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ORIGINAL ARTICLE

The formability of annealed and pre-aged AA-2024 sheets in single-point incremental forming

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Abstract The formability of AA-2024 sheets, an aerospace grade material, in the annealed and pre-aged conditions has been investigated in the single-point incremental forming (SPIF) process. The major operating parameters, namely step size, tool radius, and forming speed, of SPIF process were varied over wide ranges, and their effect on the formability was quantified through a response surface method called as central composite rotational design. It was found that the interaction of step size and tool radius is very significant on the formability. Moreover, a variation in the forming speed does not affect the formability of annealed AA-2024 sheet. However, the formability of pre-aged AA-2024 sheet decreases with the increase in the forming speed. Furthermore, the annealed sheet shows higher formability than the pre-aged sheet.

Keywords Incremental forming · Formability · Operating parameters · Response surface · Material state

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1 Introduction

Single-point incremental forming (SPIF) is a novel sheet-metal-forming process in which a steel rod with hemispherical end is employed as a forming tool to deform the sheet (Fig. 1). In this process, the component geometry is determined by a pre-defined tool path as compared to conventional stamping process employing high-cost dies. This characteristic of die-less forming enables the manufacturing of small batches and customized products at relatively lower cost. Owing to this promising feature, SPIF is gaining popularity and is gradually evolving toward industrial applicability [1–4], especially in the automobile and aerospace sectors.

The AA-2024 aluminum alloy is being extensively used in aerospace applications. It is noted for superior strength to weight ratio, good toughness and tear resistance, and adequate resistance to general and stress corrosion effects. Additionally, the alloy is heat treatable and thus provides an opportunity to enhance the mechanical properties of component by artificial aging. Several studies with emphasis on the formability in SPIF have been reported in literature [5–14]. Ham and Jeswiet [14] conducted a Design of Experiments (DoE) to investigate the effect of some process parameters on the formability of AA-3003O sheet. However, no such work for the AA-2024 sheet has been reported in the literature.

Ham and Jeswiet [14] have reported that the step size (p as defined in Fig. 1) does not significantly affect the formability. However, a close scrutiny of their study (Table 3 of [14]) reveals that the maximum step size used in their study was 0.25 m`m. A generalized conclusion about the effect of step size on the formability cannot be drawn on such a narrow range. During the current work, the preliminary experiments with the main forming

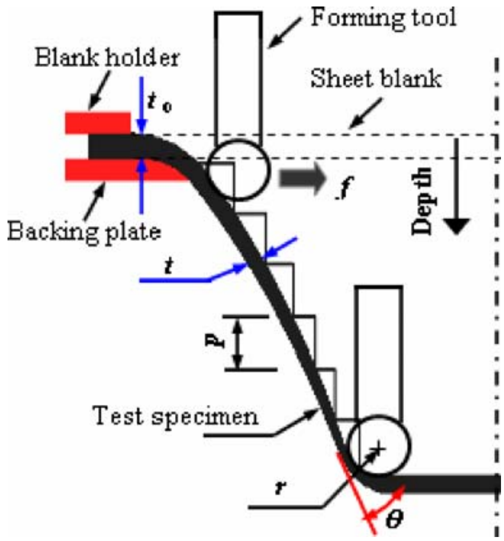


Fig. 1 Schematic and terminology of the SPIF process

parameters (i.e., tool radius, step size, sheet thickness, and forming speed) having various extreme values were carried out to ascertain the validity of the results reported by Ham and Jeswiet [14] for AA2024. During these experiments, it was observed that the results for sheet thickness show almost similar pattern, while the results for other parameters were contradictory. Keeping in view these results, systematic investigations were planned by varying parameters showing contradictory results over wide ranges to clarify their influence on the formability of AA-2024 sheet.

