Original Research

The Effect of Blankholder Pressure on the Amount of Springback in the U-Draw Bending Process

Romuald Fejkiel [iD]

Department of Mechanics and Machine Building, The University College of Applied Sciences in Krosno, ul. Wyspiańskiego 20, 38-400 Krosno, Poland

Correspondence: romuald.fejkiel@pans.krosno.pl

Abstract

Springback in sheet metal forming processes is a phenomenon that makes it difficult to obtain products with the desired geometry. This paper presents the results of research on the effect of the blankholder pressure on the elastic deformations of sheets during the forming of strip specimens (50 mm wide and 400 mm long) into U-shaped components. A special die was developed for the forming of sheet metals under variable blankholder pressure conditions in the range between 1 and 3 MPa. Three grades of sheets with significantly different properties were used as the research material: 6063 aluminium alloy, S235JR structural steel and X46Cr13 stainless steel. The research was conducted under dry friction conditions. The elastic deformations of the sheet metal in the U-draw bending process were of a different character in the punch radius and die radius areas. In the area of the punch edge, the springback coefficient decreased with increasing blankholder pressure. This relationship was observed for all the tested materials. In the area of the die edge, a decrease in the value of the bending angle was generally observed in relation to the bending angle in the loaded state.

Keywords: elastic properties, bending, sheet metal, sheet metal forming, springback

1. Introduction

A problem during sheet metal forming is the springback phenomenon. After the forming process is completed and the load is removed, residual stresses remain in the final product due to plastic deformation. Residual stresses cause an unintended change in the geometry of the formed component (El-Megharbel et al., 1990). Components formed from sheets are mainly used in the automotive industry. The growing use of high-strength steels and aluminium alloys for car bodies requires a multidimensional approach to the development of new forming technologies. One of the methods to reduce the negative impact of springback on the quality of components is to compensate for the shape of the tools (Nowosielski et al., 2013). The springback of the material depends on many factors, such as the mechanical properties of the sheet metal, material thickness, the shape of drawpiece, the forming method, bending radius, the sample orientation relative to the sheet metal rolling direction and the temperature (Lu et al., 2023; Slota et al., 2014).

Often, due to the complexity of the forming process, analytical estimation of the amount of springback is difficult. For this reason, many simple experimental tests have been developed to assess the tendency of sheets to springback. One way to investigate the springback of sheets is the technological processes of sheet forming: the L-bending process (Chen & Ko, 2006), the U-bending process (Wang et al., 2023), the U-draw bending process (Tong & Nguyen, 2018), the V-bending process (Khleif et al., 2020), draw beading (Ha et al., 2022) and the stretch bending (Slota et al., 2017). U-bending tests are the most common method to predict springback (Dessie & Lukacs, 2023). In addition to experimental studies, the finite element method (Hou et al., 2017) is commonly used to determine the elastic deformations of drawpieces. However, the accuracy of finite element method simulations depends on the approach to computational modelling, including the quality of the finite element mesh and the material model. Li et al. (2002) indicated that the direct model of work hardening affects the

accuracy of the springback simulation. Analytical methods (Zajkani & Hajbarati, 2017) expert systems using multilayer artificial neural networks (Bozdemir & Golcu, 2014), radial basis function networks (Han & Liao, 2014), genetic algorithms (Hu et al., 2011) and machine learning techniques (Wasif et al., 2023) are used to analyse the phenomenon of sheet metal springback.

The experimental analysis of the springback of sheets is focused on evaluation of the influence of material type, the bending method, the temperature and the strain rate on the amount of springback. Dessie and Lukacs (2023) used the U-bending test to study the effect of the die radius and punch radius on the springback phenomenon of DC01 steel sheets. They found that the coefficient of friction was the most influential parameter to have an impact on springback prediction. Choi and Huh (2014) investigated the effect of the punch speed on the amount of springback in dual-phase DP780 and SPCC sheets. A clear relationship was found between the material type and the springback phenomenon. For DP780 steel sheets, the amount of springback increased as the punch speed increased. For SPCC this relationship was reversed. Dou et al. (2020) used different methods (V-bend, U-bend, stretch bend and draw bend) to analyse the effect of forming speed on the springback of dual-phase steels. The amount of springback in the draw bend and U-bend samples increased as the forming speed increased. The opposite relationship was observed for the stretch-bend and V-bend tests. Sae-Eaw et al. (2013) investigated the effect of blankholder force and punch radius on the springback characteristics of ultra-high-strength steel sheets. The results revealed that increasing the blankholder force decreased the amount of springback. The amount of springback increased with increasing the punch radius value. Slota et al. (2013) investigated the effect of die radius on the springback behaviour of three grades of sheets (DC06, TRIP, H220PD) using the U-bending test. Greater die radius caused a smaller amount of springback in H220PD and DC06 steel sheets. A different relationship was observed for TRIP steel. Chen et al. (2023) explored the effects of punch motion curves on the springback of U-shaped AISI-1045 steel sheets. It was found that the punch movement strategy plays a key role in reducing the springback phenomenon. Rajesh et al. (2024) investigated the possibility of reducing the springback defect of EN AW-5052 aluminium alloy sheets using the Box-Behnken design of experiments approach. The results revealed that punch radius and sheet thickness had a major influence on the amount of springback.

