experimental tests. As it is obvious in the Figure 14, an acceptable agreement exists between the simulation and experimental results. The results show that by increasing the punch tip radius, the springback amount increases. By using larger radiuses of punch tips, less deformation will occur in the bent area and the material is less plasticized in the area. Therefore, due to staying in elastic area, the possibility of springback effect increases. By reducing the punch tip radius, the plastic deformation increases in bent area, and dimensional changes in the sheet after bending reduces. Since, the results of this research reveal that by decreasing the punch tip radius, the springback amounts reduce, therefore, it can be concluded that the most effective punch tip radius for reducing the springback amounts is r = 0. But, it is possible to the other problems occur during the bending with r = 0, such as undesired flow and fracture of material in bending zone.

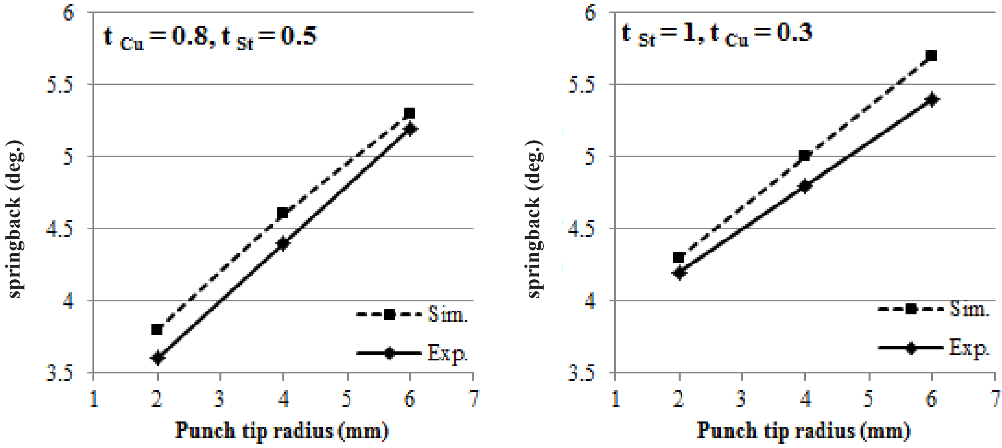

Fig. 14. Experimental and simulation results of the punch tip radius effect on springback amounts.

Figure 15 shows the punch tip radius effect on the two-layer sheets springback amounts. The results are obtained by finite element simulation and are investigated separately by considering the copper and steel thickness as constants, in order of the effect of increase of each material on the two-layer sheets springback in different punch tip radiuses. The results show that by keeping each material thickness as a constant amount, increasing the other material thickness will reduce the springback amount, because by increasing the thickness, more force is needed for elastic recovery of material. As it is clear, by increasing the punch tip radius, the springback amount increases. Comparing two diagrams in Figure 15 reveals that the effect of steel thickness on springback reduction is more than that of the copper. By regarding the steel thickness as a constant amount, and by increasing the copper thickness, no considerable influences was observed on the springback reduction; however, by considering the copper thickness as a constant, the steel thickness increase, caused the springback to reduce significantly. The results of the present study is compatible with the results reported in the literatures (Cho et al., 2003; Thipprakmas & Rojananan, 2008; Bakhshi-Jooybari et al., 2009), qualitatively.

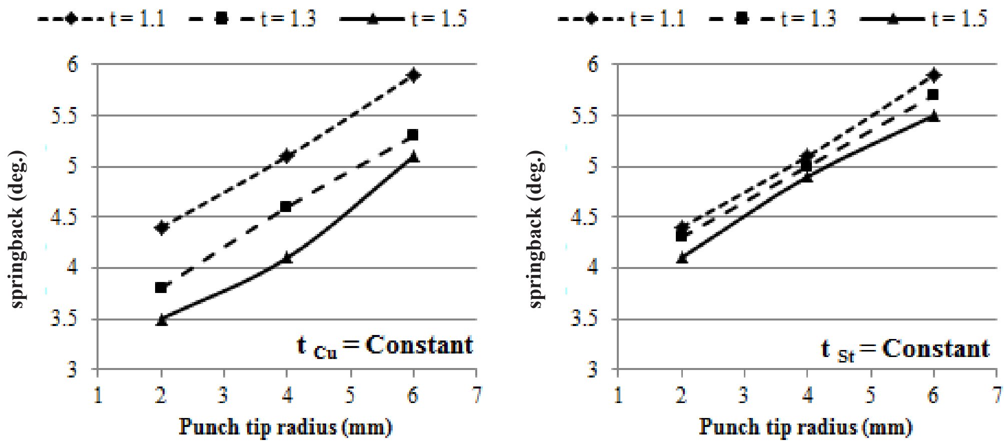

Fig. 15. Simulation results of punch tip radius effect in different thickness of two-layer sheet on springback.

The effect of two-layer sheet thickness on springback

The effect of two-layer sheet thickness of Cu-SS in punch tip radius of 4 mm, was investigated through experimental and simulation methods. Figure 16 shows the effect of thickness in both states of copper thickness constant and steel thickness constant, separately. As it can be seen, by increasing the sheet thickness, the springback amount reduces which is due to the increase of required force for elastic recovery of the sheet. There is an acceptable agreement between simulation and experimental results as well.