There were two objectives of the current study. The first objective was to investigate the effect of major operating parameters, namely tool radius (r), step size (p), and forming speed (f; see Fig. 1 for definitions), on the formability of AA-2024 sheet in the annealed and pre-aged (T4) conditions. The operating parameters were varied over wider ranges as shown in Table 1.The second objective was to draw a comparison between the formability of annealed and pre-aged conditions of AA-2024 sheet. The maximum wall angle (θ_{max}) without sheet fracturing, as employed by Ham and Jeswiet [14], was used to represent the formability.

2 Formability test

The varying wall angle conical frustum (VWACF) test [6], as compared to the fixed wall angle conical frustum test used in Ham and Jeswiet [14], was employed to evaluate the formability in this study. The former offers an advantage over the latter one in a sense that it significantly reduces the number of attempts required to determine the formability. Figure 2 shows the geometry of VWACF test. The arbitrary wall angle (θ) continuously increases along the depth, thus inducing corresponding wall thinning and leading to sheet fracture (say at point D) whenever the thinning limit of sheet is surpassed. The wall angle corresponding to fracture point is regarded as θ_{max} (please see [6] for further detail).

The geometrical parameters of the VWACF test employed for the current investigations have been shown in tabular form in Fig. 2. The annealed AA-2024 sheet was expected to show high formability. Therefore, the initial and final wall angles (i.e., θ_i and θ_f, respectively) were kept larger, as compared to those set for the pre-aged sheet (i.e., AA-2024T4), in order to reduce the testing time and wastage of material. The initial horizontal curvature radius (ρ_i as defined in Fig. 2) was kept same for each sheet. However, the final horizontal curvature radius (ρ_f), depending on the initial wall angle, underwent variation (see table in Fig. 2). For each case, annealed/pre-aged sheet, the value of ρ_f was kept large enough so as to ensure uni-axial stretching.

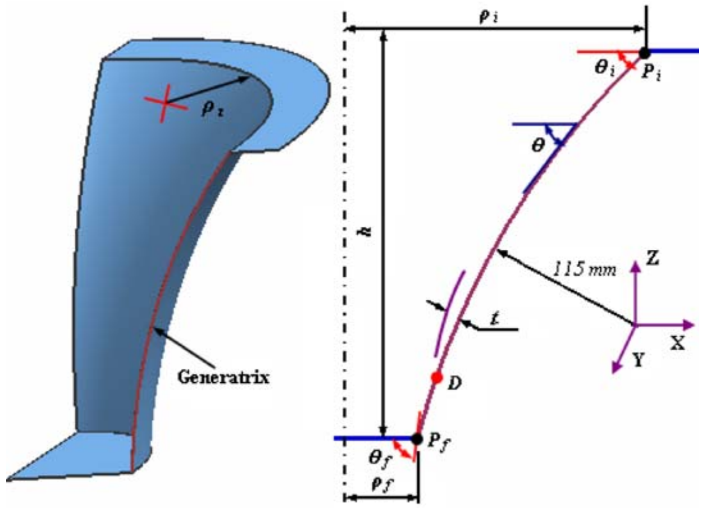
3 Experiments

In order to examine the individual and interactive effects of predictors on a response and to develop an empirical model showing the effect of considered predictors on the response, a DoE approach was adopted. The DoE was based on the central composite rotational design (CCRD) response surface method. The CCRD method is considered superior over the Box–Bhenkon method used in Ham and Jeswiet [14] in a sense that with the former a predictor can be varied over a higher number of levels (i.e., 5) as compared with the latter one (i.e., 3). The experimental design and

Table 1 Operating parameters and respective levels employed in the current study and [14]

	Ham and Jeswiet [14]			Current study		
	Step size [mm]	Tool radius [mm]	Forming speed [mm/min]	Step size [mm]	Tool radius [mm]	Forming speed [mm/min]
Levels	0.05, 0.127, 0.254	4.76, 12.7	1,270, 2,540	0.08, 0.36, 0.78, 1.2, 1.48	3, 4, 5.5, 7, 8	373, 1,200, 2,437, 3,674, 4,500

