

ORIGINAL RESEARCH PAPER

An Experimental and Numerical Investigation of Deformation Mechanics on Hole-Flanging Process of AA6061-T6 Sheets through Single-Point Incremental Forming

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Article info

Article history:

Received 17 May 2021

Received in revised form

05 July 2021

Accepted 11 August 2021

Keywords:

Single Point Incremental Forming (SPIF)

Hole-flanging

Deformation mechanics

Stress and strain state

FE simulation

Abstract

Incremental forming process, as one of the methods used for forming complex parts in rapid prototyping, has various applications in the automotive and aerospace industries. The incremental forming process can be used to flange a metal sheet that, compared to conventional flanging, not only increases the formability but also does not require expensive dedicated dies. The deformation and damage mechanisms in the incremental forming process are completely different from conventional forming processes and need exact and thorough investigation. The present study is aimed at evaluating the damage and deformation mechanics in the hole-flanging process by single-stage and multistage incremental forming on AA6061-T6 sheets, considering several parameters affecting damage and fracture, including equivalent plastic strain, stress triaxiality, and lode angle parameter. These important parameters can reveal the stress and strain states as well as the deformation mechanism, which have been less addressed in the hole-flanging by incremental forming. The results indicated that the stress and strain states varied in different regions of the flange wall, such that the strain state was as plane strain at the bottom of the wall in contact with the unformed part of the sheet, biaxial tensile state at the middle of the wall, and uniaxial tensile state at the top of the wall on flange edge. The highest damage was observed at the flange edges, and the fracture occurred at low values of stress triaxiality in this area, indicating the shear fracture in the hole-flanging of AA6061-T6 sheets during the incremental forming. Finally, a slight increase was observed in the forming limit by forming with a multistage strategy instead of the single-stage one, although the equivalent plastic strain increased significantly.

Nomenclature

F, G, H, L, M and N	Hill 1948 yield parameters	HER	Hole expansion ratio
HER_{max}	Maximum hole expansion ratio	HF	Hole flanging
I_1	First stress invariant (MPa)	IF	Incremental forming

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<http://dx.doi.org/10.22084/jrstan.2020.21422.1142>

ISSN: 2588-2597

<i>IHF</i>	Incremental hole flanging	J_2	Second deviatoric stress invariant (MPa ²)
J_3	Third deviatoric stress invariant (MPa ³)	k	Strength coefficient (MPa)
<i>LFR</i>	Limiting forming ratio	n	Strain hardening exponent
LFR_{max}	Maximum Limiting forming ratio	Q	Parameter of hardening behavior
<i>NLAP</i>	Normalized lode angle parameter	$s_{1,2,3}$	Deviatoric stresses (MPa)
SPIF	Single point incremental forming	ε_0	Pre-strain
$\bar{\varepsilon}_p$	Equivalent plastic strain	$\bar{\varepsilon}_u$	Ultimate equivalent plastic strain
η	Stress triaxiality	η_{ave}	Average stress triaxiality
θ	Normalized lode angle parameter	$\bar{\theta}_{ave}$	Average normalized lode angle parameter
$\sigma_{1,2,3}$	Principal stresses (MPa)	σ_m	Mean (hydrostatic) stress (MPa)
$\bar{\sigma}_{von}$	Von Mises equivalent stress (MPa)	$\bar{\sigma}_{UTS}$	Ultimate tensile stress (MPa)

1. Introduction

Incremental Forming (IF) process is a flexible forming process for locally and gradually forming of parts with various shapes, without needing to the dedicated dies. The Single-Point Incremental Forming (SPIF) is a type of IF in which the forming tool has contact with the part just in a single point. In this process, a blank is formed into the desired shape by a hemispherical tool moving in a predefined path on a CNC machine. In recent years, several research works have been conducted on SPIF, due to the increased formability in this process compared to that of the conventional processes such as deep drawing [1-4].

The Hole-Flanging (HF) process is a sheet metal forming process in which a sheet with an initial (pre-cut) hole is flanged by a punch as the forming tool. This is known as the conventional hole-flanging technique. The parts produced in this process have various industrial applications such as providing additional support for joining sheet parts to tubes and strengthening the edges of holes [5]. Recently, IF process has been used to form flanges; so-called incremental Hole-Flanging (IHF), as shown in Fig. 1.

In recent years, the IHF process has highly been addressed by researchers, because of its advantages over the conventional HF. Centeno et al. [6] examined the IHF process on AA1050-H111 sheets and studied changes in the pre-cut hole diameter. Based on their results, increasing the hole diameter changes the deformation state relative to the conventional incremental forming without pre-cut hole. By utilizing a circle grid analysis, Montanari et al. [7] obtained a history of stress and strain in the flanging process by SPIF. They indicated that the flange walls experienced the plane strain condition while the flange edges were under the equal biaxial tensile state. Silva et al. [8] compared IHF and conventional HF of AA1050-H111 and Titanium (grade 2) sheets. They observed that the Limiting Forming Ratio (LFR) of Titanium sheets in conventional HF was higher than that in IHF, which was contrary to what is often stated in the literature on the advantages of IF over conventional sheet metal forming processes. By applying single-stage incremen-

tal forming, Borrego et al. [9] experimentally studied the hole-flanging of AA 7075-O sheets and showed that the biaxial tensile around the middle of the flange was the dominant failure mechanism in the IHF process. Cao et al. [10] investigated the IHF process with a new tool and stated that the new tool allowed producing a part with a more uniform thickness than that of conventional ball-nose tools. Moreover, this new approach reduced the sheet thinning and increased the formability.

It is worth noting that achieving maximum formability in the flanging process requires accurate recognition of the deformation and failure mechanisms and the corresponding effective parameters of the process. With this regard, little research has been conducted. Cristino et al. [11] experimentally examined the fracture in the flanging process with SPIF. By combining circle grid analysis and plasticity theory using the stress and strain histories, they calculated critical values of ductile damage and fracture toughness based on the Ayada and Rice-Tracey ductile fracture criteria in the IHF process of AA 1050-H111 sheets. According to their findings, the highest damage occurred in the middle points of the flange wall. Martínez-Donaire et al. [12] analyzed the effect of stress triaxiality as one of the factors affecting the fracture in the IHF process. Gandla et al. [13] investigated the effect of pre-cut hole diameter on the mechanics of multi-stage IHF process. They predicted the formability of deep drawing quality steel in IHF through the Fracture Forming Limit Diagram (FFLD) determined from the experiment and six different ductile damage models.

The deterioration of materials is described by an internal variable called damage. Ductile fracture occurs in materials when the internal damage reaches a critical value or the damage is accumulated in the material due to plastic deformation. The damage accumulation occurs in three stages including the void nucleation due to the separation between interfaces of the main material and impurities or secondary phase particles, the void growth, and ultimately the coalescence of voids. Therefore, the ductile fracture can be considered as the result of three events; damage accumulation, fracture initiation, and crack propagation. To predict the

initiation and propagation of the fracture, damage and fracture criteria can be used. These criteria can be classified into three groups of micromechanical, continuum damage mechanics, and phenomenological models [14, 15].

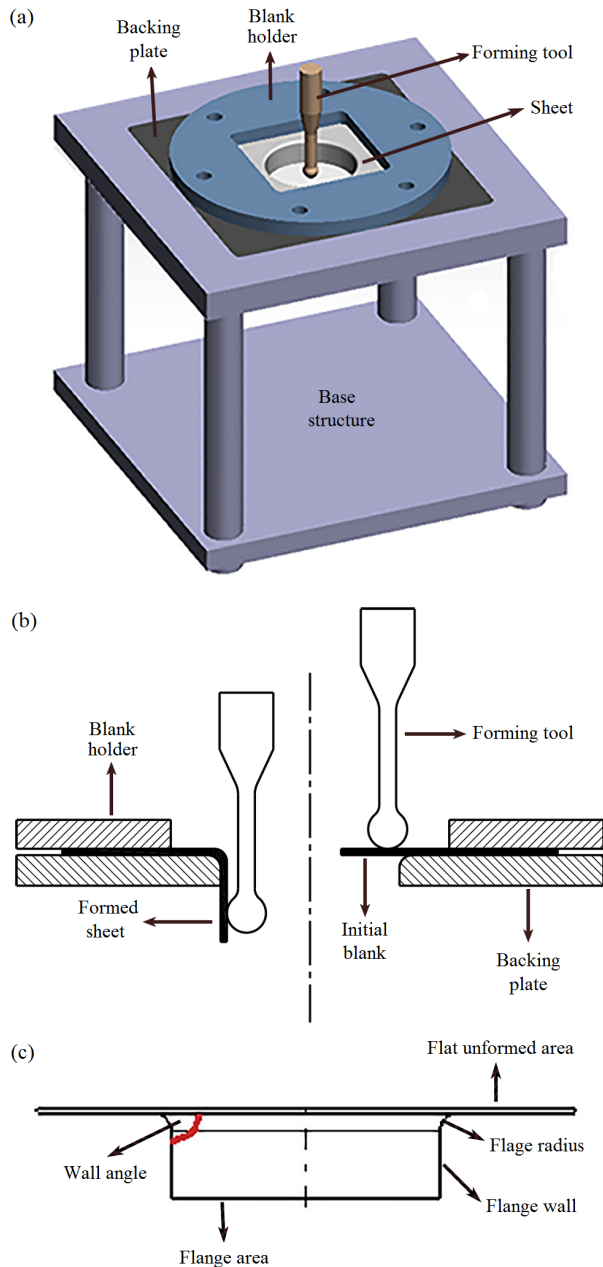


Fig. 1. Schematic of IHF process, a) Die set, b) Sheet and forming tool before and after deformation, c) Formed flange.

