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RESEARCH ARTICLE - MECHANICAL ENGINEERING

The Experimental Investigation of Springback in V-Bending Using the Flexforming Process

İbrahim Karaağaç[1]

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Abstract The flexforming process is a sheet metal forming method that uses hydraulic fluid pressure and a rubber diagram to form sheet metal with a die. This study, for the first time, experimentally investigates the factors affecting the springback resulting from the bending of copper and brass sheet metal materials in V-bending dies using the flexforming process. Additionally, the formability during the V-bending method was experimentally investigated by using thin, high-pressure-resistant rubber membranes instead of the thick ones commonly used in the flexforming processes. The process parameters in the experimental studies were determined to be: holding time (0, 5 and 10 s), bending angle (15°, 30°, 45°, 60°, 75° and 90°) and fluid pressure (10, 12 and 14.4 MPa). Sheet metals were formed in V-bending dies by both flexforming and conventional bending processes to compare the performance of the flexforming process against the conventional bending process. Springback values in the parts formed using the flexforming process for copper and brass sheet metals were determined to be 39.06 and 41.42% less, respectively, than those formed by the conventional bending method. Surface flaws occurring in the parts formed by the conventional bending method were not observed in the parts formed using the flexforming process. The springback was also estimated by using fuzzy logic based on unexecuted break-test parameters. When the outputs of the fuzzy logic system were compared with the experimental results, it was observed that the results were substantially similar.

✉ İbrahim Karaağaç
ibrahimkaraagac@gazi.edu.tr

1 Department of Manufacturing Engineering, Gazi University, 06500 Teknikokullar, Ankara, Turkey

Keywords Flexforming · V-bending · Springback · Fuzzy logic · Copper · Brass

1 Introduction

Sheet metal parts are usually formed using die-forming methods that feature a press. The main quality indicators of the formed parts are dimensional accuracy, thickness variation, surface quality and the physical and mechanical properties of the materials formed. There are many different factors that influence the quality of formed parts [1]. One of the most commonly used stamping processes used to form sheet metal materials is the bending process. Bending is the forming of solid parts, where angled or ring-shaped work pieces are produced from sheet or strip metal. In every bending operation springback occurs [2]. Springback can be considered a dimensional change that happens during unloading because of primarily elastic recovery of the part. Springback causes deviation from the designed target shape and produces downstream quality problems and assembly difficulties [3]. Tool shape and dimension, contact friction condition, material properties, thickness of sheet and sector angle are the major parameters that affect springback. The determination of springback by means of trial and error techniques not only increases the cost of the manufacturing and repair but also wastes a lot of time causing delays in the development of the product [4]. Therefore, it is important for the springback phenomenon to be taken into consideration in the design of the die. In addition to the forming of sheet metal materials by pressing a die, the bending method using the flexforming process is also widely used to form sheet metal materials. Flexforming is a type of hydroforming process in which the sheet metal is forced to take the shape of a rigid die by the action of fluid pressure which acts through a rubber diaphragm [5]. The flexforming process is used extensively in the aerospace industry that requires a variety of sheet metal parts to be manufactured in low volumes and in other industrial sectors requiring prototype production. The main advantages of the flexforming process are lower die costs—by using only half of the die—quick design modification changes to the dies allowing fast tryouts and production of sheet metals with less damage [6]. Additionally, the process has some ability to form several parts with different geometries in a single cycle and produce complex geometric parts of high quality and with tight tolerances.

There are a very limited number of studies investigating springback in the flexforming method. Palaniswamy et al. [7] studied the optimization of blank dimensions to decrease springback in the flexforming process. They conducted finite element method (FEM) simulations to determine the effects on springback of the relationship between friction and blank dimensions in axisymmetric conical parts produced by the flexforming process. Analyses showed that the magnitude of springback was substantially affected by the initial dimensions of the blank. It was determined that the combination of conventional optimization techniques with FEM could be effectively used to minimize springback. Hatipoğlu et al. [5] investigated both the modeling of the flexforming process through FEM and the effect of some parameters, such as sheet metal thickness, die bending radius and the flange length and rolling direction of the springback occurring after bending AL 2024-T3 sheet metal by the flexforming method in flat and curvilinear dies. They observed that the die radius and the sheet metal thickness significantly influenced springback. Moreover, they determined that forming pressure decreased springback. Hatipoğlu et al. [6] in another study aimed to determine the friction coefficient between the surface of the blank and the die in the flexforming process. Numerical models having different friction coefficient values were constructed, and the study was supported by experimental work. They investigated the forming capability of square trays using AL 2024-O sheet metals under different pressure and friction conditions (dry, oiled and oiled with nylon). The results obtained from both numerical models and experimental studies were compared by considering the flange geometry of the formed sheet metal material. Then, friction coefficient values were determined for different friction conditions. Kulkarni and Prabhakar [8] studied springback occurring during the forming of sheet metal material by the flexforming process. They conducted experiments using various bending angles and sheet metal thicknesses and developed a finite element simulation technique using LS-Dyna to estimate springback. They observed that springback angles obtained from finite element analyses were inconsistent with those obtained from experiments.

