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Research Article

An experimental investigation of formability of inconel sheet plate for different die angles and rolling directions in press brake bending

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Abstract: The formability of Inconel materials is important due to being used in engineering applications of aircraft and maritime. The aim of study is to investigate the bending characteristics and formability of Inconel 625 material having a property of corrosion resistance and high strength. In the paper, spring-back behavior of Inconel 625 sheet plates was examined in different die angles and orientations experimentally. The die angle was altered from 90˚ to 150˚ to and the different rolling directions of 0˚ and 90˚ were chosen to investigate the effect of grain orientation on spring-back of Inconel sheets. The bending radius was set as 2 mm for all bending tests. As a result, the spring-back angles and amounts were measured. Results show that as the bending angle is increased, the spring-back angle is decreased averagely from 3.35˚ to 2.58˚ for 0˚ rolling direction and maximum spring-back angle is obtained at a die angle of 120˚ for rolling direction of 90˚. Finally, Erichsen cupping test was also applied to determine the deformability of Inconel sheets. It was found that cup height value is 17.20 mm.

Keywords: Spring-back, Inconel, formability, die angle, bending press.

1. INTRODUCTION

Forming is commonly used plastic deformation process in manufacturing [1]. Bending is one of the significant and common forming methods in industrial applications [2]. There are many methods to bend the materials and researches had been studied on spring-back behavior in processes of V-bending [3, 4], U-bending [5, 6], tube bending [7], deep drawing [8], rubber forming [9], multi-point forming [10], stretching [11]. To form sheet plates and tubes, there are many parameters affecting the formability such as rolling direction [12], die angle [13], die width [14], bending radius [15], material thickness [15], temperature [16, 17], punch contact time [18], speed of punch [19, 20], strength coefficient [21], strain hardening coefficient [22], young's modulus [23]. In bending process, the main encountered problem is spring-back behavior of formed material [24]. Spring-back problem is about the elastically recover of the material [25]. Inconel 625 is one of the materials used in many engineering fields due to high strength and high corrosion resistance in marine mediums. The novelty of this research is that the effect of die angle on spring-back behavior of Inconel 625 sheet plate has not been investigated before and the formability of Inconel 625 sheet has been studied in Erichsen cupping test in the study.

There are some researches in literature realized by experimentally [26] and/or numerically [27, 28] to investigate the spring-back behavior of the materials in different types of bending processes [29]. Kumar et al. determined spring-back amount of aluminum sheet metal by using process of L – bending according to the gap between punch and die. The specimen sizes were 60 mm x 20 mm. Also, applied load was adjusted with respect to the thickness of specimens changing from 1 to 3 mm. It was found that as the gap is increased, the spring-back angle is increased [30]. Davoodi and Zareh-Desari used multi-forming method to bend aluminum alloy, 304 stainless steel and pure copper were tested by using V-shape and Sin-shaped dies. Experimental and numerical results were compared, and it was observed that increase in sheet thickness lowers the spring-back angle [31]. Buang et al. chose air v-die bending to determine spring-back behavior of steel sheets and changed the die and punch radius from 5 mm to 12.5 mm to find the spring-back angle. The results demonstrated that spring-back angle increased from 5.20˚ to 8.8˚ for the 5 mm of constant

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die radius and from 7.19˚ to 7.25˚ for the 5 mm of constant punch radius [32]. Saito et al. focused on influence of temperature, punch speed and holding time on spring-back angle of high strength steel. Increase in temperature lowered the spring-back angle for both punch speeds of 0.02 mm/s and 20 mm/s in U-die forming. Also, because of stress relaxation, the bending angle reduced from 100.91˚ to 97.62˚ in 5 seconds at the beginning in V-die forming drastically [33]. Qudeiri et al. investigated the influence of yield stress and young's modulus on spring-back behavior of metallic sheets. An Increase in Young's modulus from 180 GPa to 230 GPa lowered the spring-back amount. In contrast, spring-back angle decreased as the yield strength of material increased from 200MPa to 400MPa. It was claimed that higher strength coefficient provides to withstand plastic deformation and higher modulus of elasticity causes to resist elastic deformation [34]. Gupta et al. analyzed the die width effect on spring-back behavior of CR4 steel. Also, 1 mm thick CR4 steel was coated by electro galvanizing. Die width and coating thickness was changed from 40 mm to 80 mm and from 0 to 10 µm, respectively. It was obtained that spring-back is lowered as the die width and coating thickness reduce [14]. Choi et al. used rebar bending machine to form structural steel and changed size of rebar, radius of bending, yield strength and friction coefficient to determine the effect of the factors on spring-back. The bending process was modelled numerically. It was calculated that as the coefficient of friction increased from 0.15 to 0.35, the spring back angle decreased from 2.55˚ to 2.21˚ in finite element analysis and increase in initial yielding strength increased the spring-back angle for bending angles of 95˚, 135˚ and 175˚ [35].