This article presents the results of research on the effect of the blankholder pressure on the elastic deformation of sheets in the U-draw bending process. The aim of the research was to determine the effect of variable blankholder pressure on the springback of sheets with significantly different mechanical properties. There are limited studies on the U-draw bending test in the literature. This article tries to draw attention to the importance of blankholder pressure on springback behaviour. A special die was developed and built for the forming of components under conditions of variable blankholder pressure. Three grades of sheets with different elastic-plastic properties were selected for the research: EN AW-6063 aluminium alloy, S235JR structural steel and X46Cr13 stainless steel.

2. Material and methods

2.1. Materials

U-draw bending tests were carried out for three grades of 1-mm-thick sheets: EN AW-6063 aluminium alloy, S235JR structural steel and X46Cr13 stainless steel. The chemical composition of the EN AW-6063 alloy, according to the EN 571-1 standard, is (in wt.%): Mg – 0.10, Fe ≤ 0.35, Si – 0.20-0.60, Cu ≤ 0.10, Zn ≤ 0.10, Ti ≤ 0.10, Cr ≤ 0.10, others ≤ 0.05, Al (the remainder). The chemical composition of the S235JR steel, according to the EN 10025-2 standard, is (in wt.%): C – max. 0.2, Mn – max. 1.4, P – max. 0.04, S – max. 0.04, N – max. 0.012, Cu – max. 0.55, Fe (the remainder). The chemical composition of the X46Cr13 steel, in accordance with the EN 10088-2 standard, is (in wt.%): C – 0.43-0.5, Mn – max. 1, Si – max. 1, P – max. 0.04, S – max. 0.04, Fe (the remainder). The stress-strain curves of the tested sheets, determined using the Zwick/Roell Z100 uniaxial tensile testing machine, are presented in Fig. 1.

2.2. Experimental procedure

The U-draw bending tests were carried out using a stamping tool consisting of three main elements: a die, a punch and a blankholder. The appropriate pressure of the blankholder is ensured by M12×1.5×150 screws, which exert the load force on the springs, and these in turn press the blankholder against the die. The required position of the die and blankholder relative to each other is achieved

by two pins that are slidably fitted to the movable elements of the die. The base of the die was mounted in the lower holder of the uniaxial tensile testing machine Zwick-Roell Z100. The punch was mounted in the upper holder of this testing machine. A schematic drawing of the stamping tool is shown in Fig. 2. Although the stamping tool allows for forming sheet metals using draw beads, beads were not used in this work. As an alternative, stopper inserts were used.
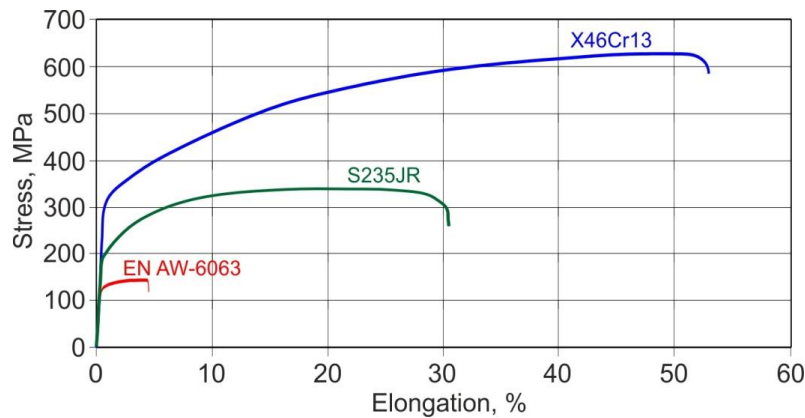