A comprehensive investigation of all the effective parameters on damage in the forming processes is difficult by performing experiments. In doing such a study, the finite element simulation is known as the most appropriate way, although this approach has its complexities. Due to the lack of detailed investigation of damage in the IHF process and the differences be-

tween this process and SPIF of parts without a pre-cut hole, this study focuses on a comprehensive analysis of stress and strain states as effective parameters on the damage. Therefore, the present study seeks to thoroughly examine the deformation mechanisms of AA 6061-T6 sheets in the flanging process by SPIF. For this purpose, in addition to evaluating the stress and strain states in the process, the stress triaxiality and lode angle parameters, which are of great importance in the fracture study, are investigated using the FE simulation. Analyzing these parameters can open new insights about damage and deformation mechanisms that have not been assessed in the literature. By carrying out a comprehensive analysis of strain and stress variations, the damage mechanism in the HF process by the single, and multistage incremental forming are explained. Finally, the effects of tool diameter on the IHF are evaluated.

2. Stress State

The stress triaxiality (η) and the normalized lode angle ($\bar{\theta}$) parameters are two important and effective parameters in the damage and ductile fracture of materials, which can be used to express the stress state [16, 17]. The ductile fracture may eventually occurs by the two mechanisms of: 1) the growth and accumulation of voids caused by internal necking of ligament between the voids, which happens at medium to high values of the stress triaxiality, and 2) the shear failure that occurs at low stress triaxiality [18-20]. The stress triaxiality parameter, which controls the growth of microvoids in ductile fracture, is not enough to interpret the fracture, especially at low levels of stress triaxiality. Consequently, another parameter is required to fully express the stress and fracture state, which is the lode angle according to references [20-22]. Regarding the studies conducted by Mirnia and Shamsari [14] and Martínez-Donaire et al. [12], it was shown that the stress triaxiality in incremental forming process varied in the range -0.66 to 0.66 , which included the low to high ranges of stress triaxiality. Moreover, Emmens and van den Boogaard [23], and Maqbool and Bambach [24] showed that shear was one of the main deformation mechanisms in the incremental forming process. Therefore, it is necessary to evaluate both the parameters of stress triaxiality and lode angle to explain the damage and fracture in the IHF process.

Considering the stress invariants I_1 , J_2 , and J_3 , which represent the first stress invariant, second deviatoric stress invariant, and third deviatoric stress invariant, respectively, the stress triaxiality and the Normalized Lode Angle Parameter (NLAP) are defined as follows [25].

$$\eta = \frac{\sigma_m}{\bar{\sigma}_{von}} \quad (1)$$

$$\bar{\theta} = 1 - \frac{2}{\pi} \arccos \left[\frac{3\sqrt{3}}{2} \frac{J_3}{J_2^{(3/2)}} \right] \quad (2)$$

$$\sigma_m = \frac{I_1}{3} \quad (3)$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \quad (4)$$

$$\bar{\sigma}_{\text{von}} = \sqrt{3J_2} \quad (5)$$

$$J_2 = \frac{1}{2}(s_1^2 + s_2^2 + s_3^2) \\ = \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \quad (6)$$

$$J_3 = s_1 s_2 s_3 = \frac{1}{27}(2\sigma_1 - \sigma_2 - \sigma_3)(2\sigma_2 - \sigma_3 - \sigma_1) \\ (2\sigma_3 - \sigma_1 - \sigma_2) \quad (7)$$

where $\sigma_{1,2,3}$, σ_m , and $\bar{\sigma}_{\text{von}}$ are the major principal stresses, mean (hydrostatic) stress, and the Von Mises equivalent stress, respectively. Furthermore, $s_{1,2,3}$ shows deviatoric stresses, which is defined as $s_i = \sigma_i - \sigma_m$. By assuming plane stress condition, the parameters η and $\bar{\theta}$ are related to each other through the following relation [25].

$$\bar{\theta} = 1 - \frac{2}{\pi} \arccos \left[-\frac{27}{2} \eta \left(\eta^2 - \frac{1}{3} \right) \right] \quad (8)$$

Under proportional loading conditions, the values of η and $\bar{\theta}$ are constant, while their values vary during the deformation process under non-proportional loading conditions. In this case, the average values of η and $\bar{\theta}$ are calculated as follows:

$$\eta_{ave} = \frac{1}{\bar{\varepsilon}_u} \int_0^{\bar{\varepsilon}_u} \eta(\bar{\varepsilon}_p) d\bar{\varepsilon}_p \quad (9)$$

$$\theta_{ave} = \frac{1}{\bar{\varepsilon}_u} \int_0^{\bar{\varepsilon}_u} \bar{\theta}(\bar{\varepsilon}_p) d\bar{\varepsilon}_p \quad (10)$$

in which $\bar{\varepsilon}_p$ and $\bar{\varepsilon}_u$ are the equivalent plastic strain and the ultimate equivalent plastic strain, respectively.

3. Experimental Tests

3.1. Materials and the Mechanical Properties

In this research, AA 6061-T6 sheets with a thickness of 1mm and in plane dimensions of 100mm×100mm were used to perform IHF tests. Mechanical properties and anisotropy coefficients of the sheets were obtained by uniaxial tensile tests according to ASTM E8-M in three directions of 0°, 45°, and 90° relative to the rolling direction as presented in Table 1. A 50mm gauge length extensometer was used to measure the exact displacement of the specimens.

Considering the local necking phenomenon in the uniaxial tensile test, the plastic behavior of material is uniform up to the necking strain, although after necking it is not possible to use the true stress-strain curve obtained from the uniaxial tensile test without appropriate correction factors. On the other hand, in the incremental forming process, the strain applied to the sheet is significantly higher than the necking strain in the uniaxial tensile test [14]. Consequently, it is necessary to extrapolate the true stress-strain curve using an appropriate hardening rule to model the plastic behavior of material after necking. In this study, the plastic behavior was first modeled using the Swift hardening law, and then the uniaxial tensile test was simulated to validate the plastic behavior. Fig. 2 depicts the force-displacement curve of the uniaxial tensile test in the rolling direction of the material in two cases of experimental-based and simulated by Swift hardening law. The predicted curve corresponds to the experimental curve up to the maximum force, but after that the curve obtained by the Swift hardening law is higher than the experimental curve.

To reduce the difference between experimental and simulation curves after necking, the Swift hardening law is used to model the plastic behavior of material up to the necking strain, and after the necking strain, it is described by the linear combination of Swift equation and no hardening behavior, as expressed by Eq. (11) [14, 26].

$$\bar{\sigma} = \begin{cases} k(\bar{\varepsilon}^p + \varepsilon_0)^n & \bar{\varepsilon}^p \leq \bar{\varepsilon}^p_{necking} \\ Q[k(\bar{\varepsilon}^p + \varepsilon_0)^n] + (1 - Q)[\bar{\sigma}_{UTS}] & \bar{\varepsilon}^p > \bar{\varepsilon}^p_{necking} \end{cases} \quad (11)$$

Table 1

Mechanical properties of AA6061-T6 sheet along with the rolling direction with anisotropy (Lankford) coefficients.

Modulus of elasticity E (GPa)	Yield strength YS (MPa)	Ultimate tensile strength (MPa)	Poisson's ratio ν	Elongation (%)	Lankford coefficients r			
					r_0	r_{45}	r_{90}	$\bar{r}$
70.41	302.45	356.47	0.34	11.7	0.68	0.78	0.83	0.77

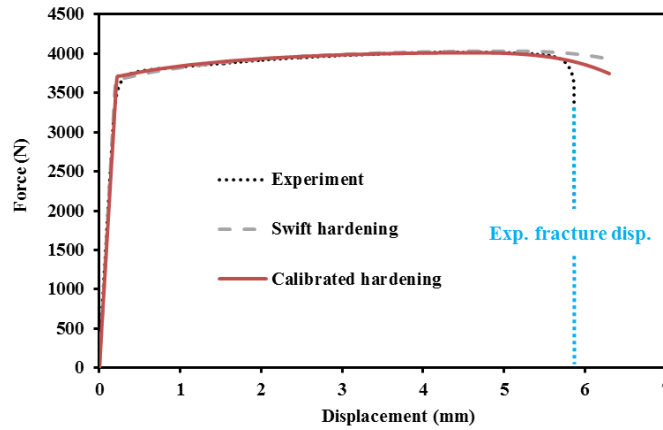


Fig. 2. Force-displacement curve obtained by experimental test and finite element simulation.

Table 2

Parameters of material hardening law based on Eq. (11).

k (MPa)	ε_0	n	$\bar{\varepsilon}_{necking}^p$	$\bar{\sigma}_{UTS}$ (MPa)	Q
461.7	0.029	0.12	0.0832	355.07	0.98

Where k , ε_0 , and n are the parameters of the Swift equation and represent the strength coefficient, pre-strain, and strain hardening exponent, respectively. Table 2 reports the values of these parameters, which are obtained through fitting the Swift relation to the true plastic stress-strain curve until necking strain $\bar{\varepsilon}_{necking}^p$ using the MATLAB curve fitting tool. The parameter $\bar{\sigma}_{UTS}$ shows the ultimate tensile stress at the necking strain. Ultimately, the parameter Q was obtained through a reverse method along with iterative simulations, by minimizing the difference between the experimental and simulated force-displacement curves of the uniaxial tensile test in the rolling direction after the necking (Fig. 2).

3.2. IHF Process

Experimental IHF tests were performed on a three-axis CNC milling machine. Fig. 3a provides the die set used in the tests. Semispherical tools with diameters of 6, 8, and 10mm were used to conduct the tests. As shown in Fig. 3b, pre-cut holes with different diameters D_0 were created on the specimens using a wire-cut machine. The final diameter (D_f) of the produced flange was 60mm, as illustrated in Fig. 3c. The path of the tool movement was extracted as a spiral way by PowerMILL software, as shown in Fig. 3d. In this research, both the single-stage and multistage strategies were used. By considering an angular multistage strategy, the flange was first formed at the wall angle of 50° , and in the next stages, the wall angle increased proportionally to the number of stages to reach the flange angle of 90° . The vertical step of the tool movement was 0.5mm and the feed rate was set to 1000mm/min

without the rotational speed. H68 Behran hydraulic oil was used during the forming process to reduce friction between the sheet surfaces and the forming tool.

