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Effect of Springback on A6061 Sheet Metal Bending: A Review

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ABSTRACT

Springback is defined as undesirable shape change that occurs after forming process upon unloading due to the occurrence of elastic recovery of the part. Aluminum alloy with high content of magnesium such as A6061 is preferred for high formability limit to be used in automotive industry. However, generally springback turns out to be a drawback. Many researchers have examined the springback of A6061 by considering parameters such as bent angle, die shoulder radius, blank holder force, sheet thickness, punch thickness, modulus young, yield strength, Poisson's ratio, annealing temperature, applied load and bending operations such as V bending, deep drawing, tube bending, 3 point bending, U bending, and wipe bending. In this research, a comprehensive review is carried out to investigate process parameters and bending operations having critical impact on springback of A6061 and publications in the literature based on springback effect for A6061 studied in order to observe the number of publications by authors and the number of publications by affiliation. It is observed that sheet thickness and bent angle parameters have substantial effect on the springback. V bending and deep drawing are the commonly used bending processes. In addition, a critical contribution is presented by considering process parameters and analysis methods in order to provide a guidance for researchers for further research studies.

Keywords: A6061 alloy; Springback; Design of Experiments (DOE); Failure Analysis; Mechanical Properties.

INTRODUCTION

Springback is one of the undesired elastic recovery of deformed parts that occurs just after completion of bending process and cause inaccuracy in bending angle. Chikalthankar, Belurkar, and Nandedkar (2014), stated that springback is a common problem in production processes where the material plastically deformed. Hence, the springback behavior of sheet metals are affected by factors related to stress generation during loading and unloading operations in bending process.

The demands for lightweight automotive parts are soaring tremendously in the quest to lighten the vehicles, to reduce fuel consumption, and to minimize carbon footprint. Most of these parts especially vehicle outer panels are produced using 6000 series alloy in order to obtain lightweight, high strength parts with good rigidity. Aluminum alloys material properties are directly influenced by the chemical composition, thermomechanical treatment, and yield strength. Dev et al. (2016) observed that the mass of an automotive body can be decreased up to 40% by the use of Aluminum alloys.

Carle and Blount (1999); Ng, Yahaya, and Majid (2017) studied aluminum alloy material properties for automotive applications. Their study concluded that aluminum sheets have the potential to be used as vehicle components. There are a wide range of opportunities for using Aluminum in automotive powertrains, chassis and body structures. Moreover, car bodies contributes to 20% of total weight of the automotive, so a promising way to reduce automotive weight is to use Aluminum alloys (Carle & Blount, 1999; Ng et al. 2017).

According to the proposed topic, the structure of paper is divided into sections in order to highlight the research. Paper layout is structured as follows; Firstly, general classifications of A6061 alloy presented and explained. The next, section 2 presents literature of A6061 alloy and recent studies on springback effect of A6061 alloy. Section 3 introduce commonly used bending processes to evaluate springback effect. Section 4 define the factors effecting springback and their impact on springback. Also, define the methods used to compensate springback. Section 5 classifies the literature of springback effect of A6061 alloy. Section 6 finalizes this paper with essential remarks and valuable suggestions for further research.

CLASSIFICATION OF ALUMINUM ALLOYS

Aluminum alloys are chemical compositions consisting pure aluminum combined with other elements. Combination of other elements to pure aluminum enhance properties of aluminum such as increase in strength. Other elements can be defined as; copper, magnesium, iron, silicon, tin, zinc and manganese at levels that combined to make up a 15% of the alloy total weight. The primary alloying element allows aluminum alloys to be categorized into several numbers of groups. These groups represent the material's characteristics such as its ability to respond to mechanical and thermal treatment. Aluminum alloys are mainly assigned with four-digit number, in which the first digit identifies the series of the alloy by characterizing its main alloying elements. Table 1 shows the designation of A6061 alloy as well as its applications. Each of the digit of series have an identity for each series. The first digit (Xxxx) describes the series of aluminum alloy and will also indicate the principal alloying element added to the aluminum alloy. The second single digit (xXxx) describes the number of modifications made to the specific alloy. The third and fourth digits (xxXX) are randomly generated numbers identify the specific alloy within the series. Example: In alloy 6105, the number 6 describes that the principal alloying elements are magnesium and silicon alloy series, while 1 indicate that it is the 1st modification to the original alloy 6005 and the 05 identifies it in the 6xxx series (Davis, 1993; Ng et al. 2017).

LITERATURE REVIEW

Details of published papers related to springback behavior of A6061 alloys gathered from SCOPUS database in order to observe number of publications. Based on SCOPUS data, researchers generally focus on springback of sheet metals. However, there are only a few publications related to springback of A6061 found in the literature. In 2019, total number of publications related to sheet metal is 1038 and total number of publications related to springback effect of A6061 is 6. Superimposed data is presented in FIGURE 1 and it can be observed that publications with the name of ("Sheet metal" AND "Steel") is slightly higher the publications with the name of ("Sheet metal" AND "Aluminum"). Amount of 15 publications under ("Sheet metal" AND "Aluminum" AND "Springback") found in the literature out of 251 publications under the ("Sheet metal" AND "Aluminum").

Number of publications related to springback of A6061 alloy sheet year by year is presented in the Figure 1. There are a few researchers specifically worked on A6061 alloy sheets such as (Abdullah, 2012; Abdullah & Samad 2013; A. F. Adnan, Abdullah & Samad 2017; M. F. Adnan, Abdullah & Samad 2016; Che Ghani et al. 2016; Li, Shi, Yang & Tian 2012). Their number of publications related to springback of A6061 alloy are slightly higher when it is compared to other researchers presented in FIGURE 2. Moreover, it is seen from the Figure 2(A) that University of Science, Malaysia has at total 7 publications related to springback effect of A6061. Based on the search from SCOPUS database with the keywords ("Springback" AND ("6061" OR "A6061" OR "A6061")), it has highest number of publications compared to other universities found in the literature based on mentioned keywords.