Copper sheet metals are used in the electrical, construction, machinery, defense and chemical industries, while brass sheet metal materials are commonly used in decorating, installation and electrical industries and in electronic products. The elimination of forming flaws and springback occurring in the products of bending dies is time-consuming and costly, especially for those applications that include prototypes, or where very limited production numbers are required. The flexforming process—owing to its superior advantages—can be effectively used to form copper and brass sheet metal materials where prototype manufacturing or limited production numbers are required. When a literature survey was carried out, it was observed that springback has only been investigated in V-bending using conventional methods; however, there was no study that investigated the springback behaviors of sheet metals using the flexforming process. Furthermore, rubber materials with at least 40 mm thick are used as membranes to resist high hydraulic pressures in the flexforming processes. When they are considered for use in forming small or narrow profiles, the formability becomes difficult because such rubbers do not fit those profiles. Thus, hydraulic pressures at a minimum of 80 MPa are necessary to form such profiles in the flexforming process. Achieving very high hydraulic pressures in the flexforming processes and operating them in a controlled and reliable manner necessitates high-energy consumption, expensive hydraulic equipment and special fabrication processes. Moreover, because thick rubber materials cannot fit into small or narrow profiles, the male parts of the dies are commonly produced by V-bending using the flexforming process and the forming is performed by using the male dies. This phenomenon constrains the designer at the design stage of the die and at the forming process. In the flexforming process, the sheet metal on the male part of the die during V-bending is stabilized by fixing onto the die using a connector like a bolt, which causes an increase in the duration of the cycle time. This study aims to experimentally investigate the springback of copper and brass sheet metals formed by V-bending using the flexforming process. In addition, unlike other flexforming processes, this study features forming that uses a thin rubber material and only the female part of the die. For that purpose, initially, experimental studies were conducted using a 4-mm-thick rubber membrane and producing only the female part of the die. Later, the aim was to determine the performance of the flexforming process over that of conventional bending process in terms of springback. Thus, V-bending experiments were also performed. In addition, the estimation of springback was based on unexecuted break-test parameters in the flexforming process. Springback values obtained from forming under the flexforming process were transferred to a fuzzy logic system, and springback values were estimated based on unexecuted break-test parameters for both copper and brass sheet metals.

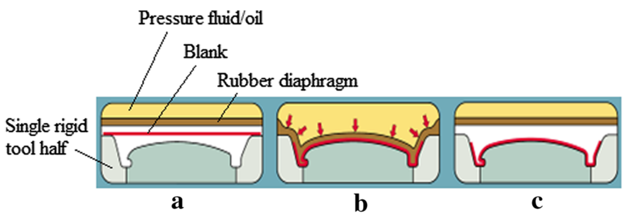

Fig. 1 Flexforming process **a** before process, **b** during process, **c** after process [9]

2 Experimental Setup and Parameters

2.1 Flexforming Process

The flexforming process is a sheet metal forming method in which a sheet metal on a rigid die is formed by using a rubber membrane and applying hydraulic pressure. In this process, the rubber membrane prevents direct contact between the hydraulic fluid and the sheet metal material and is used to transfer fluid pressure. The steps of the flexforming process are shown in Fig. 1. The first step in the process is to place the unshaped sheet metal on the die. In the second step, the upper part provides a seal by closing on the die, and then, the sheet metal material is formed by pressurizing the hydraulic fluid. In the third step, the hydraulic fluid pressure is set to zero, and the process is completed by raising the upper part of the die.

2.2 Experimental Setup

The experimental design setup for forming sheet metal by using the flexforming process was created in a 3D computer-aided design (CAD) environment. Afterward, the experimental setup was implemented and calibrated. The experimental setup included mechanical construction, hydraulic equipment, electronic data panel readout, test equipment control software and electronics panel. A general view of the experimental design setup is shown in Fig. 2.

Because only half of the die is produced in the flexforming process, design changes to the die can immediately be reflected in the product. The experimental setup was designed to be easily assembled on the die with the desired profile. Because the forming process uses high hydraulic pressure, the closure of the upper part of the die cannot be executed solely by cylinders pressing upwards. The experimental setup was designed to ensure the seal by manually locking it using a locking ring on the die part. A schematic views of the die and the hydraulic forming components and the component production are shown in Figs. 3 and 4, respectively.

The control of the experimental setup and read-data operation is conducted in a computer-controlled manner by special software designed via an electronic interface and LabVIEW media. Automatic steps in the software determine the experimental work. In the first step, the equipment is set to the “home” position. In the second step, after placing sheet metal material on the die, the press plate is closed on the lower fixture by moving downwards. In the third step, for additional safety, the locking ring is locked onto the lower fixture. The forming parameters, such as the numerical value of hydraulic fluid pressure and the holding time, are manually entered into the software. In the fourth step, the experiment is started based on the parameters entered. In the fifth step, the system is opened by unlocking the locking ring and the equipment is set to the “home” position again. The sheet metal part is then removed and another piece of sheet metal material is inserted for a new experiment.

Experimental studies were conducted using V-bending dies with angles of 15°, 30°, 45°, 60°, 75° and 90°. The dies were produced from steels by first applying heat treatment and then cutting using a wire erosion bench. Only the female part of the die was used in the V-bending experiments. For conventional V-bending experiments, in addition to the female part of the die, punches were produced for male parts of the die with a 4 mm edge radius. Manufactured female dies and punches are shown in Fig. 5.