4. Finite Element (FE) Simulation

In this research, the IHF process was simulated by using the commercial FE code Abaqus/Explicit 6.14. The sheet was discretized by shell elements S4R with five Gaussian integration points through the thickness. The backing plate and forming tool were modeled as discrete rigid element R3D4 and analytical rigid surface, respectively. Instead of modeling the blank holder, the periphery edge of the sheet was fully constrained. Fig. 4 shows the FE model of the IHF process. It should be noted that the element size of the sheet was considered 0.5mm in the forming area and 1mm in the other areas.

The Coulomb friction law with a friction coefficient of 0.1 was used to define the contact between the sheets and the forming tools in accordance with Ref. [18]. The tool path was extracted as boundary conditions based on G-codes obtained from the PowerMILL software using a code scripted in Matlab and then applied to the forming tool. To reduce the simulation time, a time scaling scheme was used so that the ratio of the kinetic energy to the internal energy was less than 1%. To evaluate the stress state in the IHF process, the parameters η and $\bar{\theta}$ were introduced to the simulation software using the VUSDFLD subroutine according to Eqs. (1) and (2).

Based on Tables 1 and 2, the plastic behavior of the material was considered as anisotropic and defined according to the Hill 1948 yield criterion as follows [27]:

$$f(\sigma) = \sqrt{F(\sigma_{yy} - \sigma_{zz})^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H(\sigma_{xx} - \sigma_{yy})^2 + 2L\sigma_{yz}^2 + 2M\sigma_{yx}^2 + 2N\sigma_{xy}^2} = 1 \quad (12)$$

where, σ_{ij} represents the stress components, and F, G, H, L, M , and N are the yield parameters, which were obtained based on the relations reported by Bagherzade et al. [28] and the anisotropy coefficients presented in Table 1, in accordance with Table 3.

5. Results and Discussion

5.1. Results of Experimental Tests

In this study, three semispherical forming tools with diameters of 6, 8, and 10mm were used to conduct the experimental tests of the IHF process. First, the maximum forming limit that can be obtained for each

tool was evaluated. In the IHF process, the forming limit is known by the hole expansion ratio (HER), which is equal to the ratio of the final flange diameter (D_f) (Fig. 3c) to the pre-cut hole diameter (D_o) (Fig. 3b). Table 4 provides the maximum hole expansion ratio (HER_{max}) in the single-stage strategy for the three tools. The maximum and minimum values for (HER_{max}) are 1.39 and 1.30, which belong to the tool diameters of 6 and 10mm, respectively. It can be concluded that an increase in the tool diameter in the IHF process can increase the smallest pre-cut hole that can be formed in the sheet without fracture, resulting in decrease of formability.

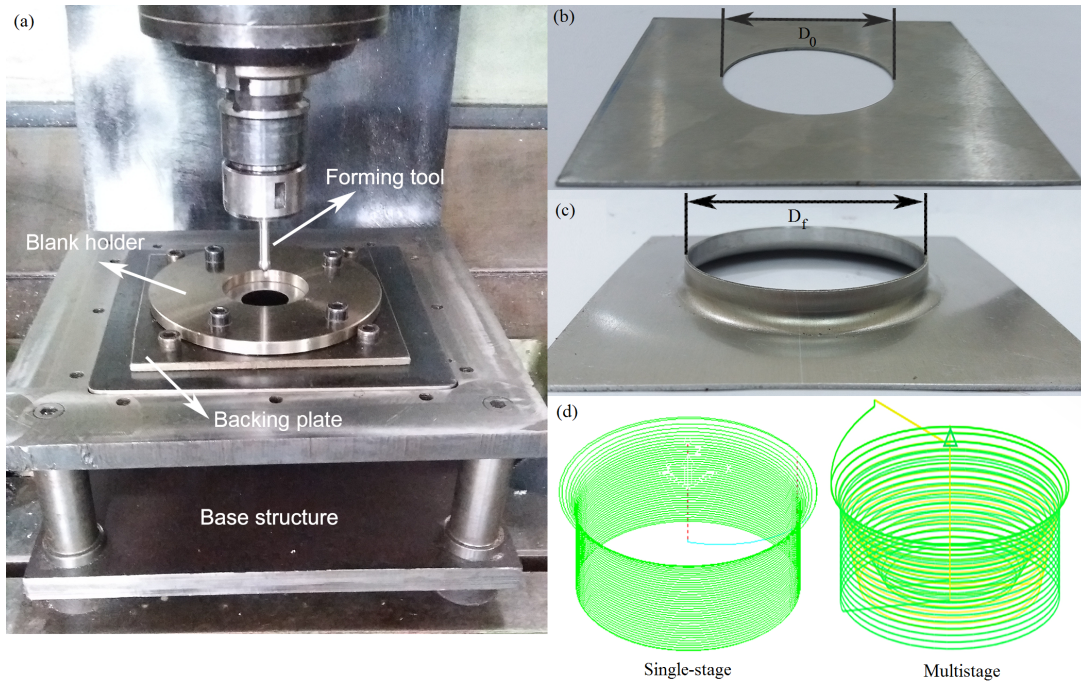


Fig. 3. a) Experimental die set, b) Initial blank, c) Formed flange, and d) Movement path of the forming tool.

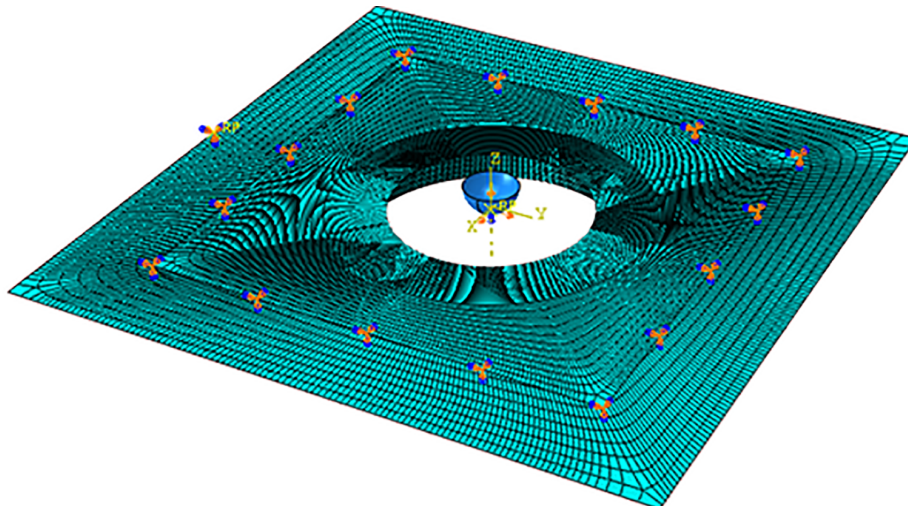


Fig. 4. The FE model of the IHF process.

Table 3

Parameters of Hill 1948 yield criterion employed for AA 6061-T6 in the present research.

F	G	H	L	M	N
0.491	0.593	0.428	1.5	1.5	1.387

Fig. 5 shows the flange with the pre-cut hole diameter of 46mm and (HER_{max}) value of 1.30, as well as the fractured flange with a pre-cut hole diameter of 44mm, corresponding to 10mm-diameter tool. Examining the fractured specimens revealed that the cracks were made at the edges of the flange and perpendicular to the tool movement path.

In the following, a multistage strategy was used to improve the formability and enhance the HER. As shown in Fig. 3d, the two, three, four, and five-stage angular strategies with an initial angle of 50° were used. Although the 6mm tool had the maximum HER in the single-stage strategy, yet because of its low strength due to the low shank diameter and its distortion during single-stage tests, the 10mm tool was used to perform the multistage tests. In Table 5, the value of HER_{max} is presented for different strategies together with the angle of stages. By conducting the tests, it was found that the multistage strategies slightly affected the LFR_{max} , so the HER_{max} values in the two and three-stage strategies were the same as that for the single-stage strategy. Concerning the four and five-stage strategies, the smallest pre-cut hole diameters to completely form the flange were 45 and 44mm, respec-

tively, which increased by 1 and 2mm, compared with that of the single-stage strategy. Furthermore, the values of HER_{max} in the four and five-stage strategies were increased by 2.3% and 4.6% , respectively, compared with that of the single-stage strategy.

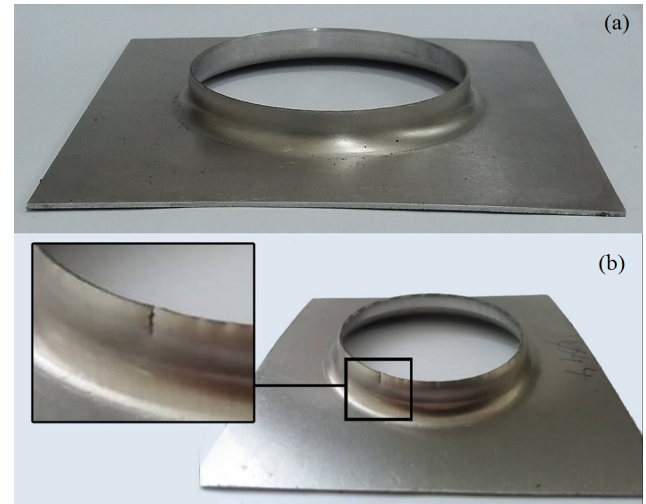


Fig. 5. a) Successfully formed flange with pre-cut hole diameter of 46mm, b) Fractured flange with pre-cut hole diameter of 44mm, tool diameter: 10mm.

Table 4Maximum hole expansion ratio, HER_{max} for different tools in single-stage strategy.