TYPE OF BENDING OPERATIONS

Sarıkaya (2008), applied mechanical processes to alter the geometry, properties and appearance of a starting sheet material to make parts angled or ring shaped which has greater value than the starting sheet material. In other words, altered material combines with other materials that have similarly altered materials to make complex geometries used in many purposes. Bending operation is the most common operation utilized for formation of sheet metal processes. Bending can be performed to form pieces such as L, U or V profiles. Bending operation mostly required in automotive, aircraft and defense industries for sheet metal bending processes.

V-die bending the punch moves down and up in order to give the V shape to the unsupported sheet metal. Die has V shape and the punch presses the sheet metal down on the V shaped die. Therefore, the sheet metal is being formed in V shape. During the process, small deviations in thickness of the sheet metal can create substantial changes in springback behavior (M. Mohamed, Farouk, Elsayed, Shazly & Hegazy 2017; M. S. Mohamed, Foster, Lin, Balint & Dean 2012). In Air bending process, tooling, punch and die are used. The workpieces stay on two points. The punch is utilized to apply bending movement. Air bending usually utilized for straightening operations. U-die bending is carried out in four steps (Fadden & McCormick 2014). 1) clamping the sheet metal between punch and die. 2) punch movement in downward direction with constant force. 3) Forming the sheet metal by the compressive force between die and punch. 4) Final unloading process. In wipe bending, blank is taken in a static position by applying the force. Punch moves down to the spring-loaded pressure pad (Sarıkaya, 2008). Rotary bending is used to form the sheet metals by a similar mechanics as edge bending. There is a cylinder works as punch. Cylinder rotates about one axis and workpiece placed at the edge of lower die. As the cylinder rotates, the sheet metal is being bend (Heng, Shi, He, & Tian, 2012). Deep drawing is commonly used in automotive and aerospace industries. Especially used in mass production of cup shapes (Sravanthi & Nethala 2015).

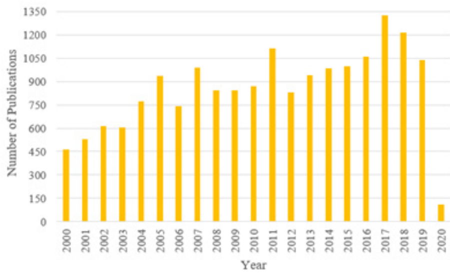
There are many other bending processes studied by the researchers. Those bending processes are explained in Table 2.

FACTORS AFFECTING SPRINGBACK IN BENDING PROCESSES

Undesired elastic recovery of sheet metals after bending operations called as springback behavior. After forming sheet metals, deviation in bend angle from the desired target shape causes quality problems and results difficulties during assembly. Inaccuracies such as springback has impacts to economy due to less overall efficiency (OE) and poor first time quality (FTQ). This is because, springback behavior creates economic challenges in manufacturing (Sarıkaya, 2008).

TABLE 1. Classification of 6000 series aluminum alloys (Woldman, 2000).

Alloy	Al contents	Alloying elements	Applications
6061	97.9	Si 0.6; Mg 1.0; Cu 0.25; Cr0.2	Universal, structural, aerospace, automotive



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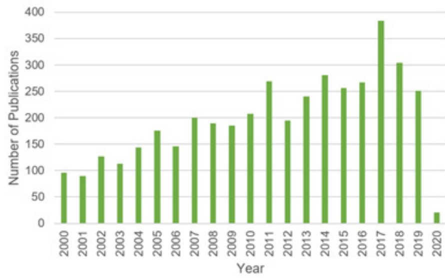

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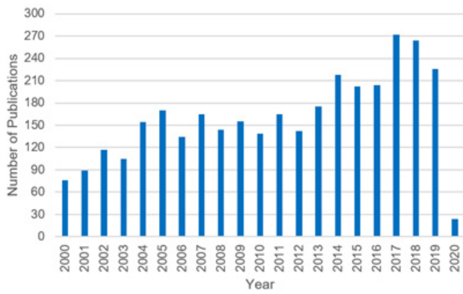

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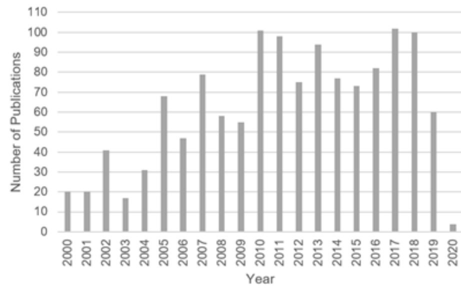

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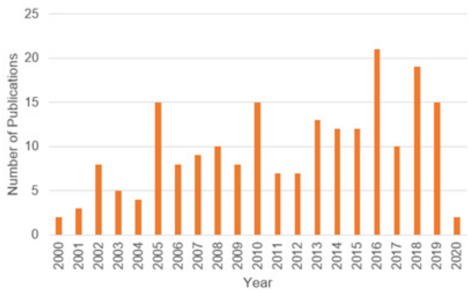

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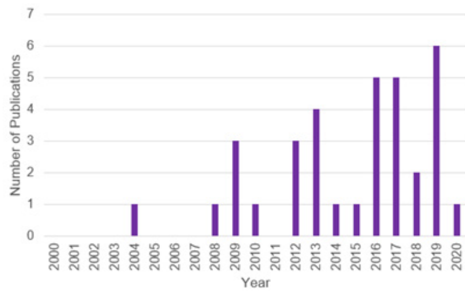