2. MATERIALS AND METHOD

2.1. 2.1 Bending process at Press Brake Machine

In the study, Press Brake Machine was used to bend Inconel 625 sheet metals due to being a simple machine and having a capability of various deforming types for designs as shown in figure 1. In bending process, tensile stresses are formed at the outer side of the sheet metal, the inner side of the sheet is forced by compressive forces. It is assumed that there is no change in the thickness of sheet metal theoretically. There is a die, punch and sheet metal in V-bending as illustrated in figure 2. The sheet metal elastically deforms back to recover after V-bending. Minimum bending force to form the sheet material is evaluated by using equation 1 theoretically whereas P is the bending force, th is the thickness of sheet plate, σ_t is the tensile strength of sheet material, bl is the width of the plate, c is the bending force coefficient and dw is die clearance [36].

$$P = \frac{c\sigma_t th^2 bl}{dW} \tag{1}$$

2.2. Material and Experimental Set up

Inconel 625 sheet metal was used in press brake bending operations. Because press brake bending machine are intensively used in industrial applications. Inconel 625 contains high Nickel and Chromium elements as given in table 1. Thus, Inconel 625 shows a resist to corrosion. So, it is used in transportation applications as a pipe material. In press brake bending, for each of the test samples, the die punch tries to reach the maximum force limit defined previously in the press brake by moving in the same direction and descending from top to bottom at a constant speed. The punch contacts the sheet material and starts to compress and bend the sheet metal according to the die shape. The automation program of the press reaches the maximum force and the defined bending angle simultaneously, and the bending process is completed, and the die angle was varied from 90˚ to 150˚ for both rolling directions of 0˚ and 90˚. All the operations were repeated four times by considering the same machine settings for each die angle and rolling direction,

Table 1. Chemical Composition of Inconel 625

Material	C	Mn	Fe	Sn	Si	Ni	Cr
% Value	0,02	0,15	3,21	0,00	0,19	61,22	22,37
Material	Al	Ti	Co	Mo	Nb	Ta	P
% Value	0,12	0,21	0,09	8,87	3,54	0,01	0,007

Table 2. Experimental Parameters

Definition	Case	Property		
Bending Radius	Constant	2 mm		
Die Angle	Variable	90 °	120 °	150 °
Material Type	Constant	Inconel 625		
Material Thickness	Constant	1.00 mm		
Rolling Direction	Variable	0 °	90 °	

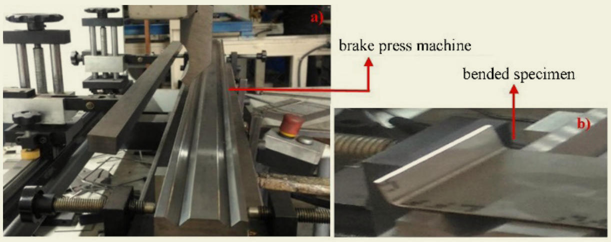

Figure 1. a) Bending Operations are performed in Press Brake, b) bent specimen.

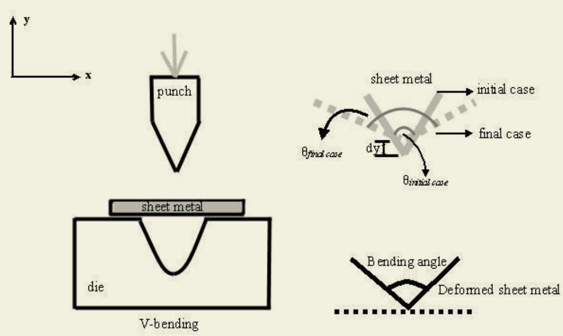

Figure 2. V-Bending and spring-back phenomena

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respectively, and bending operations were carried out to determine the amount of spring-back. The thickness of sheet specimens is 1 mm for all tests. The size of the sheet plates is 50 mmx 80mm. Sheet plates were prepared by laser cutting. The experimental parameters are given in table 2.

3. RESULTS AND DISCUSSION.

3.1. Effect of Die Angle and Rolling Direction on Spring-back Angle

The behavior of spring is evaluated based on spring-back angle, $\Delta\theta$, using the following equation 2;

$$\Delta\theta = \theta_{initial\ case} - \theta_{final\ case} \quad (2)$$

where $\theta_{initial\ case}$ is the angle during loading while $\theta_{final\ case}$ is the angle after unloading. 4 specimens were prepared to bend for each die-angle. Anisotropy is one of the reasons that sheet metal demonstrates different mechanical behavior along different directions. Thus, Bakhshi-Jooybari et al. chose CK 67 steel sheet and bent in different orientations to examine anisotropy factor [38]. To investigate anisotropy effect on spring-back behavior, sheet metal was bent in different rolling directions. The measured spring-back angles of 4 specimens for rolling directions of 0˚ and 90˚ are compared in figure in 3-5.