Test geometry



Geometrical details of the test

Annealed sheet					Pre-aged sheet				
ρ_i [mm]	ρ_f [mm]	θ_i [degree]	θ_f [degree]	h [mm]	ρ_i [mm]	ρ_f [mm]	θ_i [degree]	θ_f [degree]	h [mm]
160	70	45	85	78	160	123	30	55	33.8

Fig. 2 Geometrical details of the varying wall angle conical frustum test

Table 2 Test plan for the annealed AA-2024 sheet prepared following the CCRD response surface method

Run	r[a]	f[b]	p[c]
1	4	3,674	1.2
2	5.5	2,437	0.78
3	7	1,200	0.36
4	5.5	4,500	0.78
5	5.5	373	0.78
6	5.5	2,437	1.48
7	5.5	373	0.78
8	7	1,200	1.2
9	4	1,200	1.2
10	8	2,437	0.78
11	5.5	4,500	0.78
12	5.5	2,437	0.08
13	5.5	2,437	0.78
14	7	3,674	1.2
15	8	2,437	0.78
16	3	2,437	0.78
17	4	1,200	0.36
18	7	3,674	0.36
19	4	3,674	0.36
20	3	2,437	0.78
21	5.5	2,437	0.08
22	5.5	2,437	1.48

[a] Tool radius
[b] Forming speed
[c] Step size

statistical analyses were done using a commercial computing package named as Design Expert Dx-7. The minimum and maximum levels of each of the three selected predictors, namely tool radius, step size, and forming speed, were set as an input to the software. The software varied each predictor over five levels and prepared a set of 22 experiments with two points at the center (Table 2). The maximum wall angle was used as the response of DoE.

The experimental plan shown in Table 2 is intended for the annealed material only. The experiments with the pre-aged material were performed only for studying the effect of forming speed on the formability and to draw a comparison between the formability of the annealed and pre-aged materials. The parameter settings for the former task have been shown in Table 3. For the latter task, the same forming parameters, as shown in Table 3, with constant forming speed of 2200 mm/min were employed.

Table 3 Levels of forming speed and other forming parameters employed for the SPIF of pre-aged AA-2024 sheet

Parameter	Value
Forming speed [mm/min]	600, 1,000, 2,100, 4,500
Step size [mm]	0.36
Tool radius [mm]	4
Sheet thickness [mm]	1