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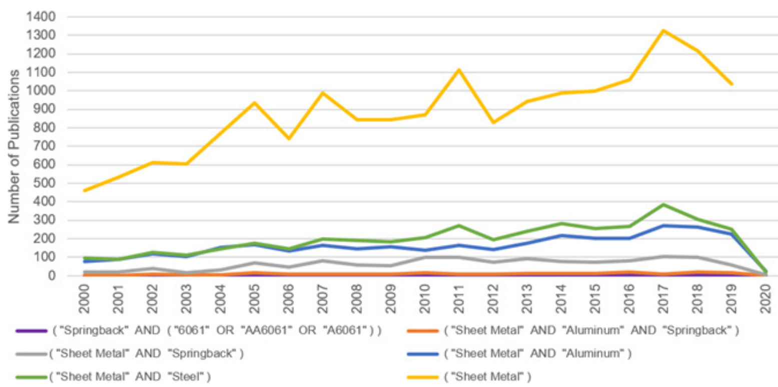

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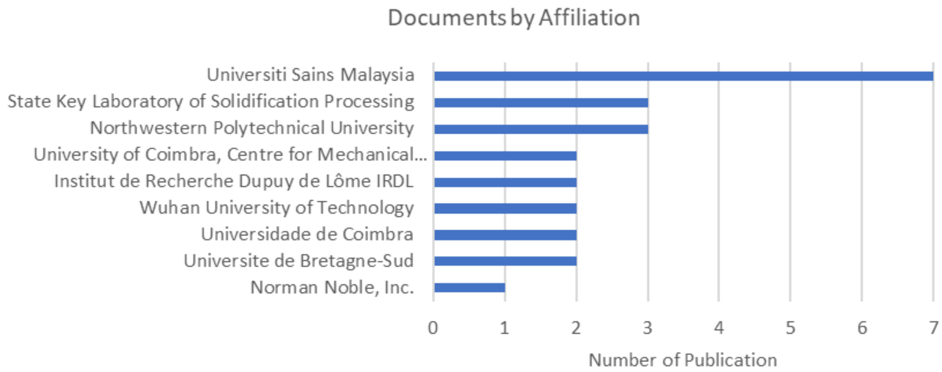
FIGURE 1. Statistics from Scopus database (Date: 12 February 2020), A) Published documents per year with keywords "Sheet Metal". B) Published documents per year with keywords "Sheet Metal AND Steel". C) Published documents per year with keywords "Sheet Metal AND Aluminum". D) Published documents per year with keywords "Sheet Metal AND Springback". E) Published documents per year with keywords "Sheet Metal AND Aluminum AND Springback". F) Published documents per year with keywords "Sheet Metal AND 6061". G) Quantitative comparison of published articles per year



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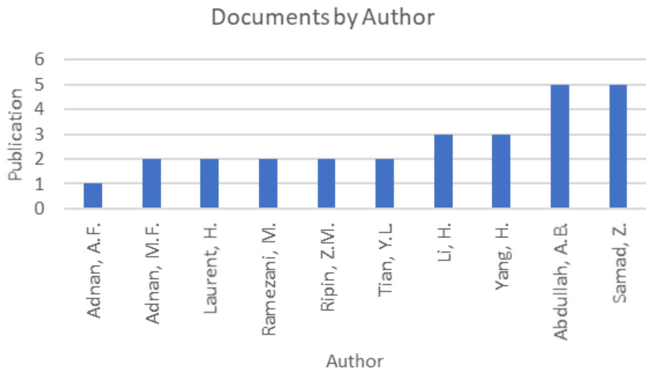


B

FIGURE 2. Statistics from Scopus database (search keywords: (“Springback” AND (“6061” OR “A6061” OR “A6061”)); Date: 12 February 2020), A) Published documents by affiliation. B) Published documents by author

Springback behavior affected by numerous factors and those factors such as sheet thickness, bend angle, modulus of elasticity, strain hardening, die and punch radius and friction coefficient are summarized in Table 3 and their impact is also discussed. Furthermore, methods utilized to compensate springback effect is presented in Table 4.

Abdullah and Samad (2013), performed an experimental study based on springback of A6061 alloy via V-bending process. Their study has presented that springback is significant to the thickness of A6061 alloy. As a result of experimental study, at lower thickness the amount of springback is higher.

Bend angle is very important for all bending processes. Its directly related to material thickness. As the material thickness increases, bend angle increases due to successful bending. Otherwise, some defects can appear on the material due to material properties of material. Bend angle is also critical parameter to observe springback. The effect of bend angle is discussed in TABLE 3.

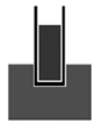
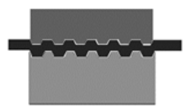
Bend radius/die radius is a significant parameter considerably affecting all bending processes of sheet metals. Thickness of material and properties of material are variables that affect determining the minimum bend radius. Tool radius impact is visually presented in Figure 3.

Li et al. (2012), performed an experimental analysis to investigate springback effect upon bending. A6061-T4 alloy of 50.8 mm × 0.889 mm (outer diameter × wall thickness) used as the material. After experimental study, it is observed that the springback angle increases linearly with the increasing of the bending angle. Therefore, with the larger bending angle, the more elastic deformation store is accumulated. Summarily, a material with higher elastic modulus present less springback.

Leu (1997) investigated simplified approach to evaluate bendability. It is resulted that materials which has lower strain hardening and sheet thickness ratio presents high springback behavior.