Tool diameter (mm)	Smallest pre-cut hole diameter (D_0) (mm)	Final flange diameter (D_f) (mm)	Result	HER_{max}
6	43	60	Successful	1.39
	42		Fractured	-
8	45	60	Successful	1.33
	44		Fractured	-
10	46	60	Successful	1.30
	45		Fractured	-

Table 5Maximum hole expansion ratio, HER_{max} for multistage strategies using the tool with the diameter of 10mm.

Number of stages	Stage angle (degrees)	D_0 (mm)	D_f (mm)	Result	HER_{max}
2	50, 90	46	60	Successful	1.30
		45		Fractured	
3	50, 70, 90	46	60	Successful	1.30
		45		Fractured	
4	50, 65, 80, 90	45	60	Successful	1.33
		44		Fractured	
5	50, 60, 70, 80, 90	44	60	Successful	1.36
		43		Fractured	

5.2. Results of the FE Simulation

5.2.1. Validation of the FE Model

Two different flange geometries with the wall angles of 60° and 70° and the pre-cut hole diameter of 38mm formed by a 10mm diameter tool were used to validate the simulation of the IHF process. Figs. 6 and 7 demonstrate the experimentally deformed parts and the simulation results of 60° and 70° wall angle flanges, respectively. In Figs. 6b and 7b, the numerically formed flanges, along with their equivalent plastic strain distribution are depicted. In both flanges, the maximum equivalent plastic strain is observed at the flange edges, where the forming tool is in contact with the sheet at the end of the process. Generally, during the incremental forming processes, the largest equivalent plastic strain occurs at the contact surface of the forming tool with the sheet. Unlike the equivalent plastic strain that is maximal at the edges, the maximum thinning and thickness strain occurs in the middle of the flange wall based on Figs. 6 and 7 (c and d). The reason is that the downward movement of the forming tool causes the upper area of the sheet to be stretched out and become thinner. When the tool reaches the flange edge, bending, instead of stretching, occurs at the edges because the other side is free with no constraint, while the walls are still stretched out. Consequently, the highest thickness reduction is in the

flange wall, instead of the edges.

Another point that can be observed from Figs. 6 and 7 is that both equivalent plastic strain and maximum thinning are higher in the 70° wall angle flange than those of the 60° flange, due to greater deformation and elongation. As can be seen in Figs. 6e and 7e, there is a good agreement between the experimental and simulated thickness distributions of the flanges; the maximum difference corresponding to 60° and 70° flanges are less than 2 and 3 percent, respectively. Moreover, the location and amount of maximum thinning are predicted accurately.

5.2.2. Evaluation of Strain and Stress State

In this section, a flange with a wall angle of 90° and a pre-cut hole diameter of 50mm is considered to evaluate the strain and stress state in the IHF process using the FE model. The path shown in Fig. 8 was selected and the evaluation of the major and minor strains for this path was investigated. As can be seen from the figure, the strain state in the flange varies from the uniaxial tensile state at the edge to near the biaxial tensile state at the wall. At the flange edge and the junction of the flange with the unformed part of the sheet, (start and end points shown in Fig. 8), the minor strain is compressive, while in the middle area of the flange wall, the minor strain is positive and tensile.

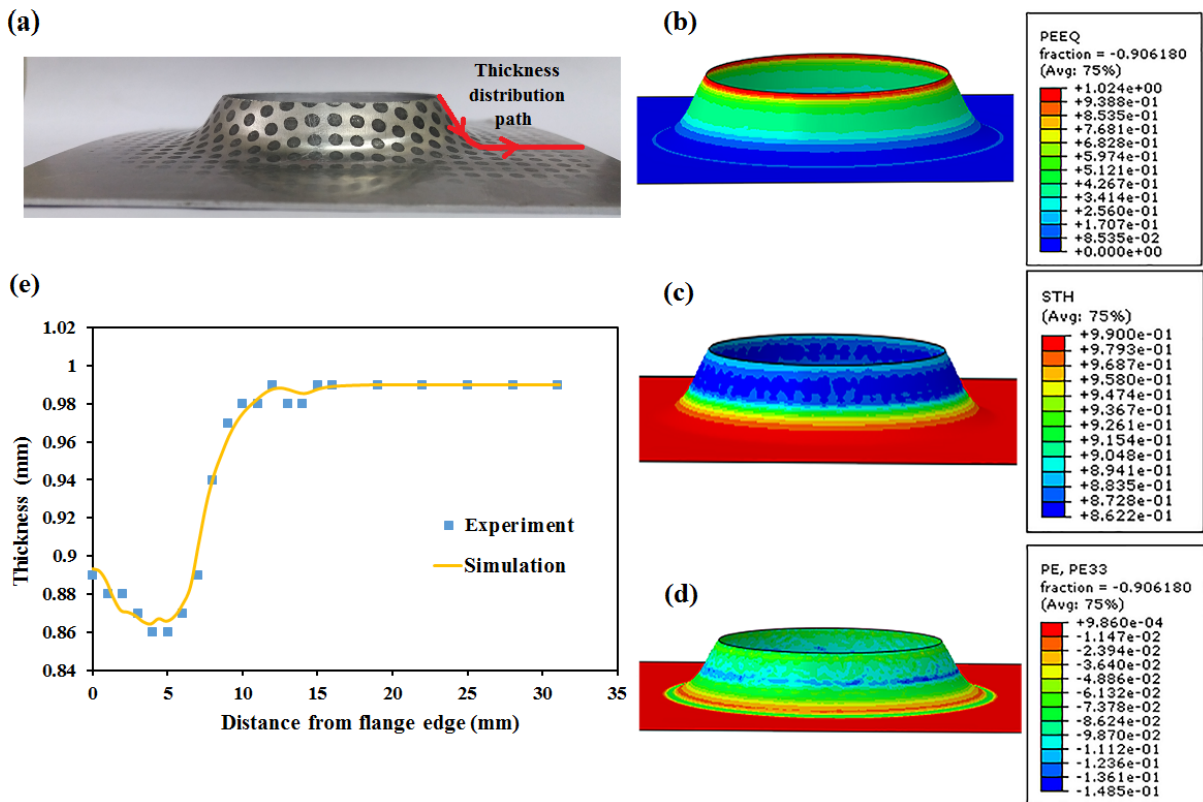


Fig. 6. a) Experimentally formed 60° wall angle flange, b) Equivalent plastic strain, c) Thickness variation, d) Thickness strain obtained by simulation, and e) Thickness distribution

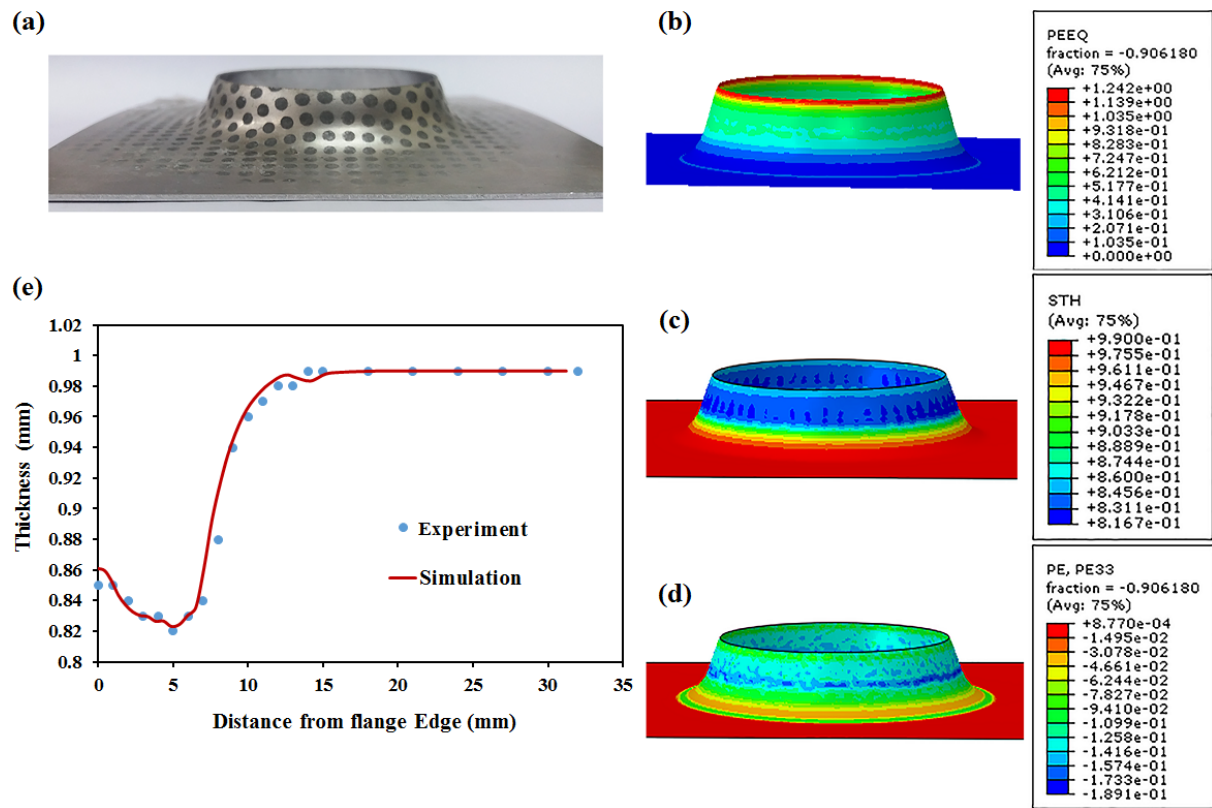


Fig. 7. a) Experimentally formed 70° wall angle flange, b) Equivalent plastic strain, c) Thickness variation d) Thickness strain obtained by simulation, and e) Thickness distribution

As a result, the middle area of the flange wall is subjected to more stretch, and as shown in the previous section, a greater thickness reduction occurs in this area. To further examine this issue, five elements were selected along the flange to evaluate the details of the changes in the strain. Fig. 9 displays the five selected elements and their strain paths. As shown in the figure, the dotted lines correspond to the top surfaces of the elements, which are in contact with the tool surface, and the solid lines indicate the strain path for the bottom surfaces of the elements. Considering the strain paths for the top surfaces of the elements, Element 1 which is located at the flange edge experiences uniaxial tensile strain conditions, due to the absence of material in front of the element. Element 2 located near the hole edge of the flange has a pure shear state at the beginning of the process, although its state changes to a uniaxial tensile state in the following. Element 3, situated in the middle of the flange wall is under a biaxial tensile strain condition. Elements 4 and 5 located in the junction of the flange with the unformed part of the sheet undergo a strain state close to the plane strain condition. Nevertheless, the strain evaluation for the bottom surface of the elements (solid lines) is completely different from the top surface. For Element 1, the strain state is between the uniaxial tension and plane strain, while the strain in Element 2 switches from the biaxial strain state to the plane strain state

during the process. For Elements 3, 4, and 5, the bottom surfaces of the elements experience a compressive state due to their locations in the inner side of the flange radius.