Fig. 1. Stress-strain curves for the test materials.
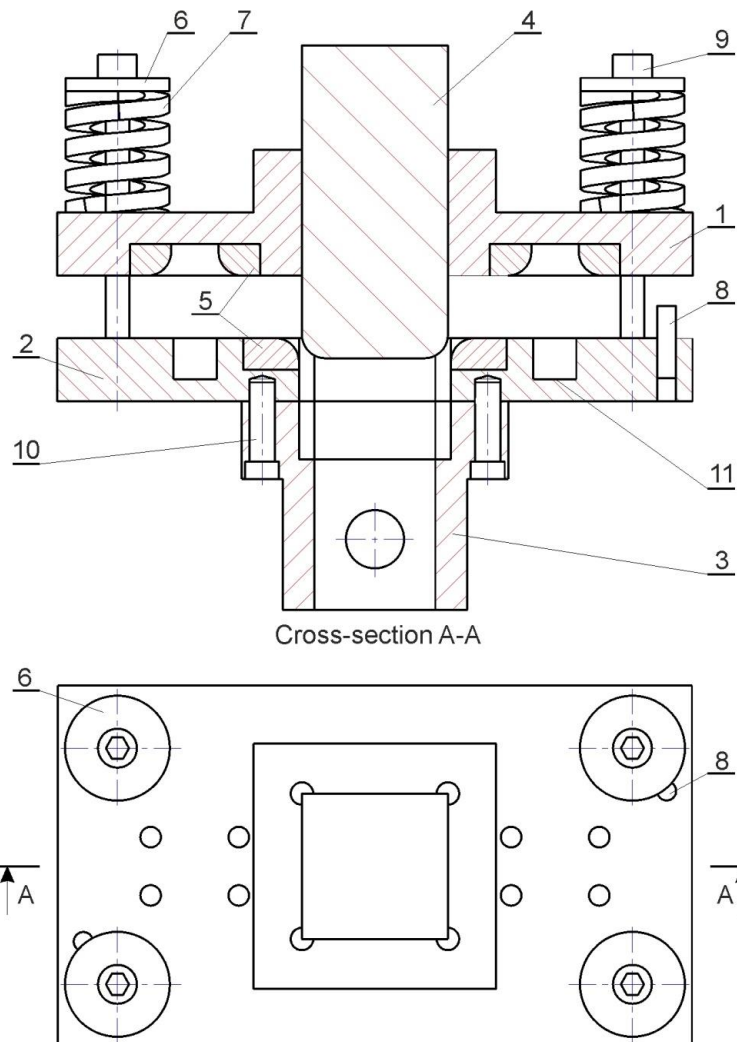

Fig. 1. Stamping die: 1 – blankholder; 2 – die; 3 – holder; 4 – punch; 5 – inserts; 6 – washer; 7 – spring; 8 – locating pin; 9, 10 – screws; 11 – draw bead socket.

The sheet metal was pressed using four springs. To accurately determine the blankholder force, it is necessary to know the spring coefficient k (spring constant). If the spring is compressed using a specific force F (in N), then the spring coefficient k is determined as the quotient of this force and the compression value Δx (in mm):

$$k = \frac{F}{\Delta x} \tag{1}$$

The springs used in the tests were R206-810 (Sodemann Industrifjedre A/S, Hinnerup, Danmark) with the parameters presented in Table 1.

Table 1. Geometric parameters of the R206-810 spring

Parameter	Value
Inner diameter	25 mm
Outer diameter	50 mm
Unloaded length	64 mm
Maximum loaded length	48 mm
Maximum travel	16 mm
Maximum load	10.344 kN

The spring constant was determined on a Zwick/Roell Z100 testing machine. Fig. 3 shows the graph of the applied force F as a function of the displacement x for the four springs used. Table 2 presents the experimental results and the average value calculated for the spring constant k.
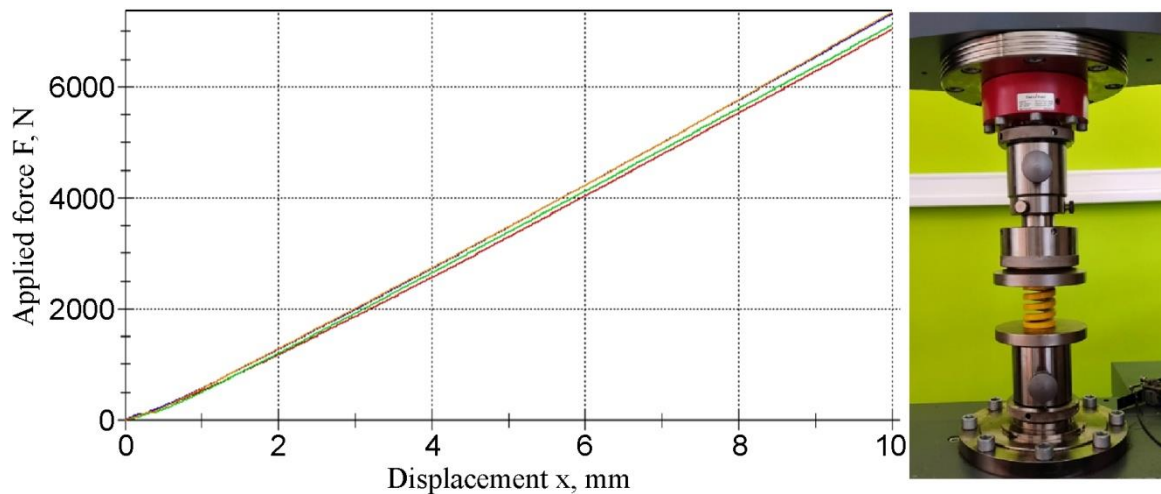

Fig. 3. Graph of the applied force as a function of the displacement of the R206-810 springs.