Fig. 2 General view of the experimental setup of the flexforming process

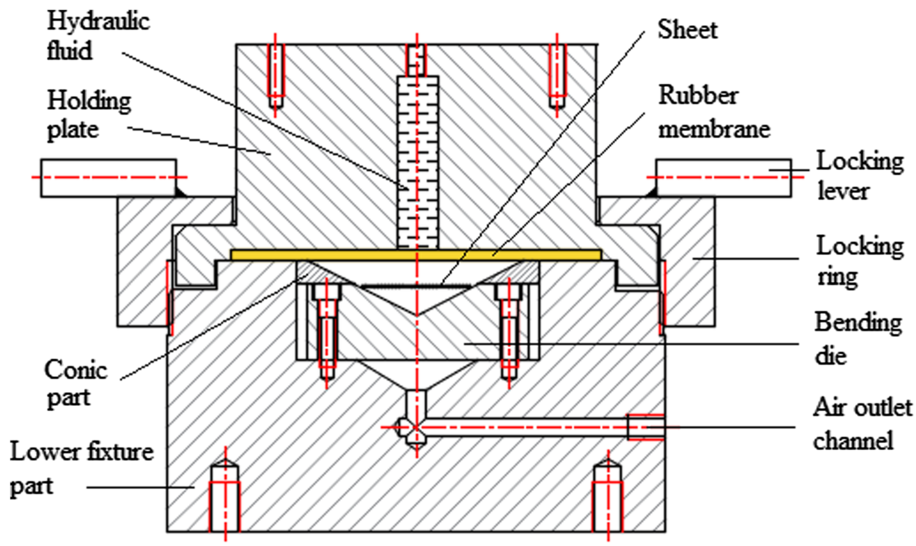

Fig. 3 Schematical view of the flexforming process

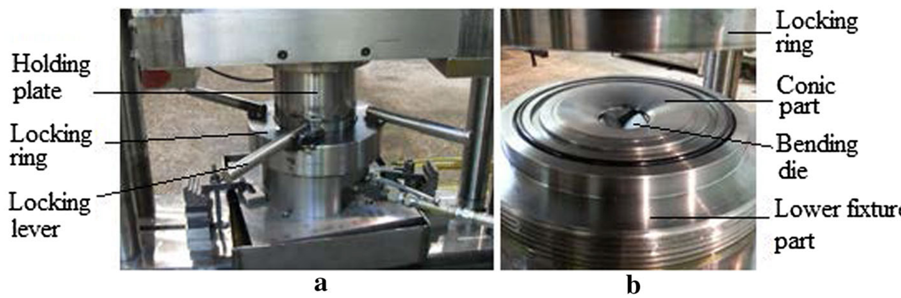

Fig. 4 Die view **a** off and **b** on

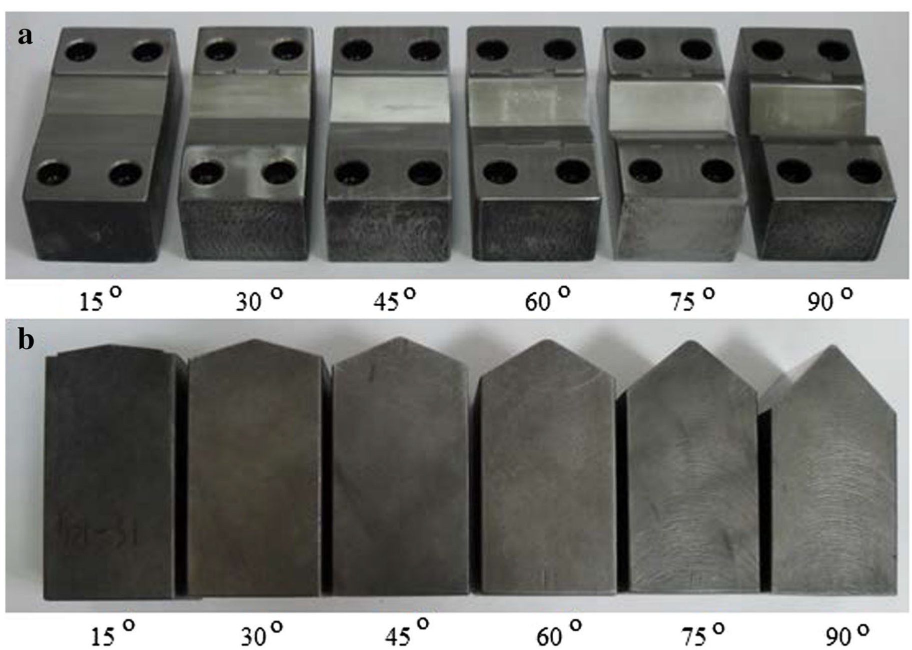

Fig. 5 Manufactured dies **a** V-bending dies for both process, **b** punches for conventional bending only

2.2.1 Test Materials

Copper and brass sheet metal materials were chosen as test materials because products produced by forming such materials are commonly used in various industry sectors. They were prepared on a guillotine press by cutting to dimensions of 20 × 26 mm. Before the experimental work to evaluate the effects of material characteristics on springback, the mechanical properties of the materials were determined by tensile and hardness tests, while their chemical properties

Table 1 Mechanical properties of experimental materials

Material	Tensile stress at yield (MPa)	Maximum tensile stress (MPa)	Elongation (%)	Young's modulus (MPa)	Hardness (Vickers)
Copper	46.480	208.093	46.171	19121.711	47.000
Deviation (σ_{copper})	3.916	6.837	0.620	8725.661	0.408
Brass	74.970	290.659	57.647	36291.085	59.166
Deviation (σ_{brass})	5.229	6.655	0.821	11355.025	1.309

Table 2 Chemical composition of experimental materials (wt%)

Material	Cu	P	Sn	Zn	Fe	W	Mg	Pb	Mn
Copper	99.909	0.025	0.046	0.136	0.033	0.041	0.002	0.031	0.027
Brass	70.434	0.000	0.012	29.539	0.015	0.146	0.000	0.004	0.011

Table 3 Mechanical properties of rubber membrane

Material	Maximum tensile stress (MPa)	Elongation (%)	Hardness (Shore)
Rubber	4.166	551.292	46.166
Deviation (σ_{rubber})	1.291	70.923	1.545

Table 4 Chemical composition of rubber membrane (wt%)

Material	Al	Si	Zn	Zr
Rubber	4.306	68.808	26.796	0.043

were determined by spectroscopy. Tensile test samples were prepared by cutting in 0°, 45° and 90° rolling directions on a wire erosion bench in accordance with the ASTM E8 standard. The hardness values of the samples were also measured. The arithmetic means of tensile and hardness test results of samples were calculated. The average values obtained from tensile tests and standard deviations are indicated in Table 1. Chemical analysis results are listed in Table 2.