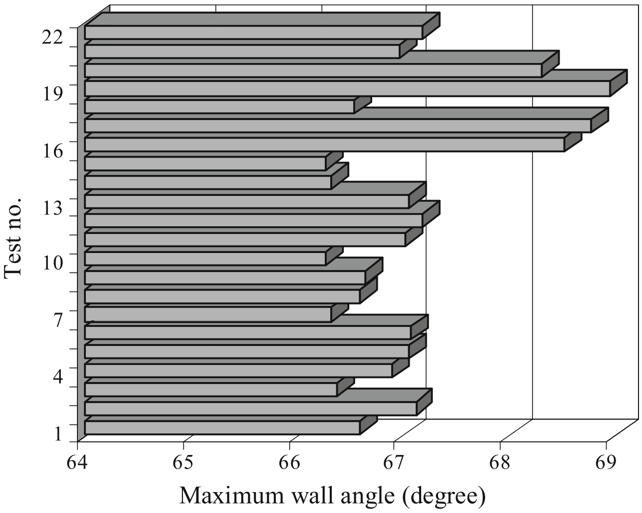


Fig. 3 The formability results for annealed AA-2024 sheet obtained from 22 tests

4 Results and discussion

4.1 Effect of operating parameters on the formability of AA-2024 sheet

For annealed sheet, Fig. 3 shows the test results obtained from 22 tests performed by varying three operating parameters, i.e., r, p, and f. Regression analysis, using Design Expert Dx-7, was performed on these results. In the first step, the software suggested a two-factor interaction (2-FI) model as the best-suited model fitting the current data. Using this fit model, an analysis of variance (ANOVA) was carried out. The summary of this analysis is presented in Table 4. It can be observed from the table that the step size, tool radius, and their interaction are significant model terms. This finding is in contrast to Ham and Jeswiet [14] who reported that the step size is not significant for the SPIF of AA-3003O sheet. It is to be noticed from the table that the interaction of tool radius and step size (i.e., $r \times p$) is more significant than their individual effect. The hierarchy, based on P value, of different parameters with respect to their significance can be given as follows: $r \times p > r > p$.

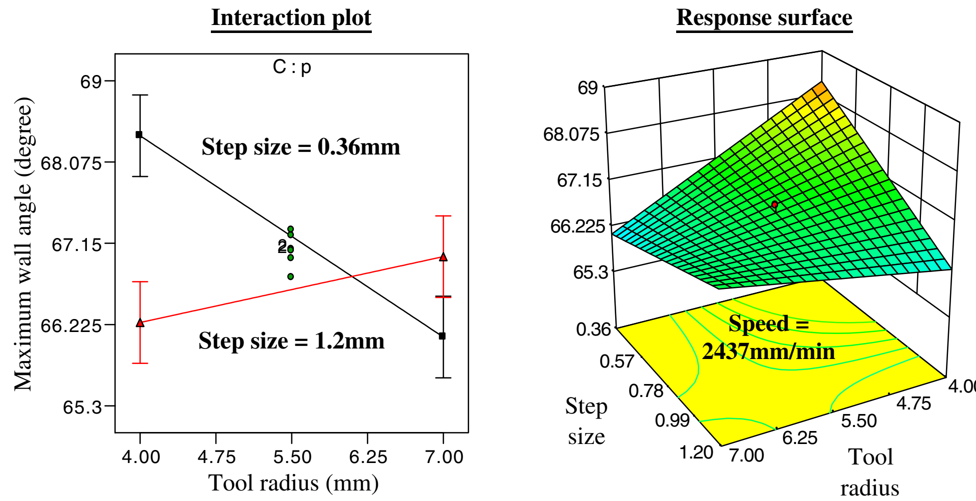
The effect of interaction of step size and tool radius on the formability of annealed AA-2024 sheet is shown in Fig. 4. At a small step size (0.36 mm), the formability decreases with an increase in the tool radius. Whereas at a large step size (1.2 mm), the formability, contrary to [12] and [13], increases with an increase in the tool radius. This reveals that the use of a large tool radius with a small step size or the use of a small radius with a large step size is unfavorable for the SPIF of annealed AA-2024 sheet. As an example, the value of maximum wall angle for tool radius= 7 mm and step size= 1.2 mm (at the right hand side of graph) is about 2% higher than that for tool radius= 7 mm and step size=0.36 mm. This seems to be coherent, for at a small step size the forming tool repeatedly deforms the same zone of sheet; this hardens the sheet which in turn can cause premature failure. Conversely, when the process is performed with a large step size and a small tool radius, excessive stresses may induce in the sheet, thus causing an early fracture and resulting in reduced formability. Therefore, in order to maximize the formability, the step size should be selected keeping in view the tool radius employed. The same fact about the interaction of step size and tool radius can be seen more clearly from the 3D response surface where the reader can find formability results for a variety of combinations of tool and step size.