The average spring-back angles and spring-back amount for both rolling directions of 0˚ and 90˚ are given in table 3.

As a result of the study, generally increases in the bending angle decrease the spring-back angle and the amount of spring-back. Also, Karaağaç showed that the more the sheet plate is bent and deformed, the more stress is occurred leading to cause the increase in springback angle [39]. Apart from this, it is seen that the choice of rolling direction also has a significant effect on spring-back. It is the fact that the rolling direction perpendicular to the bending front reduces the amount of spring-back because elastic recovery is lower for 90 orientation.

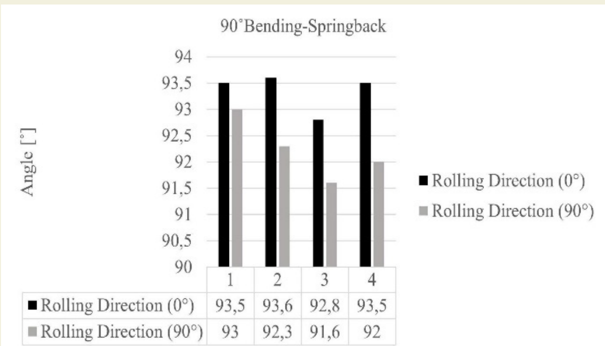

Figure 3. Angle after 90˚ bending for Rolling directions of 0˚ and 90˚

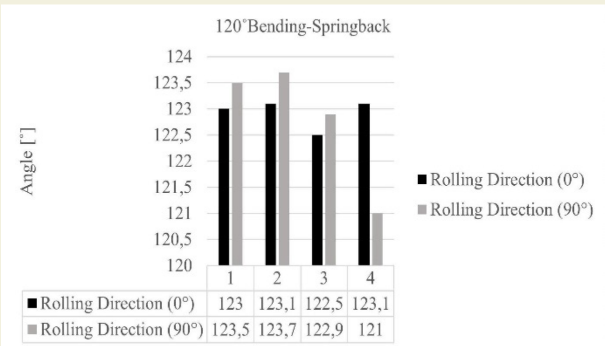

Figure 4. Angle after 120˚ bending for Rolling directions of 0˚ and 90˚

3.2. Erichsen Cupping Test and Tensile Test of Inconel 625 sheet metal.

To characterize mechanical properties of Inconel sheet plates in terms of forming ability, Erichsen Cupping test is applied. The test provides to specify the forming capacity of the material under multi-axial stresses. The test specimen is prepared according to standards of ISO 12004–2:2008. The size of sheet specimen as shown in figure 6-a is 10 mm x10 mm x1 mm. The sample prepared for the test was clamped and fixed in the jaw located in the middle of the machine. Afterwards, an increasing force was applied to the central part of the material by means of a die punch, and the material was started to be

Table 3. Spring-back angles at different conditions

Bending Angle	Sample No	Rolling Direction (0°) Ave.	Rolling Direction (0°) Spring-back Amount (mm)	Rolling Direction (90°) Ave.	Rolling Direction (90°) Spring-back Amount (mm)
90°	1	3,35	2,796	2,23	1,879
90°	2				
90°	3				
90°	4				
120°	1	2,93	1,164	2,78	1,105
120°	2				
120°	3				
120°	4				
150°	1	2,58	0,927	2	0,719
150°	2				
150°	3				
150°	4				

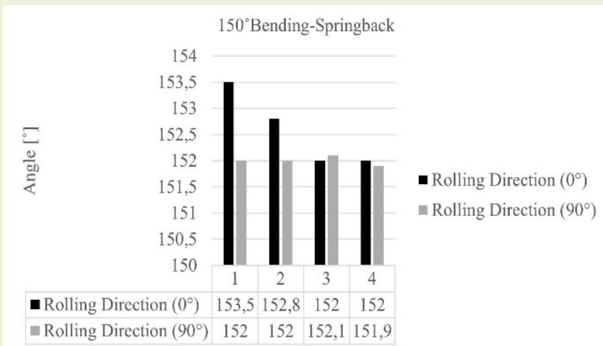

Figure 5. Angle after 150˚ bending for Rolling directions of 0˚ and 90˚

deformed.