2.2.2 Rubber Membrane Material

A 4-mm-thick rubber membrane was used to resist the high hydraulic pressure and tearing during the flexforming process. Tensile and hardness measurement tests were conducted to determine the mechanical properties of the rubber membrane, while chemical spectrometric analysis was done to determine its chemical composition. The rubber membrane was prepared for tensile tests in accordance with the ASTM E8 standard. The hardness of the rubber membrane was measured by Shore hardness measurement equipment. The mechanical properties obtained from tests and standard deviations are listed in Table 3, while chemical composition results are listed in Table 4.

Table 5 Test parameters of V-bending using flexforming process

Test parameters	Parameter values
Bending pressure (MPa)	10, 12 and 14.4
Bending die angle (°)	15, 30, 45, 60, 75, 90
Holding time (s)	0, 5, 10
Rubber membrane thickness (mm)	4

Table 6 Test parameters of V-bending using conventional process

Test parameters	Parameter values
Bending die angle (°)	15, 30, 45, 60, 75, 90
Holding time (s)	0, 5, 10
Punch radius (mm)	4

2.3 Test Parameters

Process parameters directly affecting springback were primarily considered for determining the test parameters. Bending pressure, die angle and holding time were therefore determined as test parameters. To determine the performance of V-bending using the flexforming process compared to V-bending by conventional die, V-bending experiments were also conducted using conventional dies. Die angle and holding time were set to be the test parameters in the conventional die V-bending process. Test parameters used in the experimental studies are listed in Tables 5 and 6, respectively.

Equation (1) [10] was used to calculate the bending load in V-bending experiments using a conventional die. Bending loads were calculated for copper and brass sheet metals,

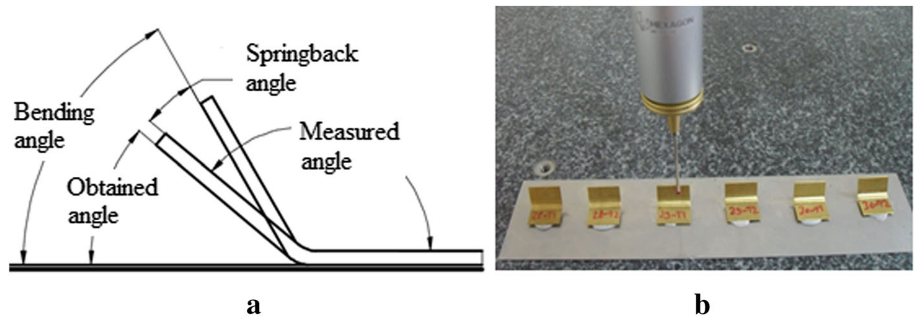

Fig. 6 Springback measurement **a** schematic view, **b** measurement in the CMM

respectively, and the calculated values were used in the experimental work.

$$L = (l.t^2.k.S)/s \quad (1)$$

where L is press load (N), l is length of bend (parallel to bend axis) in mm, t is work metal thickness in mm, k is a die-opening factor (varying from 1.2 for a die opening of 16t to 1.33 for a die opening of 8t), S is tensile strength of the work metal (N/mm^2) and s is the width of the die opening in mm.

Springback values in the formed sheet metal materials were measured using a Hexagon Performance Coordinate Measuring Machine (CMM). The first measurement step was to attach the bent sheet metal from their bent surface onto a large sheet metal material using an elastic adhesive. The probe of the measurement equipment was used to measure a plane, touching on four points of the adhered surface. Later, a second plane was measured by touching the probe on four other points of the bent surface. Springback angles were determined by subtracting the bending angle from the angle between the two measured planes. Schematic and measurement views of springback are shown in Fig. 6.

3 Results

The results of experimental studies have been evaluated in terms of the effects of process parameters and material properties on the springback in V-bending process. The results obtained are discussed below.

3.1 Influence of Die Angle on Springback in V-Bending

The amount of the sheet metal springback deformation is determined by the magnitude of the bending moment distribution since the bending moment at a given section is a function of the internal stress distribution generated by the forming process [11]. During the bending process, compression stresses occur on the inner surface of the sheet metal where the punch has been in contact with the sheet metal and the tensile stresses forming on the outer surface of the sheet metal. At the end of the bending process, these stresses move in the opposite direction after the punch moves upwards. When these stresses are in balance with each other, the deformation within the sheet metal is complete. The amount of stresses formed in the sheet metal increases with increasing bend angle, which causes more springback in the sheet metal after the bending process. It was observed that springback increased because the increase in die angle increased the amounts of stresses formed in both flexforming and conventional bending processes. Springback values obtained for different die angles in conventional bending experiments are shown in Figs. 10a and 11a, for copper and brass sheet metals, respectively. It was determined that for the conventional bending process a maximum 2.852° springback angle was obtained for copper sheet metal at a 90° die angle—the highest bending angle—while a maximum 3.600° springback angle was obtained for brass sheet metal at a 90° die angle.

In the flexforming process, the deformation is created by applying uniform hydrostatic pressure of the hydraulic fluid to the sheet metal. Therefore, stresses do not concentrate only on the edge where the punch bends it, as in the case of conventional bending processes. Because a controlled stress distribution was applied equally on the upper surface of the sheet metal, a smaller amount of springback was observed in flexforming process in comparison with the conventional bending process. However, because stress density increases with increasing bending angle, an increase in the amount of springback was not observed. The relationship between the die angle and springback angle based on different holding times and bending pressures is shown in Figs. 7 and 8, for copper and brass sheet metals, respectively. The highest springback angle for copper sheet metal material, 1.738°, was obtained in a die having a 90° bending angle at a 10 MPa bending pressure and 0 s holding time. Similarly, the highest springback angle for brass sheet metal material, 2.109°, was measured under the same conditions used for copper.

When the highest springback angles are compared for flexforming and conventional bending processes, it was determined that the springback angle for copper sheet metal decreased by 39.06% (from 2.852° to 1.738°) and for brass sheet metal it decreased by 41.42% (from 3.600° to 2.109°).