Laurent et al. (2011), carried out simulations under dry friction (friction coefficient is 0.177) and with lubrication (friction coefficient 0.1) of the specimen and tools active surfaces. The variations of springback parameters (θ1, θ2, ρ) as function of friction coefficient are springback is an undesirable shape change that occurs upon unloading the punch after sheet metal forming. Springback is expressed as dimensional change of the materials occurs due to elastic recovery upon unloading. In their study, the increase in friction coefficient causes increase in springback. Moreover, Dametew (2017) applied edge bending process to observe the impact on springback. In this study, it is resulted that

TABLE 2. Bending processes adapted from (Sarıkaya, 2008)

Bending Processes	Explanation	Figures (Black: Piece, Dark Grey: Punch, Light Grey: Die)
V Die Bending	1. Most common bending process in production. 2. Punch is used to alter the shape of workpiece in V shape.	
Edge Bending	3. It is one of the sheet metal bending process with a wiping die.	
Rotary Bending	4. A cylinder with the desired angle serves as a punch. As the punch moves, bending operation performs.	
Air Bending	5. As punch moves between two surfaces, sheet metal bending performs.	
U bending	6. U shaped punch used to make U bends.	
Offset Bending	7. Multiple bending processes combined together to create offsets and form the sheet metal.	
Corrugating	8. A symmetrical bend is used across the width of sheet metal and at a regular interval along its entire length to accomplish bending.	
Three Point Bending	9. Three-point bending is one of the other methods to measure tensile modulus of elasticity.	
Flanging	10. Flanging is called as an edge bending process. Usually 90° angle generated in the shapes.	
Beading with a single die	11. Beading forms a curl over a part's edge. This bead can be formed over a straight or curved axis.	
Hemming	12. Hemming is a bending process and edge of the sheet metal is usually bent over on itself.	
Seaming	13. Seaming is a bending process in which edge of the sheet metals are locked together.	
Roll Bending	14. Distance and angle between rolls impact the shape of bending.	

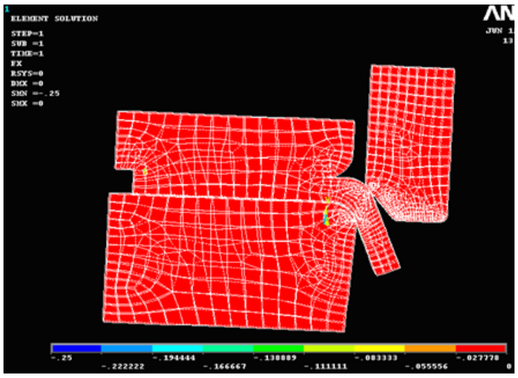


FIGURE 3. The effect of tool radius (Dametew, 2017)

TABLE 3. Factors affecting springback. Adapted from (Buang, Abdullah, & Saedon, 2014; Chikalthankar et al. 2014; Dev et al. 2016; Gebresenbet & Dametew, 2017; Kulkarni & Gajjal, 2015; Ramulu, Rao, & Yimer, 2016; Saravanan et al. 2017; Sulaiman, Ariffin, & Lai, 2012)

Factors Affecting Springback	Impact	Impact on Springback	References
Sheet thickness	High	Increase in sheet thickness results reduction of the springback effect	(Abdullah, 2012; M. F. Adnan et al. 2016; Dev et al. 2016; Le Maoût, Thuillier, & Manach, 2009; Liu et al. 2017; Namoco, Iizuka, Hatanaka, Takakura, & Yamaguchi, 2007; Raju, Ganesan, & Karthikeyan, 2010; Sarıkaya, 2008; Tanimura, Tsuda, Abe, Hayashi, & Jones, 2014; Thipprakmas & Phanitwong, 2011; Thuillier, Le Maoût, & Manach, 2011)
Bend angle	High	Increase in bend angle results higher springback effect	(A. F. Adnan et al. 2017; M. F. Adnan et al. 2016; Ikawa, Asano, Kuroda, & Yoshida, 2011; Li et al. 2012; Raju et al. 2010; Ramulu et al. 2016; Saravanan et al. 2017; Sarıkaya, 2008; Thipprakmas & Phanitwong, 2011)
Elastic modulus	Medium	Higher elastic modulus provides less springback effect.	(Mori, Akita, & Abe, 2007)
Strain hardening	Medium	Increase in strain hardening results reduction in minimum bending radius. Therefore, springback effect reduces as the strain hardening increases.	(Abdullah & Samad, 2013; A. F. Adnan et al. 2017; M. F. Adnan et al. 2016; Chen, Fang, & Zhao, 2017; Laurent et al. 2011; Liu et al. 2017; Moon, Kang, Cho, & Kim, 2003; Ng et al. 2017; Sarıkaya, 2008; Simões, Laurent, Oliveira, & Menezes, 2018)
Bend radius / Die radius	Medium	Die and punch radius are considered to determine bend radius. Therefore, springback effect is higher as the die and punch radius increase.	(Raju et al. 2010; Singh & Kumar, 2015; Tang, Wu, Kobayashi, & Pan, 2007)
Friction coefficient	Low	Increase in friction coefficient causes slight increase in springback angle.	(Heng et al. 2012; Moon et al. 2003)

TABLE 4. Methods utilized to compensate springback effect.

Method	Description	References
Over Bending	• The sheet is bent beyond the required angle. • After the elastic recovery, required dimensions will be obtained.	(Chandrasekaran & Manonmani, 2015; Saravanan et al. 2017; Sarıkaya, 2008)
Coining	• It is a type of closed die forging process. • This process provides smoother surfaces and closer tolerances.	(Saravanan et al. 2017; Sarıkaya, 2008)

increasing of friction coefficient from 0.01 to 0.50 cause 52% increase in springback (Dametew 2017).

RECENT STUDIES ON SPRINGBACK EFFECT OF A6061

Nasrollahi and Arezoo (2012) studied springback phenomenon and divided springback problems can be analyzed into two groups. 1) factors related young's modulus, yield stress, strength coefficient, strain hardening, Poisson's ratio and anisotropic coefficient. 2) factors related to bending processes such as bend angle, punch force, clearances.