Table 2. Spring constant k for each spring.

Spring number	F_{max}, N	ΔL at F_{max}, mm	k, N/mm
1	7035.17	10.00	703.515
2	7111.93	10.00	711.188
3	7317.19	10.00	731.719
4	7350.74	10.00	735.072
		Average:	720.373

The determination of the amount of springback of the sheet metal strips (400 mm long and 50 mm wide) was carried out under contact pressures of 1, 2 and 3 MPa, which corresponds to spring deflections of 3.05, 6.1 and 9.15 mm, respectively. Contact pressures of this value occur in the blankholder zone during the sheet metal forming of steel and aluminium alloys (Erbel et al., 1986). When determining the required contact pressure, the spring height resulting from its shortening by the required amount was measured.

The tests were carried out under dry friction conditions. The stamping tool was mounted in the lower holder of the Zwick/Roell Z100 testing machine (Fig. 4). The blankholder was pressed by screwing in four M12×1.5 screws through the springs mounted in the blankholder sockets.

The U-draw bending process was performed at a constant punch movement speed of 10 mm/s. The forming depth was 50 mm (Fig. 5). The force measurement during U-draw bending was recorded using the measuring system of the testing machine. The cuboid-shaped punch had a square base of 70 × 70 mm and a radius of the working edge rounding $r_s = 10$ mm (Fig. 5). The dimensions of the square hole in the die were 74.5 × 74.5 mm and the radius of the die edge rounding r_m was 10 mm (Fig. 5). Considering that the sheet thickness was 1 mm and taking into account the clearance between the die and the punch, the bending angles at the die edge and the punch edge were α = 90.49° and β = 90.49°, respectively (Fig. 5). Three samples were tested for each setup. Based on the measured values of the

bending angles after unloading, the springback coefficients K_α and K_β were determined separately for angles α and β:

$$K_\alpha = \frac{\alpha_s}{\alpha_g} \tag{2}$$

$$K_\beta = \frac{\beta_s}{\beta_g} \tag{3}$$

where α_s is the springback bending angle at the die edge, β_s is the springback bending angle at the punch edge, α_g and β_g are the bending angles (under load) $\alpha_g = \beta_g = 90.49°$ (Fig. 5).
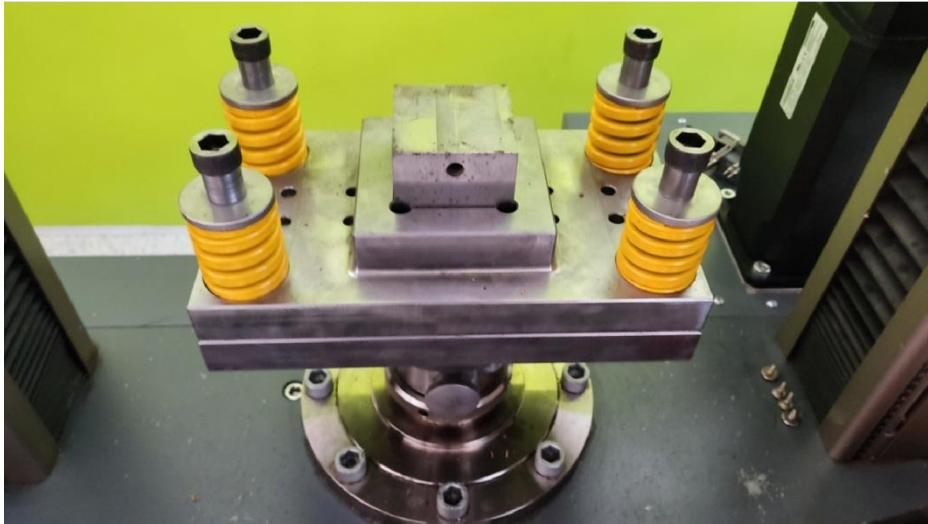