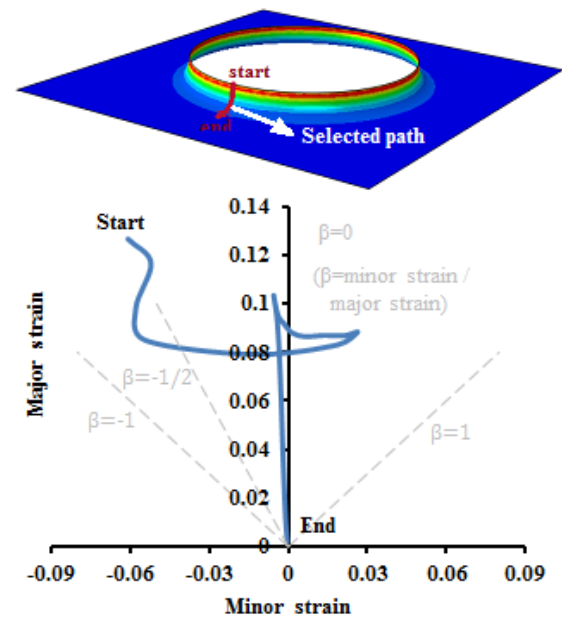


Fig. 8. Strain evaluation for the selected path along the formed flange.

Fig. 9 indicates the strain state evaluation through

the thickness in the IHF process, which is due to the successive bending and unbending in the incremental forming process, as noted by Mirnia and Shamsari [14]. According to the figure, the major strain on the outer surface of Elements 1 and 2 is greater than that of their inner surface. However, this state is opposite for Elements 3, 4, and 5 and the major strain is higher on the inner surface, as the outer surfaces of Elements 1 and 2 are in the tensile region of the flange, while the outer surfaces of Elements 3, 4, and 5 are in the compression region of the flange radius.

On the other hand, the two parameters of average stress triaxiality (Eq. (9)) and average normalized load angle (Eq. (10)) were used to study the stress state in the IHF process. Fig. 10 represents the stress state of the elements introduced in Fig. 8, along with the plane stress locus (Eq. (8)). As shown, the stress state of the top layer of elements 1, 2, and 3 lies between pure shear and uniaxial tension states, while elements 4 and 5 experience a stress state between uniaxial tension and plane strain tension states. The stress state of the bottom layer of all elements is compressive and symmetrical concerning the top layer. Fig. 10 illus-

trates that in addition to the strain state (Fig. 9) the stress state also changes through the thickness direction.

Regarding the probability of fracture initiation at the point with the largest equivalent plastic strain [14], the element with the maximum equivalent plastic strain (critical element) was selected for stress and strain analysis. Fig. 11 shows the critical element and evaluation of the equivalent plastic strain for this element. As observed, the highest equivalent plastic strain is near the edge, which increases the probability of crack initiation from the edge. The equivalent plastic strain is increased stepwise at both top and bottom surfaces to reach the maximum value. The reason for this state is the local deformation of the sheet and the movement of the forming tool, such that the equivalent strain increases when the tool reaches the element, and the equivalent plastic strain remains constant when the tool moves away from the element. Besides, the equivalent plastic strain of the bottom surface is greater than that of the top surface, which can cause more damage accumulation on the bottom surface in comparison with the top surface.

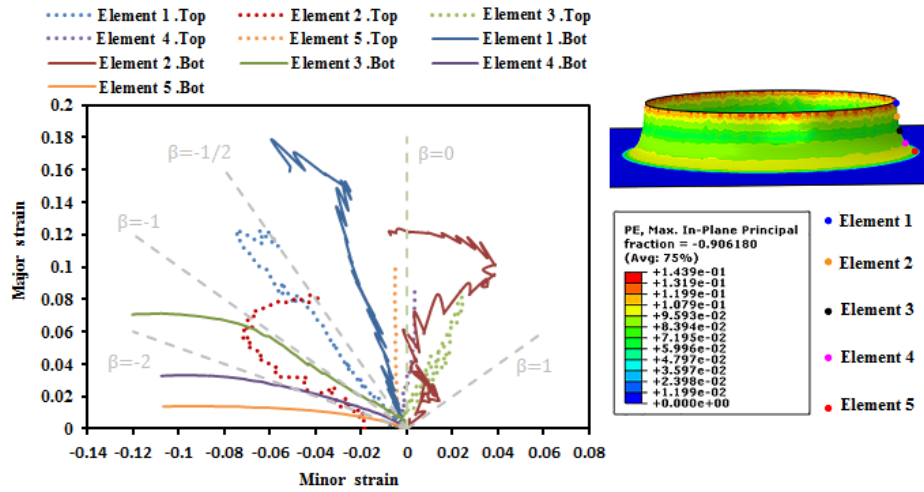


Fig. 9. Strain path for five selected elements along the flange.

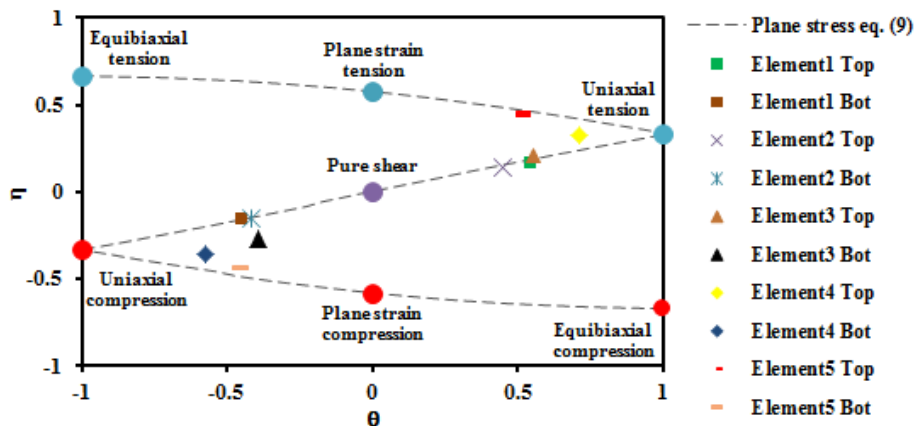


Fig. 10. Average stress state of flange elements.

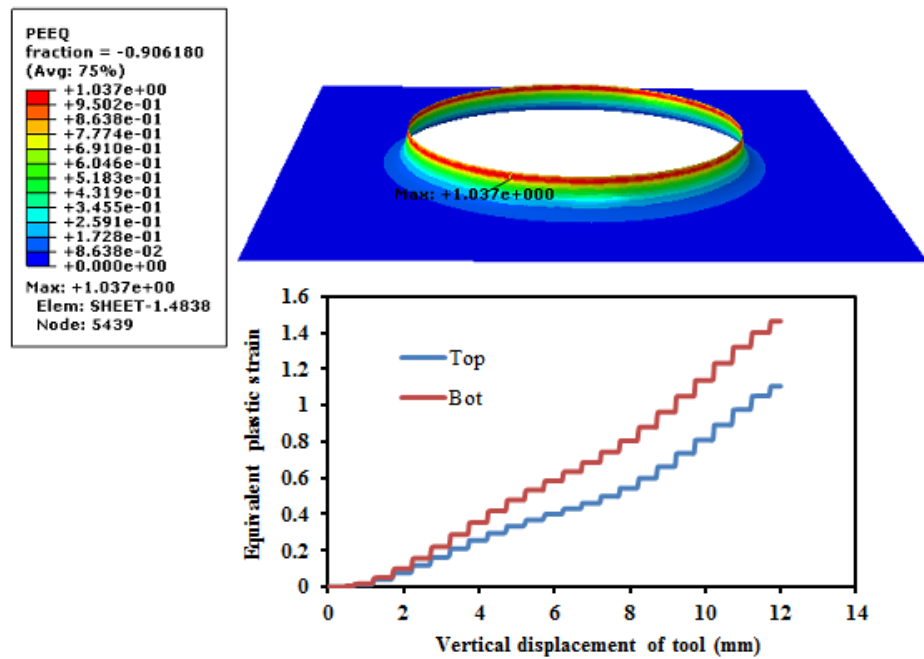


Fig. 11. Evaluation of the equivalent plastic strain for the element with the maximum equivalent plastic strain (critical element-black dot).

Fig. 12 indicates the variation of stress triaxiality for the critical element. According to the figure, the stress triaxiality of the bottom and top surfaces are symmetric and reverse to each other, and vary successively during the process between the two values of -0.6 to 0.6 , due to the tool approaching or getting away from the respective element. Fig. 13 provides the variations of the NLAP with the tool height variation for the critical element. Similar to the stress triaxiality, the NLAP changes consecutively during the process from -1 to 1 . Whenever the forming tool has a distance from the respective element, the stress triaxiality and the NLAP are constant similar to the equivalent plastic strain in that element, due to elastic deformation. However, these parameters change suddenly when the tool is located along that element and it experiences plastic deformation.