Thipprakmas and Phanitwong (2011) carried out a study to identify process parameters which has critical impact on bending angle, thickness and punch radius. Their study conducted FEM simulation associated with Taguchi and ANOVA has been studied in literature. Its concluded that material thickness is one of the important factors affecting springback. Generally, thin materials have springback effect and very difficult to prevent presence of springback. In contrast, the bending angle, 30°, 45°, 60°, 120°, 135° and subsequent material thickness, 2mm, 2.5mm, 3mm and 3.5mm and approximately calculated percentage distribution are 59.6067% and 33.4050% in V bending process.

Chikalthankar et al. (2014); Ján and Miroslav (2012) analyzed the effect of bend depth to springback. It is resulted that the higher bend depth creates higher bend angle. Investigation of springback is carried out by the use of design of experiment which is one of the Taguchi method. It is reported that there is an increase in springback as the bend angle increases.

Kamaruddin, Khan and Foong (2010) studied factors affecting desired quality characteristics such as springback behavior after bending process. Their study conducted Taguchi method in order to analyze compensation of factors that are creating economic problems in industries due to defects occurrence. There are also numerous papers base on springback with uniform section but a few studies available base on non-uniform section.

A. F. Adnan et al. (2017) carried out a study by conducting Taguchi method to find out process parameters affecting springback behavior. Springback behavior of Aluminum 6061 alloy with non-uniform section. Theoretically, Taguchi method conducted using L18 orthogonal arrays in order to discover springback behavior of A6061 Alloy. Bend angle (51.25%) found as most significant process parameter affecting springback behavior. Whereas, annealing temperature (3.89%) found as least process parameter affecting springback behavior. Thickness ratio (19.04%) has average impact on the springback behavior of A6061 (A. F. Adnan et al. 2017).

Sravanthi and Nethala (2015) performed the formability analysis on A6062-T6 and A5052 alloy sheets at different conditions (dry, lubricant and annealed). Three different samples, 70 mm x 70 mm, 70 mm x 50 mm and 70 mm x 30 mm examined and results compared. The comparison of the experimental observation, summarized as;

1. The A6061 samples examined and annealed samples presented higher formability compared to other conditions.
2. The A6061 samples compared to A5052 samples. Resulted that A6061 presents higher formability than A5052.

Le Maoût et al. (2009) examined straight and notched sample of 6000 series Aluminum alloys at different orientations to observe damage characterization based on tensile tests. Compensation of springback behavior of Aluminum alloys were displayed as the high strength over the young's modulus ratio increases. Additionally, formability of Aluminum alloy significantly high as the ratio increases. Gurson-Tvergaard-Needleman model carried out in experimental study for hemming process. Uniaxial tensile test and biaxial expansion test directly influenced the process parameters to predict the hemming limit criterion.

Geng, Wang, Wang, and Zhang (2019) investigated the effect of heat treatment conditions on springback of A6061 aluminum alloy sheets by performing three-point bending. They have also conducted simulation based and experimental based study in order to provide differences of springback estimation between simulation and experiment. Material properties and simulation conditions are presented in Table 5. Their investigation resulted that:

1. The bending radius and thickness of the sheet increase with the increase of strain-hardening exponent and elongation, while decrease with the increase of yield ratio, and the influence of strain-hardening exponent is the largest.
2. Springback increases with the increase of yield strength and strength factor, while decreases with the increase of strain-hardening exponent, and the influence of strength factor is the largest.
3. With the increase of material strength, the principal stresses of the sheet in the fillet region increase, thus motivating greater springback.

Abdullah and Samad (2013) reported that Aluminum alloy which has high amount of magnesium such as A6061 present higher formability limit. However, springback behavior becomes a substantial concern. In their study, springback behavior of A6061 analyzed in V bending process as shown in Figure 4. Most critical factors affecting springback found as bent angle, thickness and length. Finally, their study presented that springback formation can be minimized by playing with tensile strength, yield strength, thickness, bent radius and bent angle. However, very difficult to eliminate springback behavior in V bending processes.

The effect of length, thickness and bend angle to the springback pattern is investigated and the result highlighted that springback is more significant to thickness and bend angle, while the length gives less effect and springback can only be controlled and minimized by the tensile and yield strengths, thickness, bend radius and bend angle but

TABLE 5. Material properties and simulation conditions (Wang et al. 2019).

Material properties and simulation conditions	Value
Density (kg/m3)	2700
Young's modulus (GPa)	68.9
Poisson's ratio	0.33
Specimen length, width and thickness (mm)	160,20, 2
Punch speed (mm/ms)	1.0
Punch stroke (mm)	30
Static friction coefficient between punch and sheet	0.20
Dynamic friction coefficient between supports and sheet	0.15

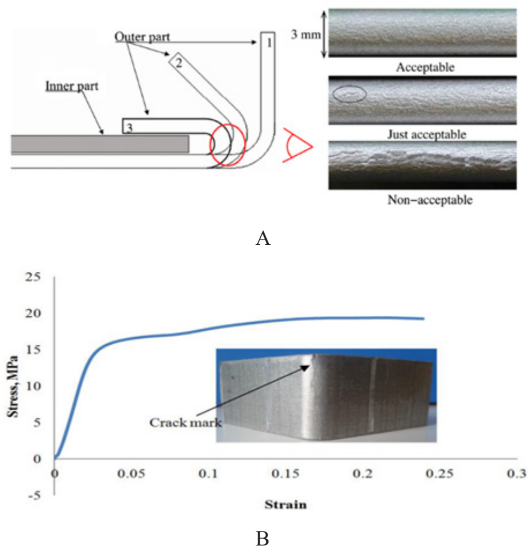


FIGURE 4. A) Crack formation of A6061 in the bent area, B) The stress strain behavior of the material (Abdullah & Samad, 2013).

quite difficult to be eliminated. The performed experiment resulted as in Figure 4.

