Onur Çavuşoğlu
Hakan Gürün

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STATISTICAL EVALUATION OF THE INFLUENCE OF TEMPERATURE AND SURFACE ROUGHNESS ON ALUMINIUM SHEET METAL FORMING

Summary

The influences of temperature and surface roughness on the forming of the AA3003-H111 aluminium alloy sheet material have been investigated by using the finite element method. For this purpose, material cards have been firstly created based on the sheet material behaviour at different deformation temperatures. As a result of the forming analyses performed at different temperature values and surface roughness values, it has been determined that the increase in the surface roughness reduces the amount of thinning while it increases the amount of forming force and the springback. It has also been determined that there is a slight increase in the amount of thinning, while the temperature rise reduces the amount of forming force and the springback. In addition, the influence levels of temperature and surface roughness have been determined by statistical analyses.

Key words: *temperature, surface roughness, AA3003, ANOVA*

1. Introduction

Aluminium alloyed sheet materials are preferred for energy saving by reducing vehicle weight, due to their high strength-to-weight ratio and corrosion resistance [1-2]. Sheet metal forming processes are affected by many different parameters such as surface quality (lubrication conditions), temperature, blank holder pressure and forming speed [3-4]. Aluminium alloys exhibit the properties of high ductility and formability at temperatures below the recrystallization temperature although they have low formability at room temperature [1-2]. Determination of sheet metal forming process parameters saves time and costs. For this purpose, the effects of the process parameters on the forming process can be determined by performing analyses using the finite element method [4-7]. Temperature affects mechanical properties of the material. Therefore, it also affects the yield surface which occurs depending on the plastic deformation in the sheet during forming. Several studies have been conducted related to this subject. Abedrabbo studied with his colleagues the deformation behaviour and formability of the AA3003-H111 sheet material depending on the temperature [8-9]. Toros et al. investigated the effects of different material models on the finite element analysis [10]. Kurukuru et al. studied the material models of the AA6016-T4 aluminium alloy under the effect of temperature in forming simulations [11]. Kotkunde et al. compared their model with experimental results by creating different material models of the warm forming of the Ti-6Al-4V alloy [12]. Naka et al. investigasted the effect of temperature on the yield surface of aluminium alloys [13]. Laurent et al. evaluated the amount of the forming force, distribution of sheet thickness and springback by analysing experimentally and numerically the warm deep drawing process of Al-Mg alloys [14]. Huang and Cheng analysed the effects of lubricant and surface roughness in the drawing process [15]. Warm temperatures in the forming process ensure better formability of aluminium alloy sheets. After evaluation of the studies found in the literature, it can be concluded that temperature is an important parameter in the forming of aluminium alloys and that influences of surface roughness have not been adequately analysed. In this study, influences of temperature and surface roughness on the forming of the AA3003-H11 sheet material have been analysed and the influence level of temperature and surface roughness have been determined.

2. Material

The widely used AA3003-H111 aluminum alloy sheet material has been selected for the analysis of the forming process. The chemical composition of this material is given in Table 1.

Table 1 Chemical composition of AA3003-H111 (weight percent) [8]

Material	Mg	Mn	Si	Fe	Ti	Zn	Cu	Ni	Cr	Al
AA3003-H111	0.02	1.10	0.21	0.50	0.02	0.01	0.07	0.005	0.005	Bal

3. Forming Analyses

The influences of temperature and surface roughness on the formability of sheet materials have been investigated by using the finite element method. The forming analyses for the AA3003-H111 aluminium alloy were performed with a hemispherical punch at 25 °C, 93 °C, 177 °C, 260 °C and 0.01 μ, 0.2 μ, 0.4 μ, 0.6 μ punch surface roughness values. For this purpose, the mechanical properties of the AA3003-H111 aluminium alloy sheet material at different temperatures have been obtained from study of Abedrabbo et al. [8]. By using the Hill yield criterion, material cards have been created in order to perform the finite element analysis at a specified temperature and transferred to the analysis software. The mechanical properties of the AA3003-H111 aluminium alloy sheet material used in the finite element analysis are presented in Table 2.