The average values of the stress triaxiality and the NLAP are positive for the top layer and negative for the bottom layer, as shown in Fig. 10. The reason is that in most of the process time when the tool is approaching or moving away from the element, the top surface is bent convexly and experiences a tensile state, and the bottom surface is bent concavely in the compressive state. Only when the tool is in contact with the element, the mentioned state is in reverse order and the bottom surface experiences the tensile bending. Accordingly, these changes and differences in stress and strain states at the top and bottom surfaces, which are consistent with the findings reported by Mirnia and Shamsari [14] and Martinez-Donaire et al.[12], indicate the evaluation in the stress and strain through the thickness, which is one of the reasons for delaying

or suppressing the necking in the incremental forming process, according to results stated by Morales-Palma et al. [29] and Seong et al. [30].

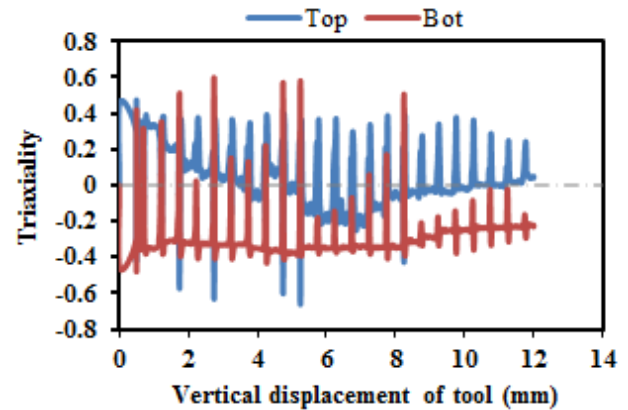


Fig. 12. Variation of stress triaxiality for the critical element.

The strain path of the critical element is demonstrated in Fig. 14. The top surface of the critical element experiences a pure shear strain state at the beginning of the process and redirects to the plane strain at the end of the process. Contrary to the upper surface, the bottom surface of the element undergoes the equibiaxial tension strain at the beginning of the process, and the strain path changes into a plane strain state at the end of the process, similar to the top surface. These changes in the strain path highlight the non-proportional loading in the IHF process. The non-proportionality affects the formability and deformation mechanics, as stated by Zhalehfard et al. [31]. Given the

higher values of the major strain and equivalent plastic strain at the bottom surface of the critical element, it can be concluded that the crack and fracture probably initiate from the bottom surface of the element and move to the opposite surface.

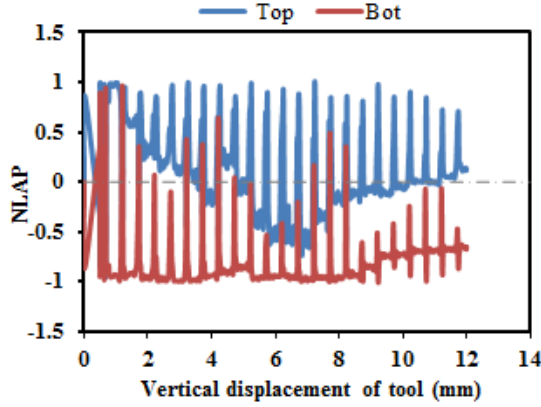


Fig. 13. Variations of the NLAP for the critical element.

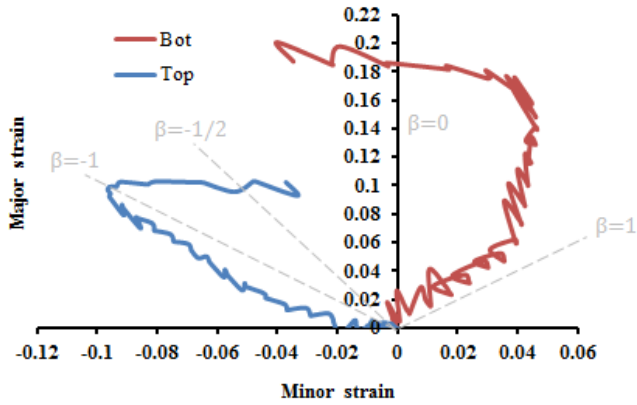


Fig. 14. Strain path of the critical element.

5.2.3. Effect of Tool Radius

In addition to the employed tools with diameters of 6, 8, and 10mm, a 4mm diameter tool that could not be used in experimental tests due to several limits such as the lack of stiffness required for testing the selected material, was also utilized to examine the effect of tool radius on the stress and strain state in a single-stage IHF process. Fig. 15 shows the evaluation of the equivalent plastic strain for the formed flange with the pre-cut hole diameter of 48mm and for different tools. As shown, an increase in the diameter of the forming tool increases the maximum equivalent strain at the bottom layer and decreases it at the top layer. Increasing the tool diameter can impose two effects on sheet deformation. First, the deformation process becomes a non-localized state, resulting in applying more deformation to the sheet at any moment. It causes the equivalent plastic strain to be greater at both beginning and end of the process in the bottom layer corresponding to the

tool with a larger diameter. The second effect is that an increase in the tool diameter leads to less bending deformation on the sheet and increases the contact surface of the tool with the top surface of the sheet. Thus, the amount of increase in the equivalent plastic strain in the upper surface of the sheet during approaching of the tool to the respective element is lower than forming with tools having smaller diameter, and ultimately, the total equivalent plastic strain is lower in the top surface for the tools having smaller diameter.

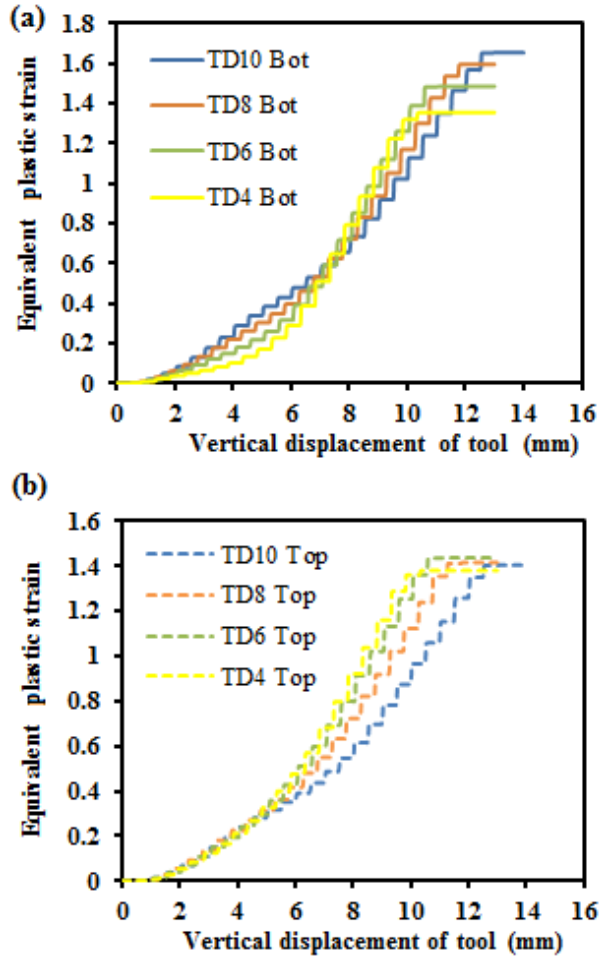


Fig. 15. The evaluation of the equivalent plastic strain for the flanges formed by different tool diameters in the a) Bottom and b) Top surfaces (TD4-TD10 stands for tool with 4-10mm diameter).

As can be seen from Fig. 15a, at the middle of the process in contrast with the beginning and end of the process, the equivalent plastic strain became higher for the tool possessing a smaller diameter due to greater bending deformation. Finally, at the end of the process, the maximum equivalent plastic strain at the bottom surface increased by increasing tool diameter. This caused the damage accumulation in the formed flange to increase, and therefore, the hole expansion ratio decreased for the tool possessing a larger diameter. However, in Fig. 15b there is an exception

which is related to the tool with the diameter of 4mm, in which the minimum equivalent plastic strain at the end of the process in the top layer is less than that of the other tools, in addition to the bottom layer. Another difference for this tool is that, unlike other tools, more strain was created at the top surface than the bottom surface. The very small tool diameter makes excessive stress concentration at the top surface of the sheet because of the low contact surface. This causes the material in contact with the tool at the top layer to squeeze extremely and to create more shear deformation.

Fig. 16 illustrates the stress state for the flanges formed with different tools. As can be observed, the values of the average stress triaxiality and NLAP are approximately equal in both top and bottom layers for the flanges formed by the 6, 8, and 10mm tools, while this value is higher for the 4mm tool, especially at the top surface. This indicates that more tension and compression are created in elements of the flange formed by the 4mm tool than the other tools.

For more investigation, the variation of the stress triaxiality and NLAP along the flange wall for the same

path shown in Fig. 8 was evaluated and illustrated in Fig. 17. According to Fig. 17a, the value of the stress triaxiality for the 4mm tool is higher in most regions of the flange than those for other tools, while other tools have almost similar stress triaxiality. The higher stress triaxiality for the 4mm tool indicates that this tool creates more damage, which could lead to less HER. According to Fig. 17b, the variation of the NLAP for the 4mm tool is different from those of the other tools and experiences a different trend.

Fig. 18 demonstrates the thickness variation in the element with maximum thinning for the flange with the pre-cut hole diameter of 48mm and tools with different diameters. As shown in the figure, the thickness decreases stepwise to reach its minimum value at the end of the process. The highest and lowest thinning are related to the 4mm and 10mm tools, respectively, indicating the thinning increase by decreasing the tool diameter, which could be due to more bending by decreasing tool radius. However, the thickness reduction for the 4mm tool is much more than those for the other tools.