The forming speed directly affects the productivity of the process. This parameter, contrary to pure titanium [13] and AA-3003O [14], does not significantly affect the formability of annealed AA-2024 sheet (Table 4). This means that the process productivity, without affecting the formability, can be enhanced by performing the process at high speeds when making components from the annealed AA-2024 sheets. However, this is not applicable to the pre-aged

Table 4 ANOVA for response surface 2-FI model

Source	Sum of squares	Degree of freedom	Mean squares	F value	P value Prob>F	Significance
Model	9.664715	6	1.610786	4.664952	0.0072	yes
r	2.843163	1	2.843163	8.234005	0.0117	yes
f	0.116028	1	0.116028	0.336027	0.5707	no
p	1.753612	1	1.753612	5.078587	0.0396	yes
$r \times f$	0.158648	1	0.158648	0.459456	0.5082	no
$r \times p$	4.623984	1	4.623984	13.39139	0.0023	yes
$f \times p$	0.16928	1	0.16928	0.490246	0.4945	no
Residual	5.179429	15	0.345295			no
Lack of fit	2.912721	8	0.36409	1.124375	0.4451	no
Pure error	2.266708	7	0.323815			
Cor total	14.84414	21				

Fig. 4 Effect of significant parameters and interaction on the formability of annealed AA-2024 sheet



sheets. The formability of pre-aged sheet reduces (about 4%) as the speed increases (see Fig. 5). It means that the forming speed is influenced by the type of treatment (annealed/pre-aged) of sheet.

The relationship between the formability of annealed AA-2024 sheet and the operating parameters can be established as follows:

$$\theta_{\max} = 73.44 - 1.01r + 0.0003f - 8.04p - 0.00008rf + 1.2rp + 0.0003fp$$

The R^2 (multiple correlation coefficient) for the above model is 75%, the R^2-adjusted is 70%, and the R^2-predicted is 65%. These correlation values show that the data is well fitted to the model. However, the fitness of model was further examined by analyzing the normal distribution[1] of residuals. The residuals followed a normal distribution (Fig. 6). This confirmed that the model is correct and can be effectively used to navigate the design space. The proposed model can be helpful to predict the formability of annealed AA-2024 sheet in the investigated range of parameters.

Keeping in view the process constraints, the optimal values of operating parameters can be found to maximize the formability. An example is presented here to demonstrate the application. The objective is to maximize the formability and minimize the forming time simultaneously. Numerical optimization, utilizing Derringer–Suich multi-

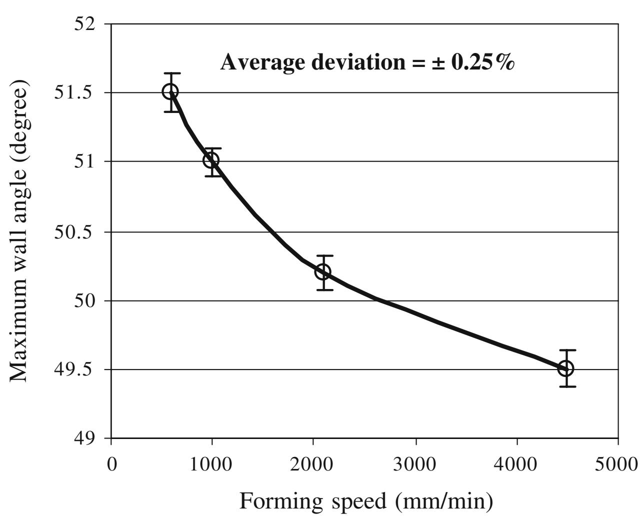


Fig. 5 Effect of forming speed on the formability of pre-aged AA-2024 sheet

[1] The normal distribution is one of the measures used to check the effectiveness of an empirical model.