Table 2 Mechanical properties of AA3003-H111 [8]

Temperature (°C)	ε_0	n value	K value	r_0	r_{45}	r_{90}
25	8.30E-04	0.215	199.82	0.827	1.126	0.773
93	6.64E-04	0.179	168.41	1.247	1.690	0.879
177	6.20E-04	0.157	119.65	1.413	1.975	1.007
260	5.05E-04	0.116	77.32	2.035	2.485	1.328

Sheet metal forming analysis software calculate the deformation in the sheet material depending on the yield function, yield stress and the anisotropy value. To this end, researchers worked on different models [8-12]. The preferred criterion is the Hill-48 model yield criterion, which is often used in forming analyses. The Hill-48 yield function is explained in Eq. (1-3) [10].

$$2f(\sigma_{ij}) = F(\sigma_y - \sigma_z)^2 - G(\sigma_z - \sigma_x) - H(\sigma_x - \sigma_y) + 2L\tau_{yz}^2 + 2M\tau_{zx}^2 + 2N\tau_{xy}^2 = 1 \tag{1}$$

where *F*, *G*, *H*, *L*, *M* and *N* are the material constants and x, y and z are the mutual orthogonal axes of orthotropy. The Hill-48 quadratic yield function can also be written as:

$$2f(\sigma_{ij}) = (G+H)\sigma_x^2 - 2H\sigma_x\sigma_y + (H+F)\sigma_y^2 + 2N\tau_{xy}^2 = 1 \tag{2}$$

In Eq. (2), the *F*, *G*, *H* and *N* parameters can also be written in terms of the anisotropy parameters r_0, r_{45}, r_{90}.

$$F = \frac{r_0}{r_{90}(1+r_{90})} \qquad G = \frac{1}{(1+r_0)}$$
$$H = \frac{r_0}{(1+r_0)} \qquad N = \frac{(r_0 + r_{90})(1+2r_{45})}{2r_{90}(1+r_0)} \tag{3}$$

The model parameters are given in Table 3. The forming process was applied by stretching the sheet with a hemispherical punch to determine the formability behavior of the sheet material. The tool model used in the forming analyses is shown in Figure 1. As a result of the forming analyses, the influences of the temperature and the friction coefficient on the forming force and the amount of thinning occurring in the sheet were determined.

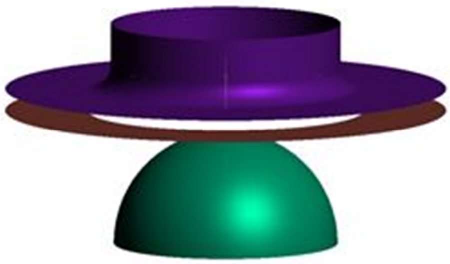

Fig. 1. Tool model

Table 3 Model parameters used in the formability simulation

Mesh Refinement	Initial Element Size	3 mm
	Radius Penetration	0.1 mm
	Max Element Angle	10º
Element Type	Elastic Plastic Shell	
Material Thickness	1 mm	

4. Results and Discussion

4.1 Forming Force

A certain amount of force is required so as to ensure sheet metal materials to change form through plastic deformation. In this study, the influences of the temperature and the punch surface roughness on the forming force were determined. It is known that the forming force decreases after the temperature increases [11,14]. The analysis of the relationship presented in Figure 2 among the forming force, the surface roughness and the temperature has shown that the forming force is substantially reduced as the temperature increases. The reason is that plastic deformation is carried out more easily due to the decrease in yield stress along with the increase in temperature. When the influence of surface roughness on the forming force was evaluated, it was determined that the increase in surface roughness increases the forming force at all temperatures. The increase in surface roughness makes the yielding of the sheet metal harder. Because of that a greater amount of force is required for the forming process to be carried out. It is also found in the studies from the literature that the increase in the surface quality leads to some increase in the forming force [15]. The lowest forming force was obtained at 260 °C at all surface roughness values used in the analyses. While the highest forming force of 22442 N was obtained at 25°C and the surface roughness value was 0.6 μ, the lowest forming force of 10055 N was obtained at 260°C and the surface roughness value was 0.1 μ.