Emmens and van den Boogaard (2010) studied deep-drawing bending method to analyze Forming Limit Curve (FLD), which defines a limit beyond which necking develops. However, Thuillier et al. (2011), reported that deep-drawing bending methods are not suitable for bending over a radius of the order of the sheet thickness. Because, bending involves a strain gradient in the thickness in this type of bending methods. Respectively, Liewald and Schleich (2010) introduced Forming Limit Curve (FLD) model and displayed good agreement with observation found in the literature. However, the model developed with some severe simplifications.

Theoretically, the strains at the outer fibers and inner fibers are equivalent in magnitude as presented below (Chikalthankar et al. 2014):

$$e_0 = e_1 = \frac{1}{\left(\frac{2*R}{T}\right)+1} \tag{1}$$

The relationship obtained for pure bending is (Chikalthankar et al. 2014):

$$Bend\ Allowances = \left(R_i + \frac{t}{2}\right)*\alpha_i = \left(R_f + \frac{t}{2}\right)*\alpha_f \tag{2}$$

Springback factor (K_S) is defined in (1.3) and an approximate formula for springback estimation is presented in (1.4) (Chikalthankar et al. 2014):

$$K_s = \frac{\alpha_f}{\alpha_i} = \frac{\left(\frac{2*R_i}{t}\right)+1}{\left(\frac{2*R_f}{t}\right)+1} \tag{3}$$

$$\frac{R_i}{R_f} = 4*\left(\frac{R_i*Y}{E_t}\right) - 3*\left(\frac{R_i*Y}{E_t}\right)+1 \tag{4}$$

Nomenclature;

e_0, e_1 Strains at the outer fibers and strains at the inner fibers, respectively.

R_i, R_f The initial bend radius and final bend radius, respectively.

α_i, α_f Bend angle before unloading, bend angle after unloading.

t Thickness.

Y Uniaxial yield stress of the material.

K_S Springback factor (K_S = 0; indicates complete elastic recovery).

Chikalthankar et al. (2014); Wagoner, Lim, and Lee (2013) investigated the root cause of springback formation that is elastic recovery during unloading in Aluminum alloy bending processes. Essential parameters that influence springback behavior are stated as sheet thickness, material properties and tooling geometry. These parameters should be accurately predicted in order to alter alloys into desired shapes. Die radius, sheet thickness and blank holder force are found as the most important parameters to eliminate springback behavior. Additionally, springback is detected in the last stage of process due to elastic recovery of the part in circular bending process.

Moreover, springback reduction can be done in four ways as follows (Chikalthankar et al. 2014):

1. Increasing blank thickness.
2. Varying bend radius.
3. Reducing the prescribed punch travel.
4. Reduce the friction between blank surfaces and die surfaces by lubricant.

Zhu, Liu, Yang, and Li (2012), reviewed the constitutive models to observe springback behavior in cold bending processes. Elastic behavior, anisotropy and work hardening conditions are examined to predict critical process parameters. Finally, following decisions were made.

1. As the elastic modulus and the elastic recovery increases, less springback behavior and higher accuracy were observed.
2. The isotropic hardening leads to an overestimation of the springback, which can be avoided by a hardening model describing the Bauschinger effect.
3. The yield criterion presented less impact on springback behavior than the hardening model.
4. In order to predict accurate springback behavior, elastic modulus, material anisotropy and non-linear hardening should be determined all together.

Thipprakmas and Phanitwong (2011), studied Taguchi method to examined process parameters for higher precision of parts in V bending process. Punch radius, material thickness and bent angle selected as main process parameters in V bending. These process parameters are analyzed by the use of FEM in which Taguchi and ANOVA techniques are associated together. These techniques utilized to present the degree of importance of parameters to springback behavior. Additionally, optimization of these process parameters can provide better bending quality with less springback behavior.

Dev et al. (2016), applied design of experiment and FEA together to provide better understanding for springback behavior of A6061 alloy in three-point bending process. Correlation between thickness and radius of punch were created after the examination of variety process parameters such as thickness at ambient temperature. Theoretical data proved that as the distance between rollers decrease and thickness of alloy getting thinner, the springback behavior is more significant. Therefore, thickness and distance between rollers are essential in order to eliminate or reduce the springback.

Buang et al. (2014), reported that gradation of importance of process parameters is prior action to find out optimal process parameters to control springback of A6061 alloy in deep drawing processes. Therefore, a statistical approach is selected and Taguchi technique is conducted to their study to investigate the degree of importance of parameters affecting springback. By this way, Essential process parameters were prioritized. Relatively, ANOVA examination carried out to predict suitable process parameters as follows (Buang et al. 2014).

1. Blank holding force is found to be a prominent parameter affecting the roughness as well as thickness. Whereas, minimum impact on roughness had been by punch nose.
2. Optimized process parameters for surface roughness in deep drawing process observed as; blank holder force is 8kN, punch nose is 5mm and die shoulder radius is 8mm for A6061 in deep drawing process. Based on considered values, surface roughness found as 1.55µm.
3. Optimized process parameters for even wall thickness in deep drawing process observed as; blank holder force is 6kN, punch nose is 5mm and die shoulder radius is 4mm for A6061 in deep drawing process. Based on considered values, wall thickness found as 1.36mm.

Raju et al. (2010) claimed that level of process parameters in deep drawing process for A6061 is critical to overcome springback. It is observed that blank holder force has major impact and punch nose radius is minor impact on thickness distribution in deep drawing process for A6061 sheet alloy based on Taguchi method related to signal to noise ratio. Experimental based study is conducted to find out optimum levels of parameters. It is concluded in the analysis that the parameter having highest impact on springback selected as die shoulder radius. Blank holder force and punch nose radius are found as parameters which has 2nd and 3rd highest impact on springback in deep drawn cup of A6061 sheet respectively.