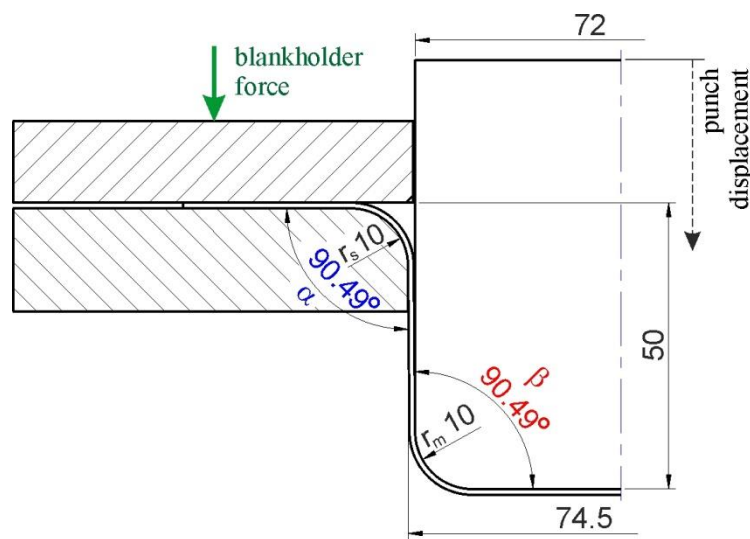**Fig. 4.** The U-draw bending tool mounted on a testing machine.

Fig. 5. Geometric parameters of U-draw bending process.

3. Results and discussion

3.1. X46Cr13 stainless steel

Figure 6a shows the average values of the springback coefficients for X46Cr13 stainless steel obtained for different contact pressures in the range of 1-3 MPa. On the punch edge, the average measured values of the bending angle increased in relation to the angle $\beta_g = 90.49°$. In the area of the die edge, the sheet bending angle decreased in relation to $\alpha_g = 90.49°$. Using this method, the springback coefficients for the punch edge are greater than 1, while in the die edge area it is the other way around. This is due to the compressive stresses prevailing on the inner side of the bended sheet metal and the

tensile stresses resulting from the use of the blankholder. With the increase in the contact pressure, the springback coefficient K_β on the punch edge increases. The increase in the tensile stresses in the sheet metal resulting from the increase of the contact pressures reduces the value of elastic deformations on the punch edge. Nevertheless, for the entire range of the analysed contact pressures, the springback coefficient K_β is greater than 1.12. This indicates high elastic properties of the tested X46Cr13 stainless steel.
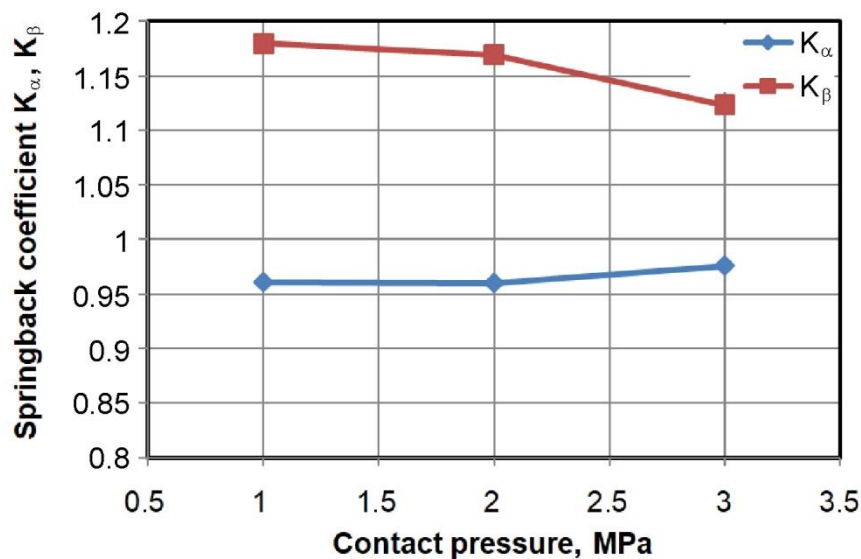
Fig. 6. Variation of die springback coefficients depending on contact pressure for the X46Cr13 stainless steel sheets.