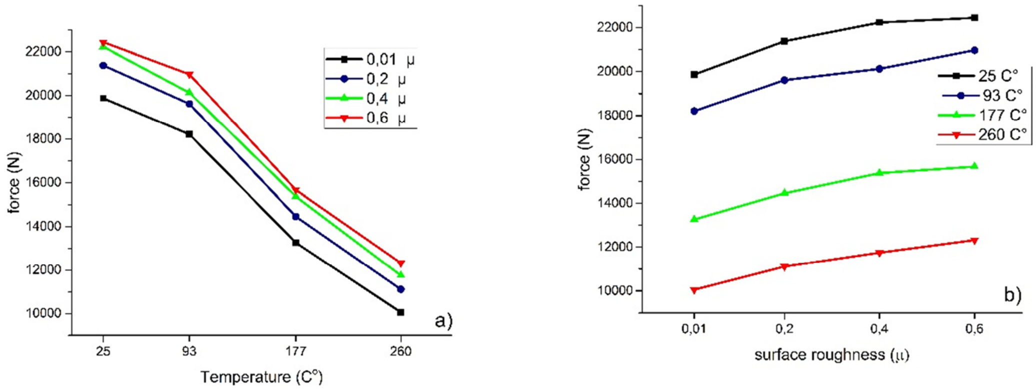

Fig. 2 Temperature-force (a) and surface roughness-force (b) relationships

4.2 Thinning

Thinning in the sheet thickness occurs subsequent to the forming process depending on the deformation in the forming processes of sheet metal materials. The relationship between thinning and temperature and thinning and surface roughness is given in Figure 3. It can be seen that the amount of thinning decreases as the surface roughness increases, while the amount of thinning shows a tendency towards an increase as the deformation temperature increases. This result is in accordance with the study of Laurent et al. [14]. While the highest amount of thinning is determined to be 34.4% at 260°C and the surface roughness value is 0.01 μ, the lowest amount of thinning is determined to be 31.4% at 25°C and the surface roughness value is 0.06 μ.

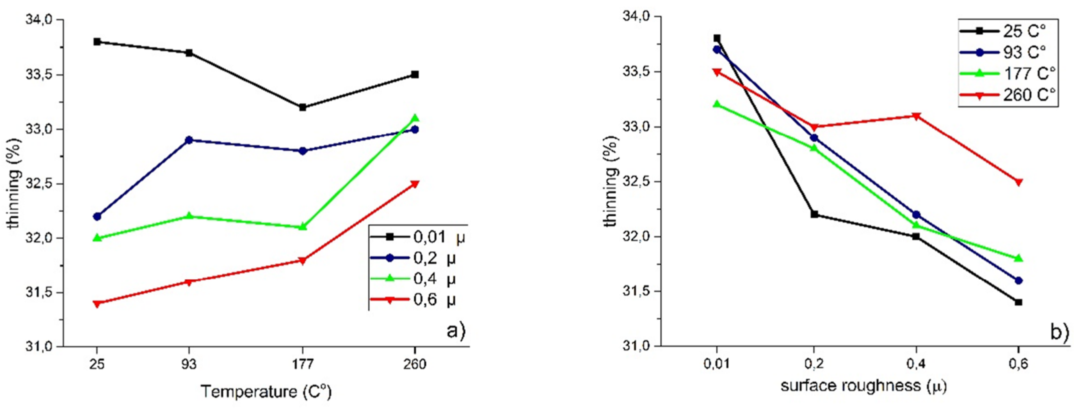

Fig. 3 Temperature-thinning (a) and surface roughness-thinning (b) relationship

4.3 Springback

In the sheet metal forming process, the product geometry must be within the dimensional tolerances. However, dimensional errors due to the springback occurring following the plastic deformation are known to be among the most important problems encountered in the sheet metal forming process [4]. The influence of the surface roughness on the springback in the forming process is presented in Figure 4. A slight increase in the amount of springback occurring in the sheet material was determined as the surface roughness increases from 0.01 μ to 0.4 μ. However, a significant change was not observed in other surface roughness values. It can be seen that the increase in the temperature value reduces substantially the amount of springback. The decrease in yield strength and strain hardening along with the increase in temperature [11] leads to the reduction in the amount of springback occurring after the forming process [14]. While the highest amount of springback is measured at the temperature of 25°C and the surface roughness value of 0.4 and 0.6 μ, the lowest amount of springback is measured at the temperature of 260°C and the surface roughness value of 0.01 μ. Besides, the lowest amount of springback was obtained at the temperature of 260 °C at all surface roughness values.