Sarıkaya (2008) analyzed influence of heat treatment of A6061 alloy on springback behavior. Experimental analysis by the use of FEM conducted to their study to investigate

TABLE 6. Treatment Process for A6061 (Sarıkaya 2008)

Treatment Condition	Process
T4 and T6 condition	1. Obtained by dissolving the material at 529°C with soaking 40 minutes in an air convection Aluminum heat treatment furnace and then water quenching. 2. Afterwards material was naturally aged at room temperature for 96 hours, when its hardness and conductivity values according to SAE AMS 2658 standard. 3. After T4 treatment, artificial aging was employed to obtain T6 condition by aging the material at 177°C for 8 to 10 hours again in air convection furnace.
O condition	1. SAE AMS 2770G directs the same processes for full annealing which was achieved soaking the materials at 427°C for minimum one hour and then furnace cooled at 28°C /hour maximum to 260°C and then air cooled to room temperature

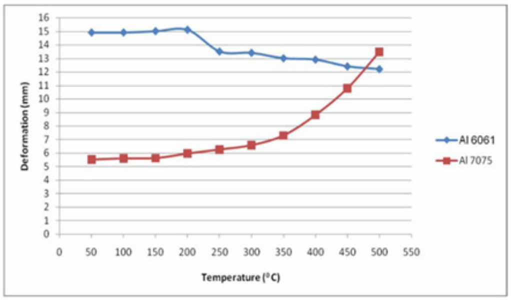


FIGURE 5. Deformation versus temperature graph (Venkateswarlu et al. 2010)

the effect of heat treatment on springback. Different heat treatment strategies such as T6 heat treatment, T4 heat treatment and O heat treatment applied to A 6061 alloy for the experimental work to monitor the springback behavior. Three different thickness of Aluminum sheets (1.6 mm, 2 mm, 2.5 mm) are bent at different angles (60°, 90° and 120°) while stress distributions, elastic recovery of the Aluminum sheets were being analyzed.

Summary of Sarıkaya (2008)'s study presented below:

1. Higher springback behaviors are observed in T6 condition compared to T4 and O conditions.
2. Maximum stress occurred in T6 condition and minimum stress occurred in O condition for the same bending conditions.
3. Smaller plastic strain value observed in O condition compared to T4 and T6 conditions.
4. Its observed that springback behavior decreases if the thickness of Aluminum sheet increases.
5. Increase in bend angle created higher springback behaviors.
6. The analysis highlighted that applied force to punch in order to bend the Aluminum sheet is higher in T6 condition compared to other conditions. Minimum force is required in O condition.

(Heng et al. 2012) performed an orthogonal test to A6061 T4 Aluminum alloy tube to achieve the precision bending deformation. In this study, thin walled 6061 T4 alloy tube of 50.8 mm (outer diameter) × 0.889 mm (wall thickness) is taken as base material. Different parameters and applications carried out to find the best combination. It is resulted that increment of the bend angle causes increase in springback behavior. Additionally, critical parameters that has significant influence on springback are listed as bending radius, friction between tube and die, die force, thickness of Aluminum alloy sheet.

Venkateswarlu, Davidson, and Tagore (2010) carried out a deformation analysis at elevated temperatures to determine the effect of blank temperature on forming behavior of sheets and damage factor of Aluminum sheet alloys 6061. Results showed that the temperature of sheet metal forming causes variation in product height of A6061. A6061 displayed great formability between 150°C -250°C and A6061 provided identical cup heights at the temperature of 475°C.

Ramulu et al. (2016) reported that sheet metal forming processes has a direct impact on economy and weight reduction ratio in automotive industry. One of the important issues for forming processes is bending operation. Experimental study carried out in the paper to observe springback effect in number of 21 A6061 Aluminum alloy sheets (1.7mm) with different rolling directions. It is resulted that roll direction has significant impact on springback behavior. The observations presented that springback behavior is observed between 75° and 98° die angles for A6061.

Simões et al. (2018) analyzed A6061 alloy with T6 condition by using uniaxial tensile test, cylindrical cup test and split ring test in order to discover warm formation of Aluminum alloys to springback. Results show that temperature increase causes an increase in elongation of A6061. This increase in ductility is an advantage to enhance formability of parts. In addition, results highlighted that temperature between 200°C and 250°C can be selected as an effective solution parameter to minimize the influence of natural aging on springback variability.