3.2. S235JR structural steel

Fig. 7 shows the average values of the springback coefficients K_α and K_β for S234JR structural steel obtained for different contact pressures in the range of 1-3 MPa. Samples made of S235JT structural steel are characterised by a low value for the springback coefficient K_β in the area of the punch radius. Even at the lowest contact pressure, the springback coefficient value is below 1.1. For both analysed areas of the bent sample, it can be seen that the values of the springback coefficient show a tendency to decrease with increasing contact pressure. In the area of the punch radius, the values of the springback coefficient K_β were lower than the angles for the X46Cr13 stainless steel sheets by about 8.1%, 8.4% and 6.0% for contact pressures of 1 MPa, 2 MPa and 3 MPa, respectively. The value of the springback coefficient in the area of the die radius K_α is more stable for the entire range of analysed contact pressure values, compared to the results for the X46Cr13 stainless steel (Fig. 6).
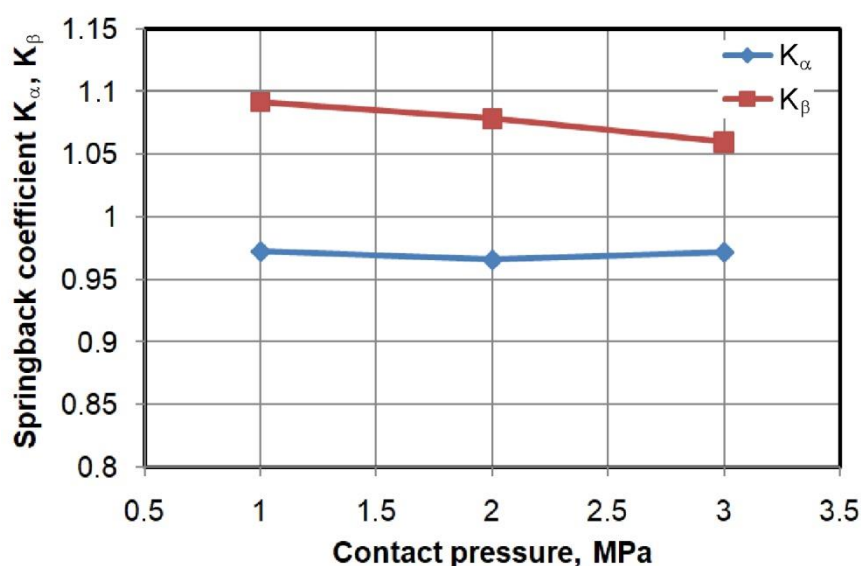
Fig. 7. Variation of the springback coefficients depending on contact pressure for the S235JR structural steel sheets.

For all applied contact pressures, the value of the punch force first increased linearly to a punch displacement of about 15-18 mm, and then stabilised at values of about 600 N (Fig. 8a), 800 N (Fig. 8b) and 1500 N (Fig. 8c) for contact pressures of 1 MPa, 2 MPa and 3 MPa, respectively. The initial almost linear range of changes in the punch force with the punch displacement can be associated with the gradual bending of the sheet metal on the punch and die radii, the value of which was $r_s = r_m = 10$ mm (Fig. 5). In this range of deformation, small sheet metal slip velocities occur where there is blankholder influence. At the same time, at the initial stage of U-draw bending, the bending area of the sheet metal increases as the radii of the punch and die gradually increase to the value $\alpha = \beta = 90.49°$. After completing this stage, the punch force value stabilises because the sheet metal moves on the rounded punch and die radii with a constant value of $\alpha = \beta = 90.49°$. At this stage, the contact surface of the sheet metal on the edges of the punch and die does not change. A similar character of punch force changes was observed for all tested materials.
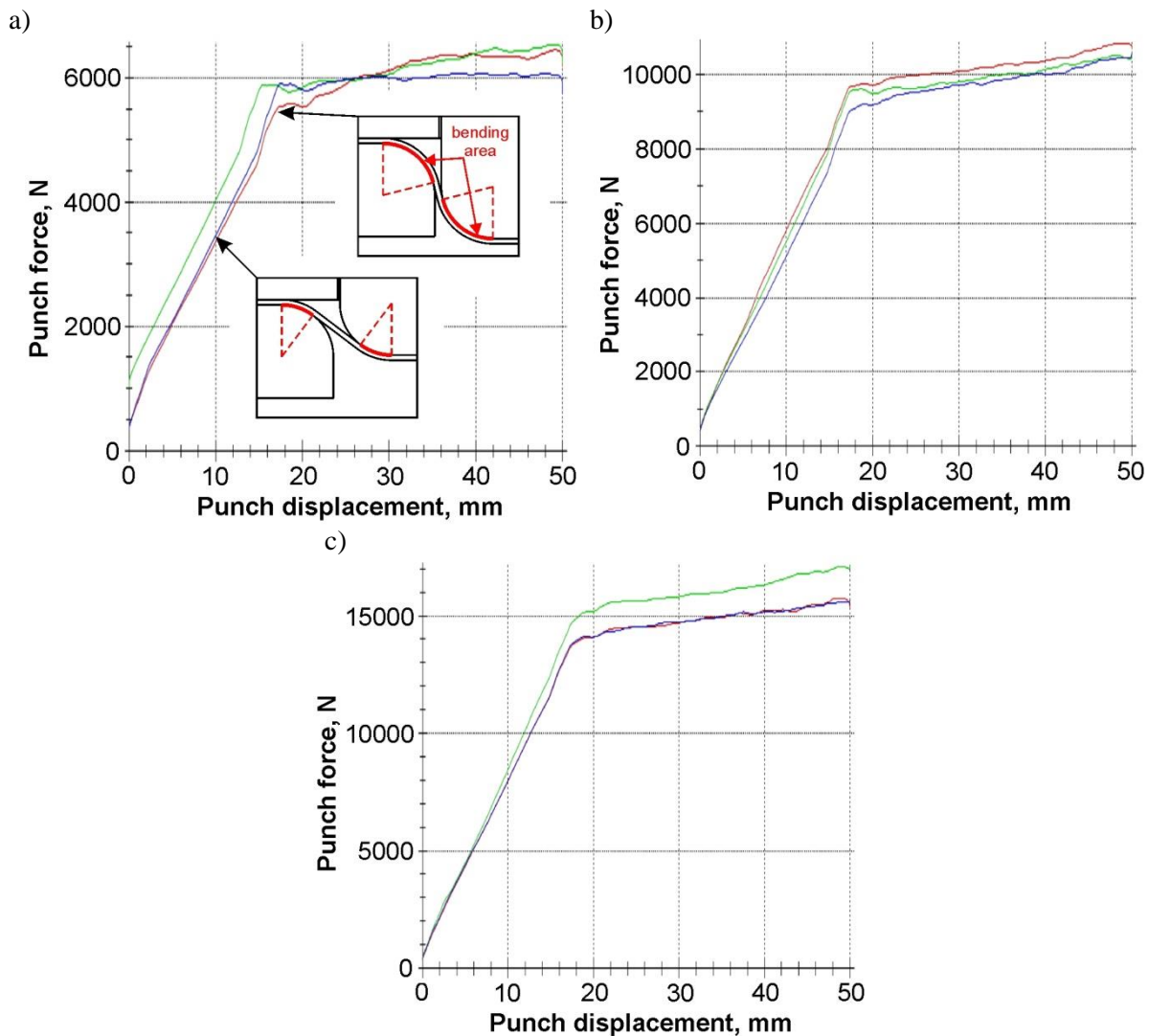