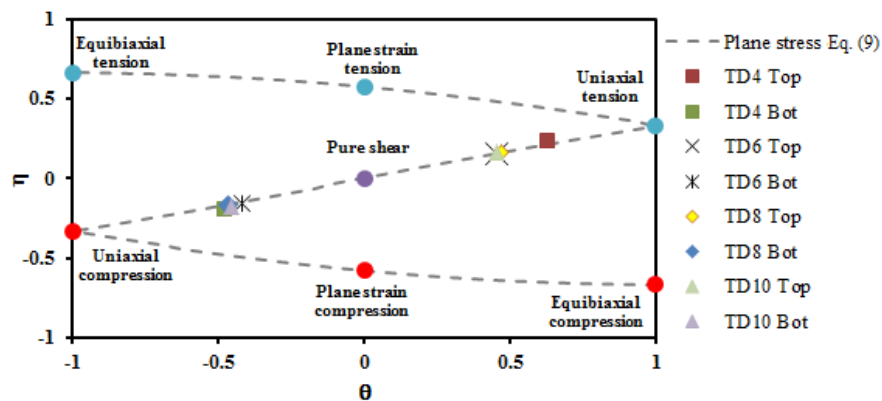


Fig. 16. The stress state of critical element for the flanges formed by different tools.

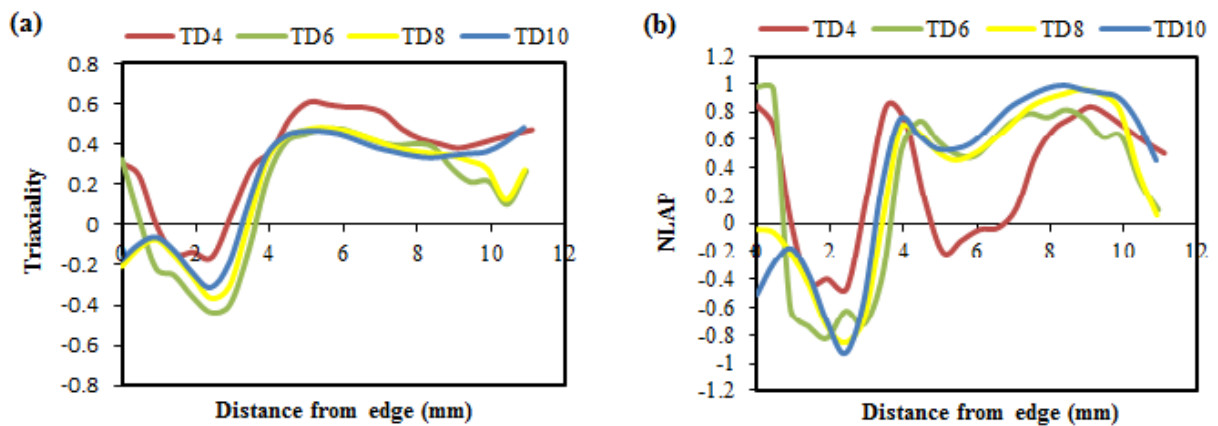


Fig. 17. Variation of a) Stress triaxiality and b) NLAP along flange wall for flanges formed by different tools.

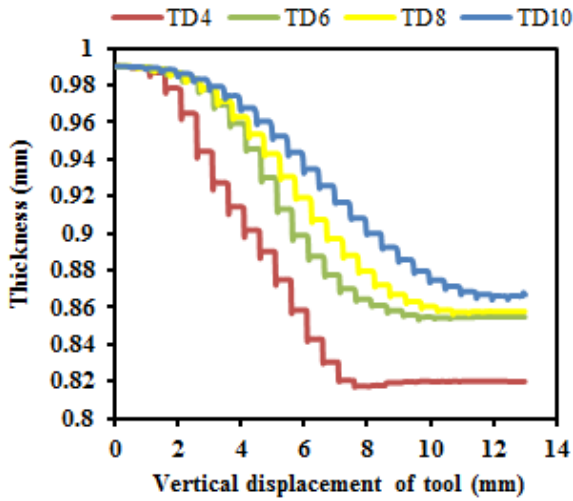


Fig. 18. The thickness variation in the element with maximum thinning for the flanges formed by tools with different diameters.

In Fig. 19, the thickness distribution along the flange for different tools is shown. By reducing the tool diameter, in addition to further thickness reduction, the position of the maximum thinning also moves to the top of the flange wall. From all discussions in this section, it can be concluded that the damage caused by the 4mm tool is greater than those by the other tools, and therefore the tool diameter cannot be reduced to any extent to increase the formability. This result is consistent with what was stated by Al-Ghamdi and Hussain [32] that there is a threshold tool radius which further reduction of the tool radius decreases the formability.

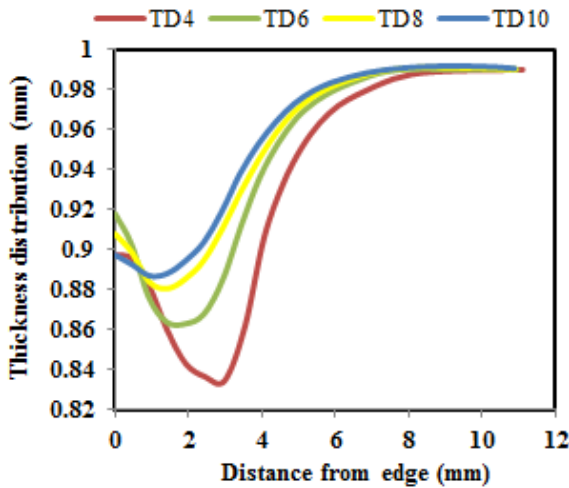


Fig. 19. The thickness distribution of the flanges formed by different tools.

5.2.4. Stress and Strain State in the Multistage Strategy

As mentioned in section 5.1, two to five-stage angular strategies were used to evaluate the flange formability. In this section, the multistage strategy was done on

the sheets with a pre-cut hole diameter of 46mm by a tool with a 10mm diameter. For example, the strain and stress evaluations in the three-stage strategy for a flange with a pre-cut hole diameter of 46mm are represented in Figs. 20 to 22. Fig. 20 shows the variation of the equivalent plastic strain of the critical element with the simulation time in the three-stage strategy. Similar to the single-stage flanging process, the equivalent strain increases stepwise at each stage to reach its maximum value at the end of the final stage. During the process, the equivalent plastic strain value in the bottom layer is higher than that of the top layer, except at the beginning of the first stage, which reveals more damages in the bottom layer than that of the top layer. Figs. 21 and 22 provide the variation in the stress triaxiality and the NLAP, which is a function of the simulation time for the three-stage strategy. Similar to the single-stage state, the stress triaxiality for the top and bottom layers varies in each stage between the maximum and minimum values. When the forming tool is away from the respective element, the NLAP similar stress triaxiality is constant; however, it reaches its maximum value when the tool is located along the element. Accordingly, this process is repeated successively. The average value of the stress triaxiality and NLAP, as shown in two successive stages, are positive for the top layer and negative for the bottom layer. Specifically, changes in the stress and strain states in other strategies are similar to the three-stage strategy.

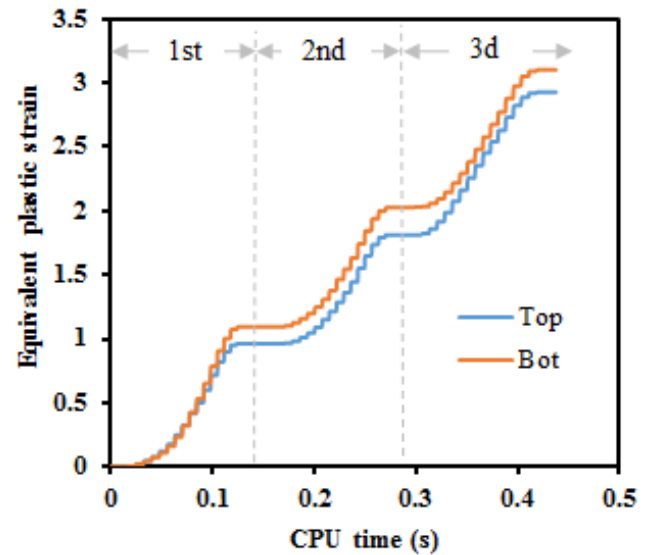


Fig. 20. Evaluation of the equivalent plastic strain of the critical element for flange formed by the three-stage strategy.

Fig. 23 shows the maximum equivalent plastic strain in different strategies for a flange with a pre-cut hole diameter of 46mm. On the one hand, an increase in the number of stages increases the maximum equivalent plastic strain in both top and bottom surfaces, due to the accumulation of deformation and

strain. Furthermore, the difference in the maximum equivalent plastic strain between the top and bottom surfaces increases by increasing the number of stages. This increase in the equivalent plastic strain prevents HER from increasing for more stages. On the other hand, as the number of stages increases, the slope of the increasing equivalent plastic strain decreases. This is because of the division of the total sheet deformation in the more stages and less deformation in each stage which hinders a sudden increase in the strain.

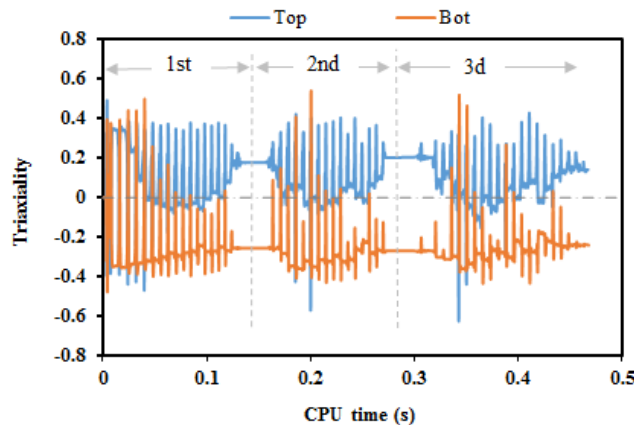


Fig. 21. Evaluation of stress triaxiality of the critical element for flange formed by the three-stage strategy.