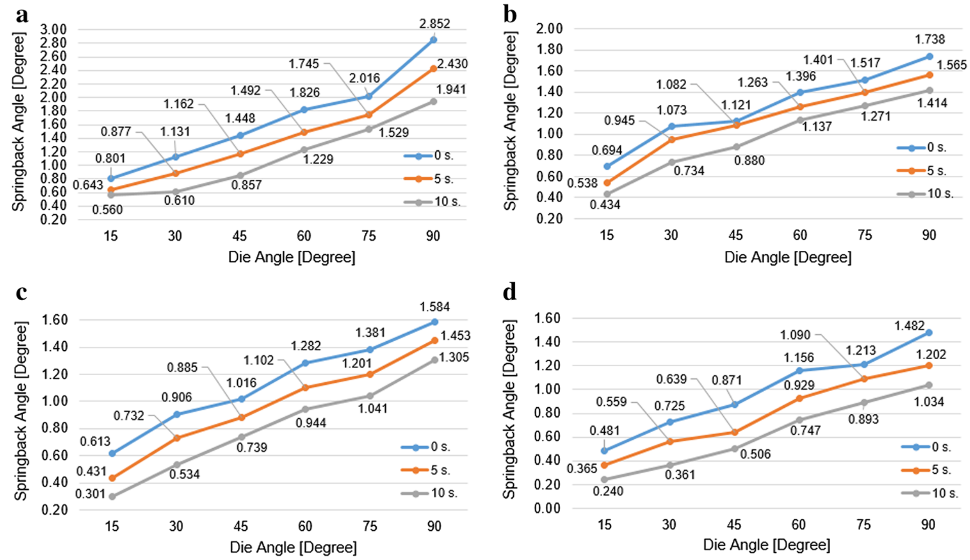

Fig. 7 Effect of die angle on the springback in copper sheet metal **a** conventional bending, **b** 10 MPa bending pressure, **c** 12 MPa bending pressure and **d** 14.4 MPa bending pressure

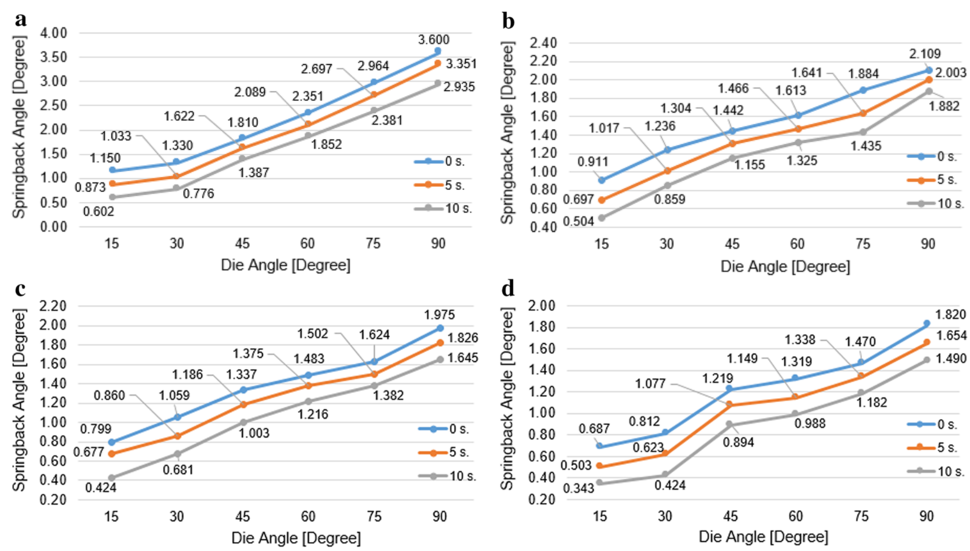

Fig. 8 Effect of die angle on the springback in brass sheet metal **a** conventional bending, **b** 10 MPa bending pressure, **c** 12 MPa bending pressure and **d** 14.4 MPa bending pressure

3.2 Influences of the Bending Pressure and Holding Time on the Springback

Bending load is the load required for sheet metal to form by deforming to a desired angle. In the forming of sheet metals by a bending process, bending load is a significant parameter affecting springback that needs to be taken into account. Therefore, different coining forces were applied to the radius region in V-bending. A reduction, elimination and even an advance in the springback for V-bending were observed when higher forces were applied in the process [12]. Also, in the conventional bending process, a decrease in friction increases the springback [13]. Experimental studies were conducted using three different bending pressures (10, 12 and 14.4 MPa) to observe the effects of bending pressure on springback angle. Due to pressure increases and the uniform pressure applied on the sheet metal, a decrease in springback was observed based on frictional increases. Changes in the springback angle based on bending angle are shown graphically in Figs. 9 and 10, for copper and brass sheet metals, respectively. It was determined that a 10% increase in bending pressure caused a decrease in the springback angle of 0.153° and 0.2158°, for copper and brass sheet metals, respectively.