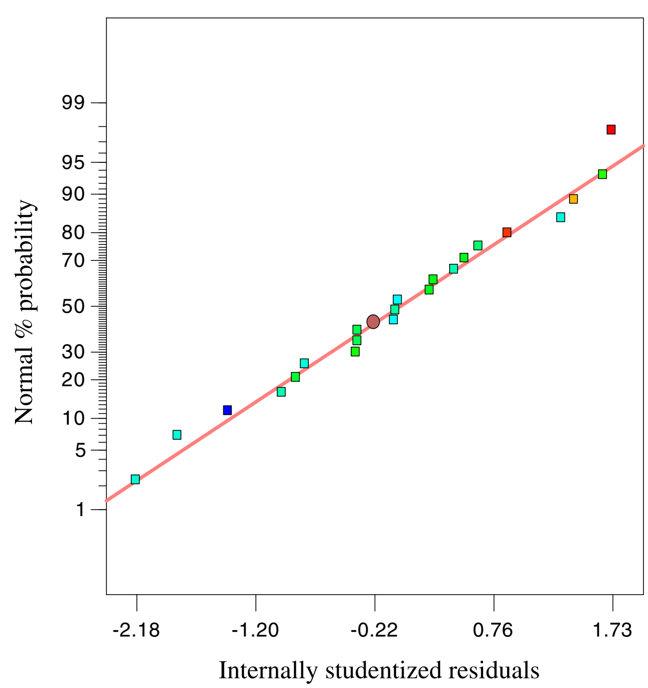


Fig. 6 Normal distribution of residuals

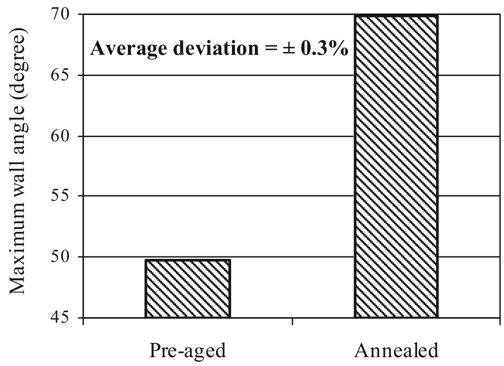


Fig. 7 Comparison between the formability of annealed and pre-aged AA-2024 sheets

criterion decision making algorithm [15], was applied on the experimental results. The optimization criteria used was as follows: r = in range, p = in range, f = maximize, and θ_{max} = maximize. The following solution after undergoing several iterations was recommended by the Dx-7 software: r=4 mm, p=0.36 mm, and f=4,500 mm/min. This combination of the process parameters is believed to provide 69° θ_{max} provided that the other forming conditions remain unchanged.

4.2 Comparison between the formability of annealed and pre-aged AA-2024 sheets

Figure 7 presents a comparison between the formability of annealed (AA-2024O) and pre-aged AA-2024 sheets. It can be seen from the figure that the formability of the pre-aged sheet is about 28% smaller than the formability of the annealed sheet. This may be attributed to decrease in the hardening exponent (annealed=0.24, aged=0.17) and increase in the yield strength (annealed=80 MPa, aged=296 MPa) of material after aging.

The high residual stresses in pre-aged sheet can cause distortion after the formed component is unclamped. However, no such distortion was observed when the test specimens of aged sheet were unclamped. It means that SPIF is capable of manufacturing parts from the high strength/hardened pre-aged sheets with an acceptable quality.

5 Conclusions

In the current work, the formability of an aerospace grade aluminum alloy (AA-2024) sheet in SPIF process under annealed and pre-aged conditions has been investigated using the response surface methodology. The following conclusions can be drawn from the study:

1. The effect of step size and its interaction with the tool radius are found to be very significant on the formability. The formability, depending on the tool radius selected, can either increase or decrease with an increase in the step size. Therefore, the combination of these two parameters should be chosen rationally so as to enhance the sheet formability. In this regard, 3D response surface presented in this paper can be helpful.
2. A variation in the forming speed, in contrast to pure titanium [13] and AA-3003O [14], does not influence the formability of annealed AA-2024 sheet. Therefore, the process productivity while manufacturing components from the annealed AA-2024 sheet can be enhanced without affecting its formability. However, the formability of pre-aged AA-2024 sheet decreases with an increase in the forming speed.
3. The pre-aged AA-2024 sheet shows lower (28%) formability than the annealed AA-2024 sheet.
4. An empirical model describing the effect of operating parameters on the formability of annealed AA-2024 sheet was developed. This model, in the investigated range of parameters, can be employed to predict the formability without conducting test.

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