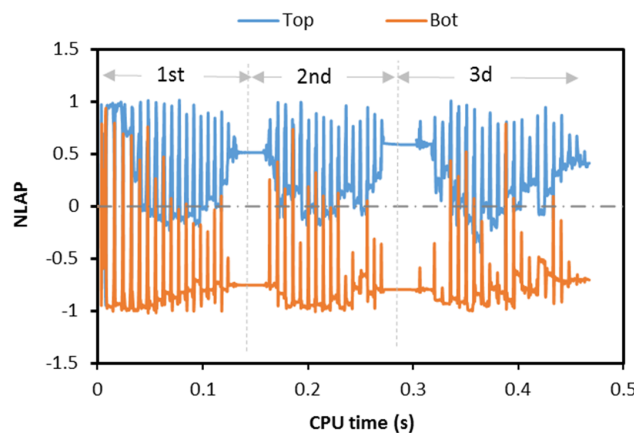


Fig. 22. Evaluation of the NLAP of the critical element for flange formed by the three-stage strategy.

Fig. 24 displays the average value of the stress triaxiality and the NLAP for the critical element in different strategies. Based on the results, a slight increase is observed in the average value of the stress triaxiality and the NLAP by increasing the number of stages. Increasing the stress triaxiality increases the growth rate of the micro-voids created in the deforming specimens, which will lead to more damage accumulation. However, since the amount of increase in the stress tri-

axiality is not too high, its effect on the damage will be negligible.

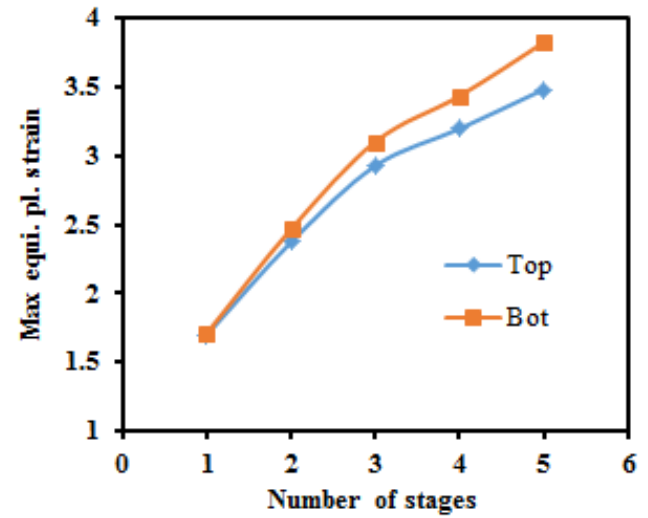


Fig. 23. The maximum equivalent plastic strain in different strategies.

Fig. 25 shows the equivalent plastic strain along the flange wall in a path similar to the path shown in Fig. 8 for flanges formed by different strategies. As can be observed, the maximum equivalent plastic strain occurs near the flange edge for all the strategies, and by increasing the distance from the edge, it reduces. Moreover, the greater the number of forming stages, the higher the equivalent plastic strain along the entire path. Fig. 26 presents the strain path for the top and bottom surfaces of the critical element in different strategies. As shown in Fig. 26a, the strain state of the top surface in the single-stage strategy is a uniaxial tensile state, in which the graph moves to the right-hand side by increasing the number of forming stages, and the strain state changes into the plane strain and biaxial tensile state. Contrary to the top surface, the bottom surface of the critical element in the single-stage strategy experiences a plane strain state. However, in multistage strategies, the strain state is the biaxial tension state at the beginning of the process, but by increasing the stage number, the minor in-plane strain becomes smaller and the strain state converts to the uniaxial strain state at the end of the process (Fig. 26b). Another point that can be expressed from Fig. 26 is that as the stage number increases, the fluctuations of the strain path and strain state increase, which causes the major strain to rise gradually, contrary to the single-stage strategy. It leads to improved formability by increasing the number of stages.

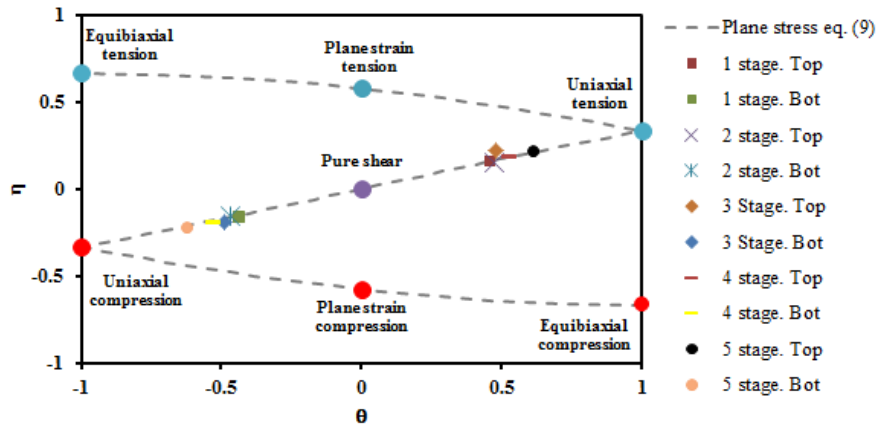


Fig. 24. The stress state of critical element for flanges formed by different strategies.

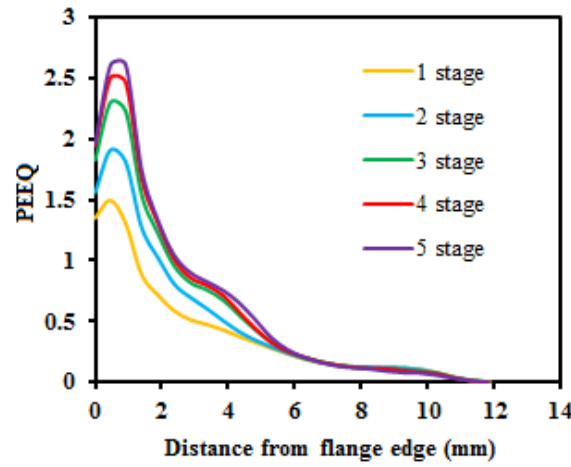


Fig. 25. The equivalent plastic strain along the flange wall for flanges formed by different strategies.

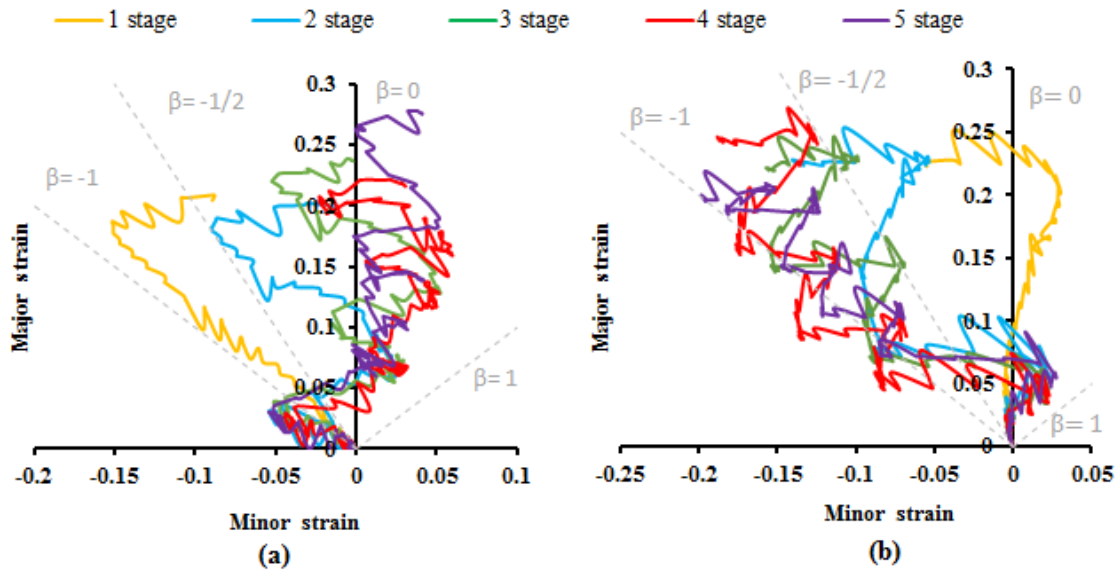


Fig. 26. The strain paths on the a) Top and b) Bottom surfaces of the critical element in flanges formed by different strategies.

6. Conclusions

In this paper, the damage and deformation mechanics were studied by accurate investigation of the stress and

strain states in the flanging of AA 6061-T6 sheets by using the incremental forming process. Effective parameters on damage such as equivalent plastic strain,

stress triaxiality, and NLAP were evaluated thoroughly during the process. The conclusions of this research are summarized in the following:

1. Examining the variations of the major and minor strains along the flange wall revealed that different parts of the flange wall experienced different strain states from pure shear to biaxial tension. Meanwhile, the strain creation was non-proportional.
2. The largest equivalent plastic strain was at the flange edge that led to higher damage accumulation in this zone and consequently, the crack initiation from this area. Moreover, the equivalent plastic strain at the bottom surface of the flange was greater than that of the top surface at the side of the forming tool.
3. The stress triaxiality and the NLAP changed sequentially and reversely during the process at the top and bottom surfaces, indicating nonlinear variations in the stress state during the IHF process. The average stress triaxiality and average NLAP were positive on the top surface and negative on the bottom surface.
4. Evaluating forming tools with different diameters in the IHF process highlighted that a small-diameter tool resulted in lower equivalent plastic strain, even though no significant change was observed in the stress state up to the diameter of 6mm. By further reducing the tool diameter after 6mm, the amount of stress triaxiality increased, and the stress state changed. In addition, as the tool diameter decreased, the thinning increased. As a result, by reducing the tool diameter to a diameter of 6mm, the formability increased and, less than it, the formability decreased.
5. Applying multistage angular strategies revealed no significant change in the formability, so the hole expansion ratio of the five-stage strategy increased by about 4.6% compared with the single-stage state. Although the stress state in multistage strategies was approximately similar to that of the single-stage strategy, the strain state varied in these two states.

Acknowledgment

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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