During the bending process, holding time is another parameter that plays an important role in reducing springback. Increasing the holding time restrains the shape of the sample, allowing for a period of internal stress relaxation. This decrease in internal stress of the bending side and the flattened arc leads to decreased elastic strain, a behavior that causes increase in permanent strain. As the holding time increases, creep deformation increases and elastic recovery decreases. The creep deformation rate decreases with time due to the decrease in internal stress [14]. It was observed that spring-

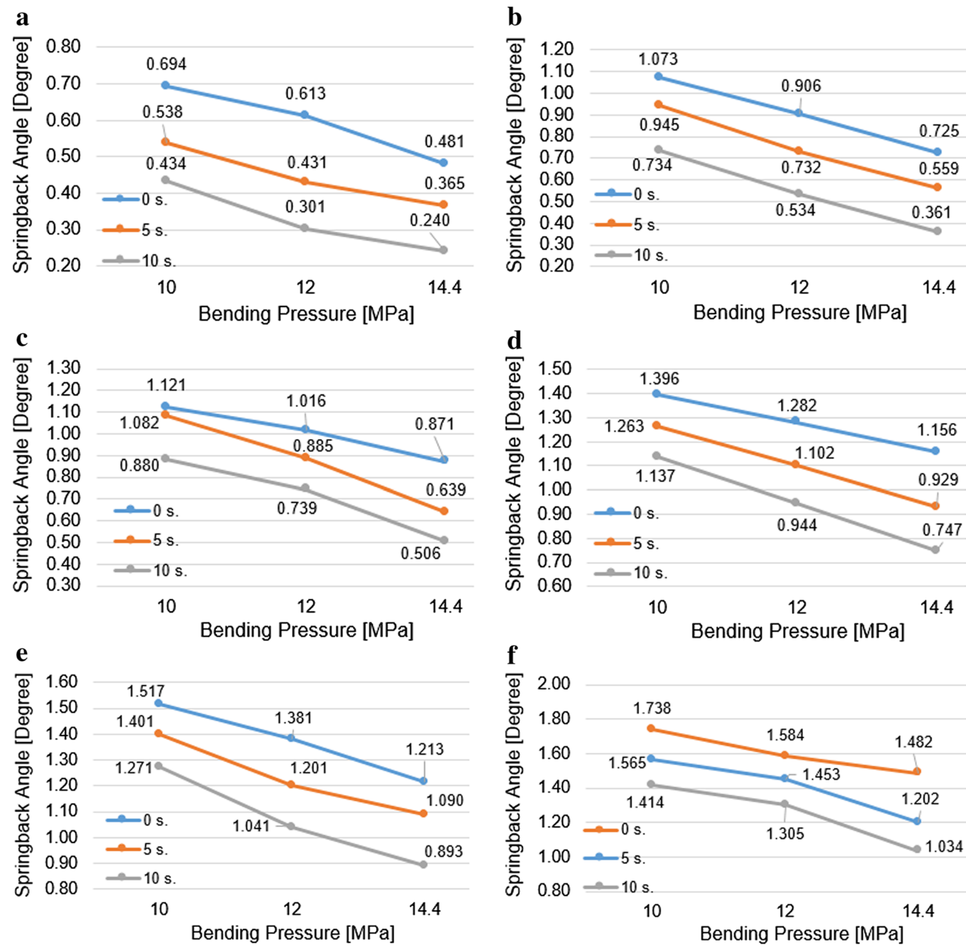

Fig. 9 Effects of bending pressure on the springback in copper sheet metal **a** 15°, **b** 30°, **c** 45°, **d** 60°, **e** 75°, **f** 90° die angles

back angle decreased with increasing holding time due to a decrease in internal stress. For the 5-s increase in holding time, springback angle decreased to 0.158° and 0.164°, for copper and brass sheet metals, respectively.

3.3 Influence of Material Properties on Springback

Springback values obtained from experimental studies have been evaluated in terms of material properties, such as yield strength and hardness, which were determined prior to the experimental studies. Springback depends on the properties of materials such as yield strength, strain hardening exponent, the Bauschinger effect, Young's modulus and the plastic strain ratio. The high-strength metals always exhibit greater springback in comparison with ductile metals, and the springback increases with increasing strength. The springback increases with an increase in yield stress and strain hardening [4,15–17]. It was observed that material properties were important factors affecting springback. Brass sheet metal—having higher a yield strength and hardness values—had more springback than copper sheet metal for both flexforming and conventional bending processes. Under the same test conditions, the highest springback angle of copper sheet metal obtained by the conventional bending process was 2.852°, while it was 3.300° for brass sheet metal. The highest springback angle of copper sheet metal obtained in the flexforming process was 1.738°, while it was 2.109° for brass sheet metal.

3.4 Forming Defects on the Parts in V-Bending

One of the most important problems encountered in conventional bending processes is the formation of surface flaws on formed parts occurring when the sheet metal is squeezed between die and punch during bending. If the formed part is to be used for an application that necessitates esthetics, surface flaws should be eliminated by applying surface treatments. Such additional treatments are significant factors increasing the production cost of a part. The formation of surface flaws in the parts formed by conventional bending processes is shown in Fig. 11. Because a rubber membrane is used in the flexforming process instead of a rigid punch, no formation of flaws was observed on the surface of the sheet metal. This phenomenon is an important advantage of the flexforming process.