Fig. 8. Variation of the punch force during the forming of S235JR sheets under contact pressure conditions: a) 1 MPa, b) 2 MPa and c) 3 MPa.

3.3. EN AW-6063 aluminium alloy

Fig. 9 shows the average values of the springback coefficients K_α and K_β for the EN AW-6063 aluminium alloy sheets, obtained for different contact pressures in the range of 1-3 MPa. During the U-draw bending process with a pressure of 3 MPa, the sample ruptured (Fig. 10b). This means that the contact pressure of 3 MPa for this sheet was too high. Under such conditions, the friction forces between the flat surfaces of the blankholder and the die were too high and caused the sheet metal to stop moving. The EN AW-6063 aluminium alloy exhibits a low tendency to strain hardening and is characterised by low elongation (Fig. 1). With the increase in the blankholder pressure, the value of the

springback coefficient of this sheet decreases, but it was only measured at the edge of the punch. At the die edge, increasing the contact pressure caused an increase in the springback coefficient K_α (Fig. 9). The value of the maximum punch force for contact pressures of 1 MPa and 2 MPa stabilised at about 6000 and 10000 N, respectively. At the contact pressure of 3 MPa, the destructive force of the sample was about 13000 N (Fig. 10a). The most stressed region of the sheet metal was the transition of the punch radius into the flat part of the bent element. In this respect, the experimental results are consistent with theoretical and experimental studies of the deep drawing process, in which the most dangerous cross-section in terms of destruction is the side surface of the drawpiece (Gierzyńska, 1983).
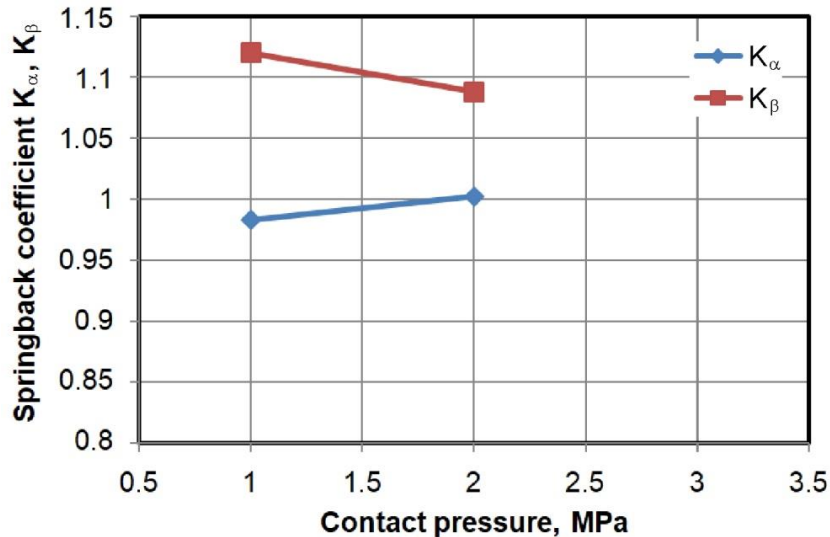