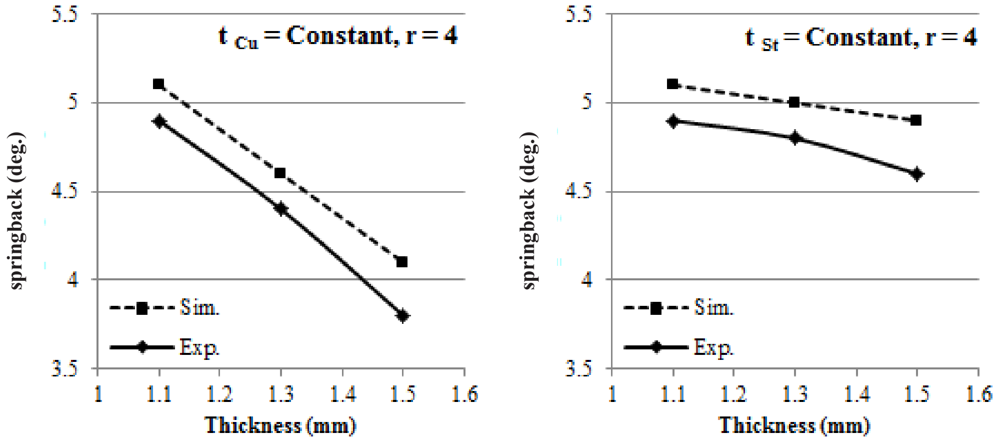

Fig. 16. Experimental and simulation results of two-layer sheet thickness result on springback amount.

The effect of two-layer sheet thickness on springback for different punch tip radiuses and two states of constant steel and copper thicknesses are presented in Figure 17. As it is obvious, by increasing the thickness, the springback reduces and by increasing the punch tip radius, the springback increases. The results of the present study is compatible with the results reported in the literatures (Cho et al., 2003; Tekıner, 2004; Bakhshi-Jooybari et al., 2009), qualitatively.

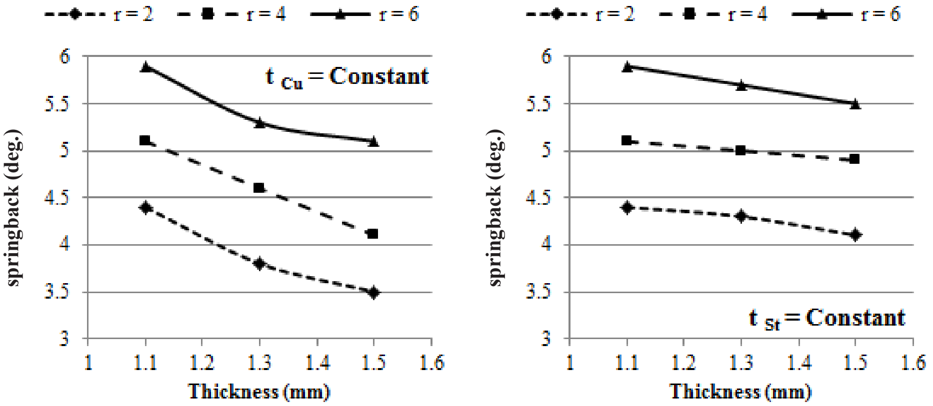

Fig. 17. Simulation results of two-layer sheet thickness result on springback in different punch tip radiuses.

The effect of friction coefficient on springback

Figure 18 shows the effect of friction coefficient on the two-layer Cu-SS sheet springback. As it is clear, by increasing the friction coefficient from 0 to 0.2, the springback reduces and after reaching 0.2, by increasing the friction coefficient, no significant change is seen in springback. According to the results of simulation in the literature (Kadkhodayan & Pourhasan, 2011), by increasing the friction coefficient, the plastic deformation region is enlarged under definite deformation and as a result, the springback amount will reduce by enlarging the deformation region.

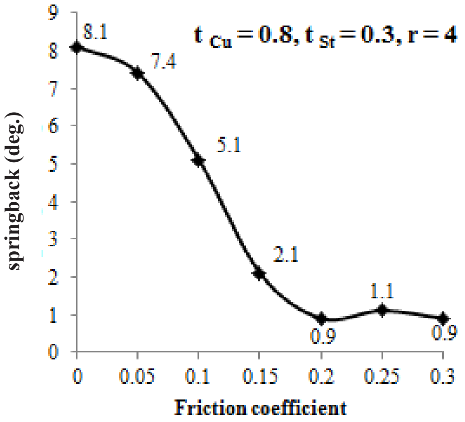

Fig. 18. The effect of friction coefficient on two-layer Cu-SS sheet in U-shape die.

CONCLUSION

The results of finite element simulation and experimental tests on the bending force and the springback amount of the two-layer Cu-SS sheets under different thickness and punch tip radius conditions can be summed up as follows:

- By reducing the thickness and increasing the punch tip radius, the bending force in two-layer Cu-SS sheet is reduced.
- The effect of decreasing the steel thickness on bending force reduction is more than effect of the copper thickness reduction in two-layer Cu-SS sheet.
- By increasing the strength and elasticity modulus of the material, the sheet springback amount reduces; therefore, steel has less springback than copper.
- By reducing the punch tip radius and increasing the thickness, the springback of the two-layer Cu-SS reduces.
- The effect of increasing the steel thickness on the springback reduction is more than effect of increasing the copper thickness in two-layer Cu-SS sheet.
- By increasing the friction coefficient, the two-layer Cu-SS springback amount reduces and then remains fixed.

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