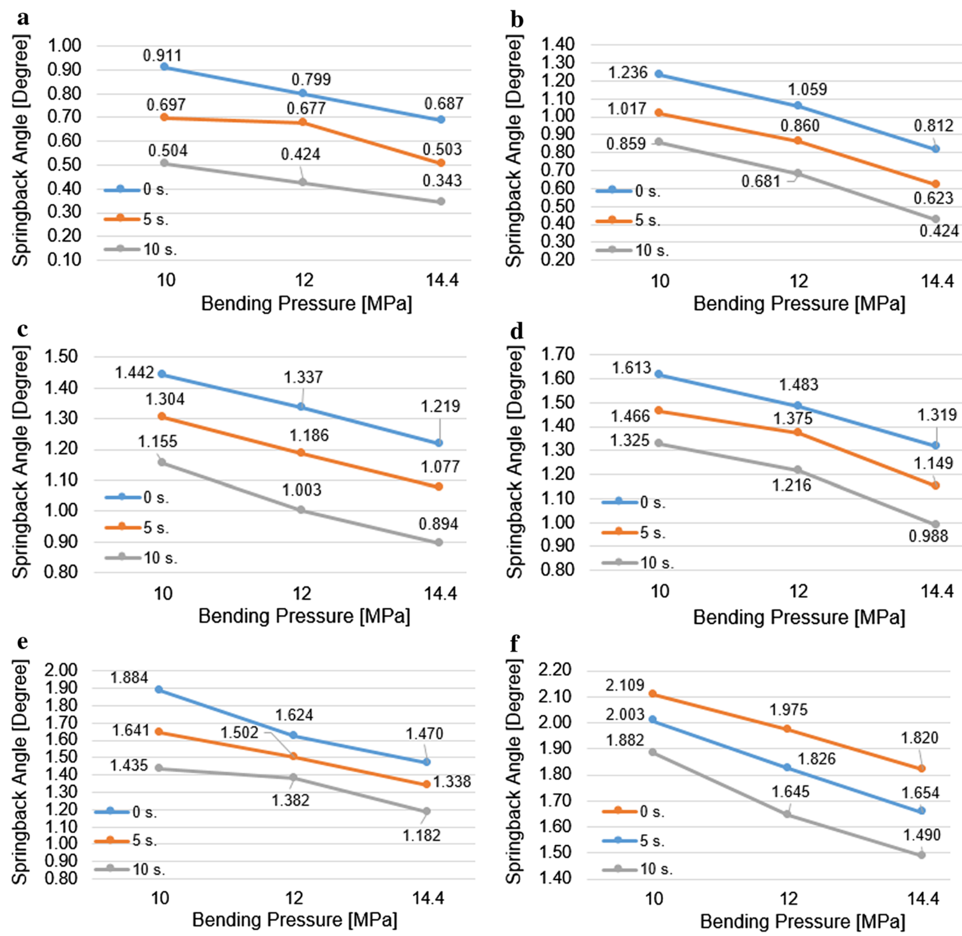

Fig. 10 Effects of bending pressure on the springback in brass sheet metal **a** 15°, **b** 30°, **c** 45°, **d** 60°, **e** 75°, **f** 90° die angles

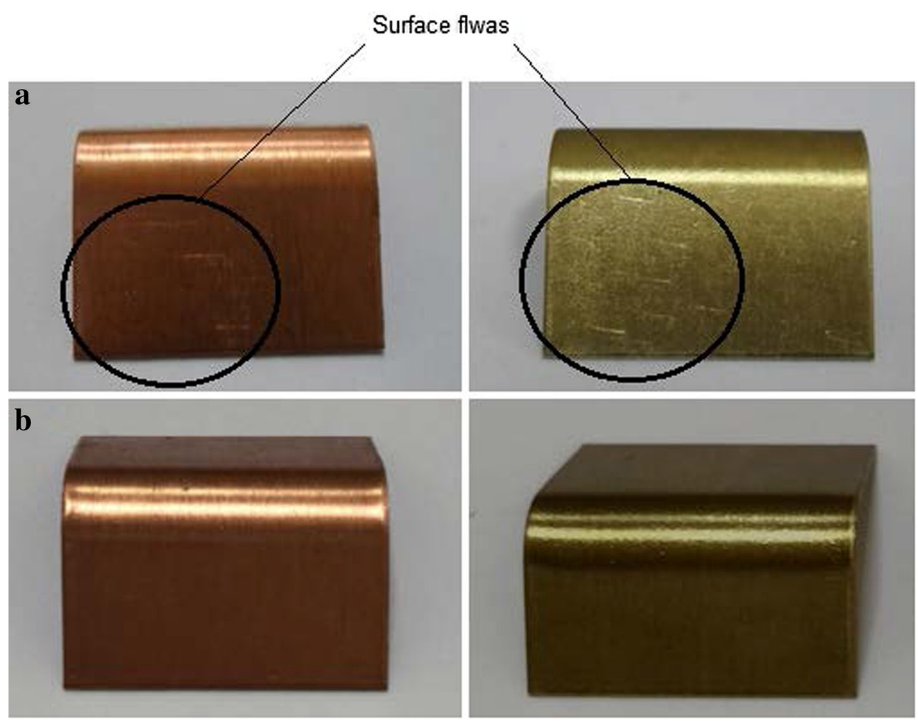

Fig. 11 Parts formed by bending process **a** conventional bending, **b** flexforming bending

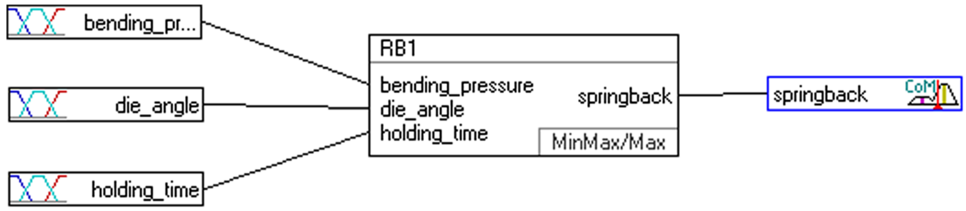

Fig. 12 Structure of the fuzzy logic system

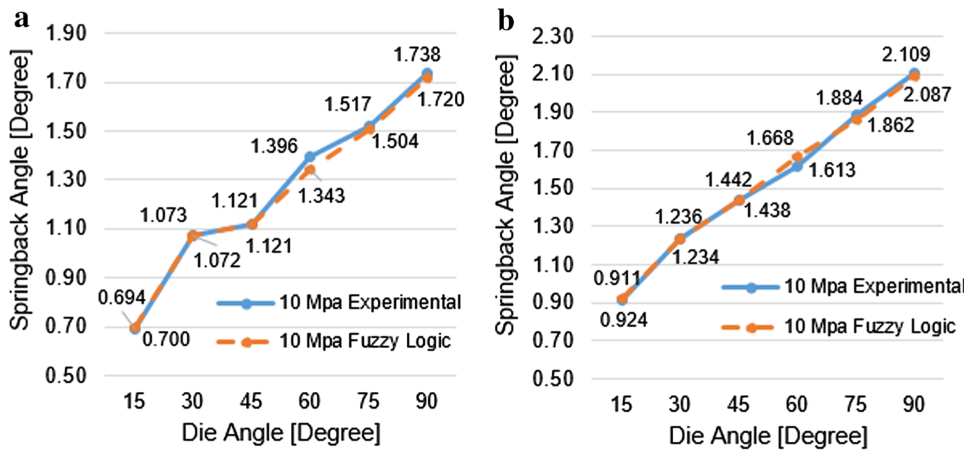

Fig. 13 Experimental results and fuzzy logic model results **a** copper, **b** brass