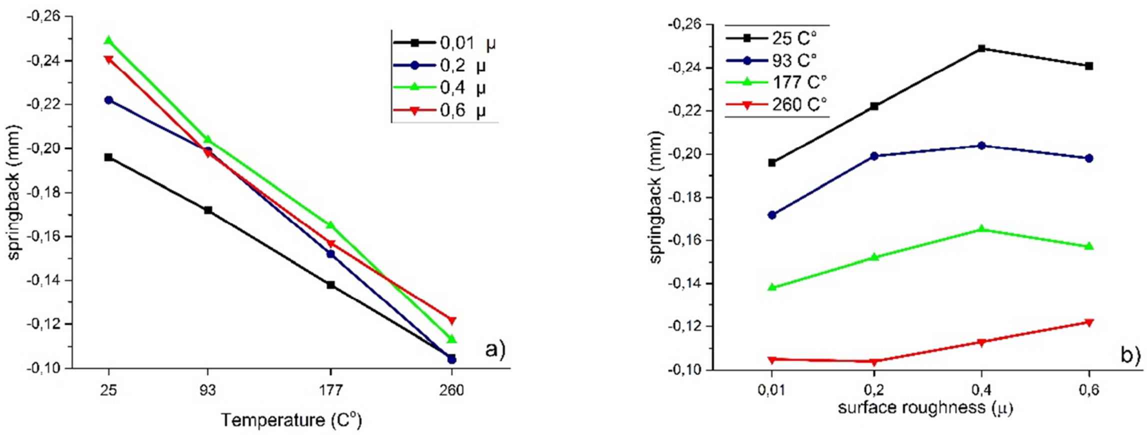

Fig. 4 Temperature-springback (a) and surface roughness-springback (b) relationships

5. Statistical Evaluation

The analysis of variance (ANOVA) and full factorial analyses were performed in order to determine the influence level of the investigated parameters in the scope of the study. The factors are given in Table 4.

Table 4 Factor levels

Factor	Levels			
Temperature (C°)	25	93	177	260
Surface roughness (μ)	0.01	0.2	0.4	0.6

The temperature and surface roughness were found to be significant factors ($P<0.05$) when the ANOVA and full factorial analysis results for temperature, forming force and surface roughness were analysed (Table 5). It has been found that the influence of temperature is 94.7%, of surface roughness 5.2% and of temperature together with surface roughness 0.1%

regarding the forming force. Accordingly, it can be said that temperature is the main factor affecting the forming force.

Table 5 ANOVA and full factorial analysis results for temperature, forming force and surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	P	C
Temperature	3	260454637	260454637	86818212	0.01	94.7%
Surface roughness	3	14257402	14257402	4752467	0.01	5.2%
Temperature*Surface roughness	9	224016	224016	24891	-	0.1%
Error	0	-	-	-	-	-
Toplam	15	263564439	R-Sq = 99.92%			

Temperature and surface roughness are significant factors (P<0.05) regarding the amount of thinning according to ANOVA. Full factorial analysis results for temperature, forming force and surface roughness are given in Table 6.

It is concluded that the influence on thinning of temperature is 31.2%, of surface roughness 56%, and of temperature together with surface roughness 12.8%. Thus, surface roughness is observed to be the main factor affecting thinning.

Table 6 ANOVA and full factorial analysis results for temperature, forming force and thinning

Source	DF	Seq SS	Adj SS	Adj MS	P	C
Temperature	3	3.46250	3.46250	1.15417	0.009	31.2%
Surface roughness	3	6.19250	6.19250	2.06417	0.001	56%
Temperature*Surface roughness	9	1.42250	1.42250	0.15806	-	12.8%
Error	0	-	-	-	-	-
Total	15	11.07750		R-Sq = 87.16%		

Temperature and surface roughness are observed to be significant factors (P<0.05) affecting the springback when ANOVA and full factorial analysis results carried out for the springback are analysed (Table 7). Temperature is determined to be the main factor affecting the springback by the influence of 91.3%. In addition to this case, it can be said that surface roughness does not have significant influence on the springback with its influence of only 6.6%.

Table 7 ANOVA and full factorial analysis results for the temperature, forming force and springback

Source	DF	Seq SS	Adj SS	Adj MS	P	C
Temperature	3	0.0302202	0.0302202	0.0100734	0.004	91.3%
Surface roughness	3	0.0021857	0.0021857	0.0007286	0.001	6.6%
Temperature*Surface roughness	9	0.0006991	0.0006991	0.0000777	-	2.1%
Error	0	-	-	-	-	-
Total	15	0.0331049		R-Sq = 97.89%		

6. Conclusions

The results obtained in this study are summarized as follows:

- As a result of the forming analyses it has been found that the required forming force has largely been reduced because the increase in temperature has reduced the mechanical properties of the material. Surface roughness has also increased the forming force because it made the yielding of sheet hard.
- A slight increase in the amount of thinning occurs as the deformation temperature increases and a reduction in the amount of thinning occurs as surface roughness increases. However, the change takes place over only a very small range.
- The amount of springback occurring in the sheet material following the forming process is significantly reduced as temperature increases and the amount of springback is not significantly affected by the increase in surface roughness.
- The analysis of the influence of the forming parameters showed that temperature highly affects the forming force (influence of 94.7%) and the springback (influence of 91.3%) and that surface roughness has an influence only on the amount of thinning (influence of 56%).

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Onur Çavuşoğlu
Hakan Gürün
Gazi University,
Faculty of Technology,
Department of Manufacturing
Engineering, Ankara - Turkey
onurcavusoglu@gazi.edu.tr,
hgurun@gazi.edu.tr