The spherical punch moved to Inconel sheet plate to create permanent deformation until a crack formation occurred. 43.9 kN is applied to deform the sheet material and the fracture that is parallel to rolling direction is formed as shown in figure 6-b. Also, Matjaz et al. used low carbon steel to deep draw and observed that cracks were formed in longitudinal direction of rolling [40]. The depth value was found as 17.20 mm after Erichsen cupping test and it is compared with DP 780 in table 4 [37]. A higher depth of cut represents the higher formability. In addition to that, tensile specimen was used to characterize mechanical properties of Inconel sheet. Inconel 625 material tensile specimen was prepared in units of mm according to TSE ISO 6892 Standards as illustrated in figure 7. The test result shown in figure 8 is that ultimate tensile strength is 920 Nmm^{-2}, the yield strength is 474 Nmm^{-2}, and the elongation amount is 52.7%.

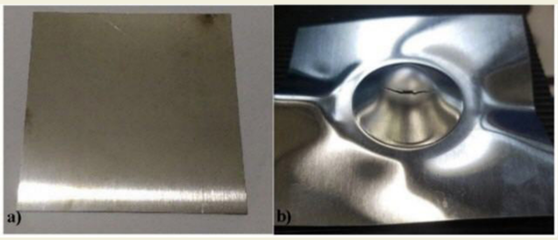

Figure 6. a) The specimen is prepared for Erichsen cupping test, b) Crack formation after the specimen is deformed in Erichsen cupping test.

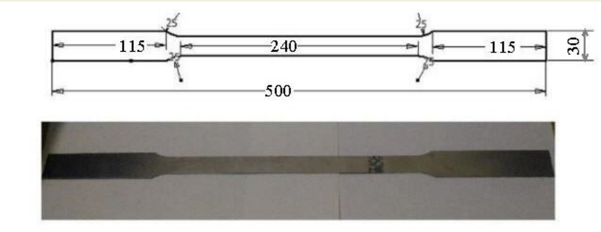

Figure 7. The dimensions of specimen used in tensile test

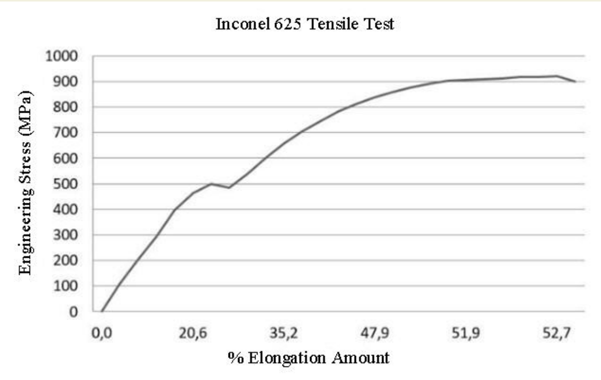

Figure 8. The yielding curve of Inconel 625 sheet plate.

Table 4. Comparison of Inconel 625 and DP 780 in Erichsen Cupping Test

Material Type	Thickness (mm)	Erichsen Cupping Test Value (mm)
Inconel 625	1.00	17.20
DP 780 [37]	1.00	8.24

4. NOMENCLATURE

P	Bending force, N
th	Thickness of sheet plate, mm
	Tensile strength, Nmm^{-2}
bl	width of plate, mm
c	Bending force coefficient
dw	Die clearance, mm
$\Delta\theta$	Spring-back angle
$\theta_{initial\ case}$	Initial angle
$\theta_{final\ case}$	Final angle

5. CONCLUSIONS

The study was focused on formability of Inconel 625 sheet metal for different die angles. It provides high strength and high corrosion resistant for both applications of aircraft and marine medium. Also, spring-back is a significant problem to form the sheet material. The bending amount can be adjusted according to spring-back character of material to form a desired geometry by predicting the spring-back amount. Thus, in the study the sheet metal spring-back behavior was characterized by using brake press bending machine for different bending angles and spring-back angles for each bending angle were measured by a goniometer. 4 specimens prepared for each bending angle was bent and the average of spring back angle of all 4 specimens were taken. Also, influence of rolling direction was investigated on spring-back behavior due to causing anisotropy. It is concluded that for rolling direction of 0° angle, the increase in bending angle from 90° to 150° lowers the average spring back-angle from 3.35° to 2.58°, experimentally. Tensile test results show that ultimate tensile strength is found as 920 Nmm^{-2}, the yield strength is found as 474 Nmm^{-2} for Inconel 625 sheet metal for rolling direction of 0°. To characterize Inconel 625 sheet plate under multi axial stress, Erichsen Cupping Test was applied. 17.20 mm cup height was obtained until the fracture occurred and crack formed. It is also higher than AISI 304 stainless steel having an Erichsen index of 12 mm for 1.0 mm thickness [41]. So, Inconel 625 sheet metal has a capability of higher formability than the stainless steel [41].

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