4 Estimation of Springback via Fuzzy Logic

A fuzzy logic system is built with fuzzy logic rules that operate between input and output variables. In the system, the "fuzzification" unit converts numerical values in the input unit into fuzzy variables. A fuzzy inference process is set into the rules table that includes linguistic control rules. The outcomes of this rules table are linguistic variables. The "defuzzification" unit in the output unit converts these available linguistic variables back into numerical values [18]. In the system designed for this study, die angle, bending pressure and holding time are used as independent input variables, with the output variable providing the springback angle. There is one rule block consisting of 90 rules and 16 membership functions. In this study, the membership functions were used during the transferring of the experimental results to the fuzzy logic system. The Compute MBF method was used as the Fuzzification Method due to its conformability to the system structure. The maximum membership method (Center of Maximum—CoM) was used as the Defuzzification Method, as the most appropriate rising method. A schematic view of the fuzzy logic system is shown in Fig. 12. Springback angles obtained from experimental studies were used to test the fuzzy logic system, and the experimental results and fuzzy logic model results are shown in Fig. 13.

Maximum deviation values (R^2) between the estimated results obtained from the fuzzy logic system and the test results were calculated to be 0.96, for both copper and brass sheet metals. Springback angle values were estimated using the fuzzy logic system for both types of sheet metals, based on unexecuted test parameters. The springback angle values are shown in Fig. 14.

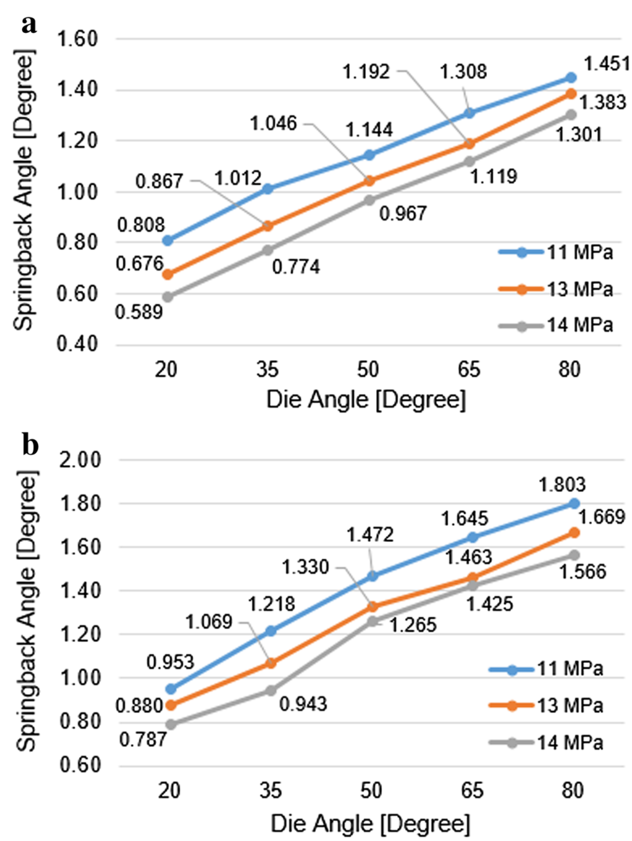

Fig. 14 Springback estimations via fuzzy logic system **a** copper, **b** brass

5 Conclusions

The flexforming process is a sheet metal forming method used to form sheet metal parts with complex geometries and in small quantities. In this study, for the first time, the parameters affecting springback were experimentally investigated in V-bending forming of copper and brass sheet metals using the flexforming method. Furthermore, as opposed to other flexforming processes, experimental studies were conducted using thin rubber membrane materials. The results obtained from the study are indicated below:

- It was observed that thin rubber membrane materials can be effectively used for forming small and narrow profiles in the flexforming process.
- In the flexforming process, while connectors were necessary to fix the sheet metal part during forming using only the male part of the die, forming using the female part of the die did not require any connector to fix the sheet metal part.
- In the conventional bending process, the highest springback angle was obtained at the minimum holding time (0 s) and maximum bending angle (90°); springback angles for copper and brass materials were 2.852° and 3.600°.
- It was determined that the use of the flexforming process decreased springback angles for copper and brass sheet metals by 39.06 and 41.42%, respectively.
- It was determined that the increase in bending pressure and friction was a factor affecting springback. In the flexforming process, it was observed that a 10% increase in the bending pressure decreased the springback angles of both copper and brass sheet metals by 0.15° on average.
- It was determined that the springback angle decreased for both flexforming and conventional bending processes with increasing holding time. Based on a 5-s increase in the holding time, it was observed that in the flexforming process springback angle for copper and brass sheet metals decreased 0.158 and 0.164° on average, respectively.
- While surface flaws were observed on the surfaces of the parts formed by the conventional bending process—due to the squeezing of the sheet metal between the die and the punch during bending—such flaws were not observed on surfaces of the parts formed by flexforming.
- Moreover, experimental results have been estimated using a fuzzy logic system for unexecuted test parameters. When the results obtained from the fuzzy logic system have been compared with those obtained from experimental studies, it was observed that they were very similar to each other. These results showed that a fuzzy logic system can be used to estimate springback angle with a high accuracy based on unexecuted break-test parameters.

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