Fig. 9. Variation of the springback coefficients with contact pressure for the EN AW-6063 aluminium alloy sheets.
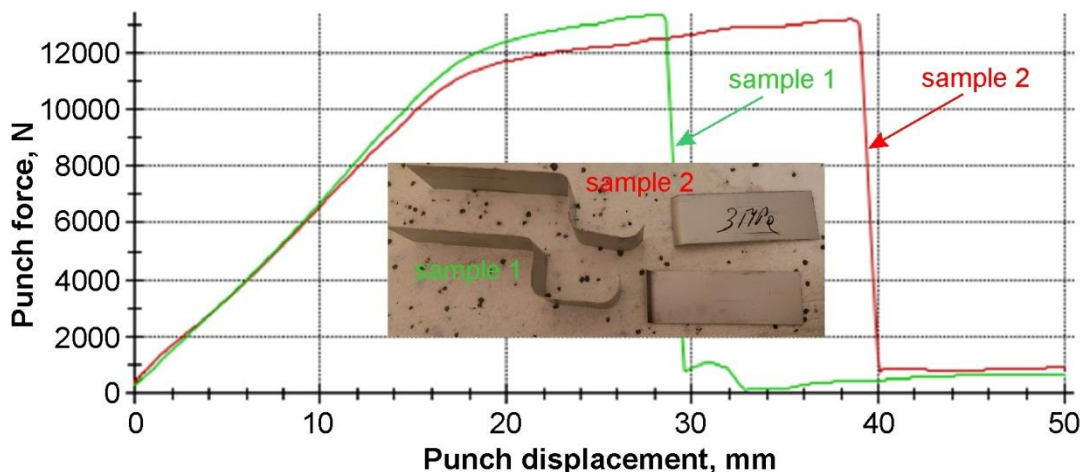

Fig. 10. Variation of the punch force during the forming of EN AW-6063 aluminium alloy sheets under a contact pressure of 3 MPa.

4. Conclusions

The springback investigations in the U-draw bending process presented in this article are aimed at comparing the behaviour of three grades of materials with different mechanical properties. A special die was built for this purpose, enabling the performance of tests with variable blankholder pressure. Moreover, due to its universal construction, the device can be mounted on a conventional uniaxial tensile testing machine. The common feature of the results obtained is that the springback phenomenon decreases with increasing blankholder pressure. Springback in the U-draw bending process has a different character in the punch radius and die radius areas. In the area of the die radius, an increase in the bending radius was observed after unloading the components. In the die radius area, the situation was the opposite – the bending angle in this area decreased in relation to the bending angle occurring in the loaded state.

The variations recorded for the punch force depending on its displacement during the U-draw bending of all grades of materials clearly indicates the occurrence of two specific stages of the bending

process. During the first stage, the angle of wrapping of the die edge and the punch edge gradually increases until the maximum value is obtained ($\alpha = \beta = 90.49°$). In this stage, the force increases approximately linearly. After the wrapping angles reach the value (90.49°). the punch force stabilises at a value dependent on the blankholder pressure. At the same time, the value of the maximum punch force depends on the material type (the mechanical properties of the sheet metal) and the blankholder pressure. The higher the blankholder pressure, the greater the maximum punch force. This is caused by the increased friction forces under the blankholder pressure, which must be overcome during U-draw bending. Moreover, increasing the bending angle intensifies the work hardening effect of the sheet metal and, consequently, the punch force increases.

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Wpływ Nacisku Dociskacza na Wartość Odkształceń Sprężystych w Procesie Gięcia Blach w Kształcie Litery U

Streszczenie

Sprężynowanie jest zjawiskiem, które utrudnia otrzymanie wyrobów o pożądanej geometrii w procesach kształtowania blach. W pracy przedstawiono wyniki badań wpływu nacisku dociskacza na odkształcenia sprężyste blach podczas ich kształtowania pasów blachy o szerokości 50 mm i długości 400 mm w wyroby w kształcie litery U. Opracowano specjalny tłocznik pozwalający na kształtowanie wyrobów w warunkach zmiennego nacisku dociskacza w zakresie 1-3 MPa. Jako materiał badawczy wykorzystano trzy gatunki blach o znacznie różniących się właściwościach: stop aluminium EN AW-6063, stal konstrukcyjna S235JR oraz stal nierdzewna X46Cr13. Badania przeprowadzono w warunkach tarcia suchego. Odkształcenia sprężyste blachy w procesie gięcia w kształcie litery U miały inny charakter w obszarach promienia stempla i promienia matrycy. W obszarze krawędzi stempla współczynnik sprężynowania zmniejszał się ze wzrostem nacisku dociskacza. Tę zależność zaobserwowano dla wszystkich badanych materiałów o różnych właściwościach mechanicznych. W strefie krawędzi matrycy generalnie zaobserwowano zmniejszenie kąta gięcia w stosunku do kąta gięcia w stanie obciążonym.

Słowa kluczowe: właściwości sprężyste, gięcie, blacha, kształtowanie blach, odkształcenia sprężyste