TABLE 7. Classification of research

Category	Subcategory	Item	Wang, G. Et al. (2019)	Nagaraju, K.N. Et al. (2018)	Simões, V. Et al. (2018)	Liu, Y. Et al.(2017)	Ng, C.H. et al.(2017)	Adnan, M.F. Et al.(2017)	Namoco Jr., C.S. Et al. (2017)	Saravanan S. et al. (2017)	Chen, Z., Et al. (2017)	Pradeau, A. et al.(2016)	Dev, G.P. Et al.(2016)	Abdullah, A.B. Et al.(2016)	Ramulu, P.J. Et al. (2016)	Siska, Filip et al.(2015)	Singh, M. et al.(2015)	Sravanthi, G. Et al.(2015)	Pandivelan, C. Et al. (2015)	Tanimura, S. et al.(2014)	Abdullah, A.B et al.(2013)	Abdullah, A.B. et al.(2012)	Heng, L. I. Et al. (2012)	Davidkov, A. et al.(2011)	Ikawa, S. Et al. (2011)	Thipprakmas, S. Et al. (2011)	Almaraz, G.M.D. et al.(2010)	Venkateswarlu, G. Et al.(2010)	Thuillier, S. Et al. (2010)	Raju, S. et al. (2010)	Maout, N.L. et al. (2009)	Sarıkaya, O.T.(2008)	Tang, S.H. et al.(2006)	Mori, K. Et al.(2006)	Yoon, S.J. et al.(2003)
Analysis	Mathematical Model	Granato–Lucke's model																															X		
		pulse–echo-overlap (PEO) method																															X		
		CowperSymonds equation (CS model)																	X																
		Cockcroft Latham algorithm																									X								
		Euler–Bernoulli beam theory													X																				
		Finite element analysis (FEA)	X										X			X						X	X		X	X	X	X			X	X	X	X	
		Response Surface Methodology																																	
		Hosford-Coulomb Rupture										X																							
	Method	Distance to Edge effect, Taguchi Method																																X	
		Design of Experiment (DOE)		X	X				X		X	X	X	X	X		X	X			X			X	X				X					X	X
		Orthogonal test - Taguchi Method																					X												
		The analysis of variance (ANOVA).						X					X				X									X									
		Signal to noise ratio - Taguchi Method																												X					
	Simulation	MSC.MARC/MENTAT																														X			
		MATLAB								X																									
		ANSYS AUTODYN																	X																
		LS-DYNA																	X																
		Deform-2D															X																		
Bending Types	Test	Bulge Test										X																							
		Three Point Bend Test							X				X												X										
		Uniaxial tensile test	X		X						X																								
		Repetitive tensile testing (RURC testing)																	X																
		Split ring test			X																														
		Cylindrical Cup test			X																														
		Deep Drawing Test			X										X												X		X						
	Bending	Hemming Process																						X					X		X				
		Pin head embossing process																				X													
		Rotating Bending																									X								
		V Shaped Bending						X						X	X						X					X						X		X	
		Groove Pressing		X																															
		U Shaped Bending																													X	X			
		Tube Bending																					X												
		Cold Embossing Pin Head																																	
		Moment Bending																														X			
		Wipe Bending								X																						X			
		Rotary Bending																					X									X			
Parameters		Applied Load		X											X			X							X		X					X			
		Frequency																									X								
		Die friction																					X												
		Annealing temperature		X		X		X			X							X									X	X				X			
		Punch velocity																					X					X							
		Tickness of Punch							X																X	X				X					
		Sheet Thickness				X		X	X				X	X						X	X					X			X	X				X	X
		Bulge height							X	X											X	X													
		Hot Forming-Quenching (HFQ) / Stamping	X		X	X					X																					X			
		Poisson Ratio																																X	
		Heat Treatment Conditions	X																																
		Die closing pressure																																	
		Yield Strentgh																																X	
		Modulus of Elasticity																																X	
		Initial Blank Temperature																																	
		Blank Holder Force															X													X					
		Die shoulder radius												X			X									X				X		X			
		Bent angle						X		X				X	X		X				X		X		X	X				X		X			

Saravanan et al. (2017) investigated two critical methods to compensate springback behavior in bending processes. Over bending and coining are found as technique to compensate springback. Over bending technique is explained as sheet metal bending process performed beyond the required angle. Therefore, bending angle will return back to desired angle with the springback behavior. This technique most commonly used in industrial production plants. Coining is other technique to eliminate springback behavior. In this method either edge of punch or the surface undergoes coining.

CLASSIFICATION OF LITERATURE

According to the articles, which have reviewed in the field of springback effect of bending processes for A6061 Aluminum alloy, various bending processes of A6061 and bending parameters were studied to highlight the springback effect and the parameters which has a direct impact on the springback. Reviewed articles mostly related to A6061. However, some papers focus on A6061 with different tempering, different thickness and different bending operations. Researchers generally focused on specific parameters such as bent angle, die shoulder radius, blank holder force, sheet thickness, punch thickness, punch velocity, annealing temperature and applied load. Whereas, researchers rarely focused on bulge height, frequency and displacement. V shaped bending and U-shaped drawing bending methods mostly selected as bending type to investigate springback effect of A6061 Aluminum alloy. Additionally, Finite Element Analysis (FEM) selected as commonly conducted simulation method and Analysis of Variance (ANOVA) and Design of Experiment (DOE) selected as commonly conducted Taguchi methods in the reviewed papers. In addition, Classification of the research presented that researchers preferred to conduct simulation and Taguchi methods rather than mathematical models. Details about the reviewed papers are shown TABLE 7.

CONCLUSION

In this paper, a comprehensive review on springback analysis of A6061 Aluminum alloy sheet is presented. A critical comparison of process parameters affecting springback behavior of A6061 alloy in bending operations studied. The aim of the paper is to let more experts know about the current research status of springback behavior of A6061 alloy and provide guidance to researchers for further studies. Springback effect of A6061 Aluminum alloy sheet observed in several bending operations that are defined as; V bending, deep drawing, tube bending, 3-point bending, U bending, and wipe bending. Springback creates inaccuracies in bending operations that cause economic effects in production. This inaccuracy is not common problem for A6061 Aluminum alloy, this inaccuracy also occurs in other materials upon bending by the use of studied bending methods due to springback effect.

The research presented that bent angle, die shoulder radius, blank holder force, sheet thickness, punch thickness, modulus young, yield strength, Poisson's ratio, annealing temperature, applied load are parameters having essential impact on springback. Nevertheless, less considerations were given to the effect of bulge height, die friction, load frequency. It is also observed that sheet thickness and bent angle parameters have substantial effect on the springback. V bending and deep drawing are the commonly used bending processes. Over the years, many techniques are applied A6061 Aluminum alloy sheet in order to analyze springback phenomena. Very few researchers conducted mathematical modelling to their studies to evaluate springback effect of A6061 Aluminum alloy sheet. Most frequently used methods found as Taguchi method and FEA. Most researchers from 2003 to 2019 applied to their study this technique. However, there is still room for application of simulation methods as well as design of experiment (DOE) methods for further researches. Moreover, application of variety bending operations to A6061 Aluminum alloy sheet with a certain thickness can help to observe impact of process parameters for different bending methods.

DECLARATION OF COMPETING INTEREST

None.

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