



Experimental Formability Study of Ti6Al4V Sheet Metal using Friction Stir Heat Assisted Single Point Incremental Forming Process

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Single Point Incremental Forming (SPIF) process is a novel approach of flexible sheet metal forming method in which 3D component can be allowed to form. The process is characterized by die less flexible, lower lead time and higher formability as compare to conventional stamping process. The present work involves set of experiments of 1 mm thick Ti6Al4V sheet using the friction stir SPIF process at room temperature and investigating the effect of wall angle, speed, feed and step size on formability of the sheet. The results revealed that, the maximum formability of frustum cone specimen was obtained at wall angle of 45° and wall angle is the most significant parameter. With an increase in wall angle and feed, the formability of sheet blank decreases while increases in tool rotational speed, the formability found to increase. In addition, it is also observed that, there was no significant influence of step size on formability of sheet.

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1. INTRODUCTION

Single point incremental forming (SPIF) process is a novel sheet metal forming process. SPIF process is characterized with higher flexibility, lower tooling cost and reduces lead time due to die-less sheet metal forming process [1]. It is more suitable for rapid prototypes and small - medium scale production of sheet metal parts, which needs no special type of tooling and has low initial cost as compared to conventional stamping forming process [2]. The blank sheets metals are localized incrementally deformed using a simple hemispherical end forming tool, whose path is specified in a CNC machining center or robot. SPIF process has higher formability because of mode of deformation of sheet under stretching and shearing action [3]. Due to great formability at room temperature, the SPIF method is extensively used for the aluminum and steel alloy sheet material. However, the process has limited to industrialize because of lower surface quality, uniform

thickness, geometrical accuracy and higher forming time of formed parts [4].

The uses of lightweight material such as titanium alloy components have continuously increased in the important fields such as aeronautical, automotive and biomedical field due to economic, environmental and biomedical compatible in nature. These alloy materials have good mechanical properties such as high strength to weight ratio, toughness, wear resistance fatigue behavior and corrosion resistance compared to other materials such as aluminum and steel alloys [5]. Among the titanium alloys, the Ti6Al4V is used 80 % of total titanium alloy in the USA [6]. However, the Ti6Al4V titanium sheet is difficult to form at room temperature because of they possess low uniform elongation, resistance to deformation, high springback and yield to tensile ratio (high hardness and poor formability). So, they are commonly formed with low-speed forming at elevated temperature of 750~950 °C [7]. Lightweight materials such as AA2024-T3, AZ31 B-O, AA6061-T6,

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AA6063 and titanium alloys and high strength alloy such as MnB5, DP 980 and DC04 steel alloy have possessed a poor formability at room temperature. In order to form these alloys, heat assisted incremental sheet forming (ISF) techniques are more suitable with minimum tooling cost and lower lead time at higher temperature such as laser heat assisted, electrical heat assisted, induction heat assisted friction stir heat assisted processes [8].

In the past two decades, many researchers and academicians have carried out experiments to analyze the forming of lightweight sheet materials using different types of the heat assisted ISF techniques. Duflou et al. [9] have formed cone shape specimens of Ti6Al4V with laser heat assisted technique of ISF with local dynamic heating. The results showed that cone shape specimens were formed with lower forming force and higher dimension accuracy. Ambrogio et al. [10] studied the influence of process parameters such as tool diameter, step size, feed rate and lubrication on the formability of magnesium alloy AZ31B at the room temperature and in warm condition. The formability of AZ31B was observed higher in warm conditions as compared to room temperature. Further, complex design of heating equipment is creating difficulties while carried out the forming of sheet. Fan et al. [11] developed a new technique to heat the sheet metal based on electric current. In this technique, the localized heat is generated at tool-sheet interference by DC power supply. They investigated maximum formable angle and part accuracy on the TiAl2Mn1.5 titanium and the AZ31 magnesium alloys. In 2010, Fan et al. [12] were formed sheet metal of the Ti6Al4V alloy by using electrical heat assisted technique and observed that this technique is more suitable to form a desired shape in the range of temperature 500–600 °C with a minor oxidation. Later on, Ambrogio et al. [5] used electrical heat assisted incremental forming technique to form difficult to form-alloy such as AZ31B-O, AA2024-T3, Ti-6Al-4V. They investigated the influence of different operating parameters on formability and surface quality of formed parts. Rahmani et al. [13] have investigated the process of incremental forming on AA6063 material using warm heating. They have reported that, axial feed and temperature most significant parameter on formability and surface roughness.

The heat assisted techniques of SPIF process have been classified for global heating and local heating of blank sheet by Xu et al. [14]. These heat assisted techniques showed the substantial enhancements in the formability of hard to form materials but there is a significantly increase in both the process complexity and tooling cost. However, friction stir heat assisted SPIF is the most suitable as direct heating method with higher flexibility and lower cost [15, 16]. In friction stir heat assisted technique, sheet metal is formed with tool

spinning at very high relative speed, which generates frictional heating of the sheet. The use of this technique are mainly found in technical literature that focuses on steel and aluminum sheets. Ambrogio et al. [17] investigated the influence of the step size and the tool feed rate on temperature deviations at the tool interface, during the SPIF of aluminum alloy (AA5754) and titanium Ti6Al4V sheets. They have reported that optimized feed of the tool and step size give better formability along with process productivity and quality of formed part without any external heating equipment. Chausov et al. [18] suggested that a range of deformation rates of high-strength titanium alloys pass into a state of increased ductility without loss of strength properties by using additional force impulse loading, and the implementation of dynamic non-equilibrium processes. Grün et al. [19] investigated the behavior of Ti6Al4V sheet formability with friction stir SPIF process technique. The result showed that medium tool rotation of 2000 rpm speed lead to lower the rate of tool wear, improved the formability and reduce the forming forces.

To the best of author's knowledge, experimental investigation of process parameters on forming of Ti6Al4V sheet metal without use of heating equipment in single point incremental process is not reported so far. Because of wide use of Ti6Al4V titanium alloy in the field of biomedical, aeronautics and automotive, friction stir heat assisted single point incremental forming of Ti6Al4V sheet has been investigated in this study. In order to evaluate the formability of sheet metal part in SPIF process, the parameters like speed, feed, step size and wall angle were selected.

2. PRINCIPLE AND EQUIPMENT OF EXPERIMENTAL SETUP

Figure 1 shows the principle experimental set up employed in present work. The experimental set up consist of basic elements such as sheet blank, forming tool, vice, fixture and a CNC vertical machining center. The 3-axis CNC Machine (Jyoti PX20 with Siemens controller) with a maximum working space of 510 x 510 x 510 mm³ and 400 kg_f load capacity of table is used for experimental work.

The tool is made of tungsten carbide (WC) material with a 10 mm diameter hemispherical-end; it is selected due to its high hardness, heat resistance and wear resistance. The blank sheet is firmly clamped with clamping screws in the fixture. A tool with hemispherical shape is forming the blank sheet incrementally in to desired shape. The Ti6Al4V alloy, a hard-to-form lightweight alloy sheets has been selected for experimental tests. Its chemical constituents (as-received condition) are Ti- 87.49 % Al-6.8 %, V- 4.8,

H-0.015 %, Fe-0.3, O-0.2%, Si-0.15%, C-0.1 %, N-0.05 and others-0.4 % in mass percentage. Titanium is an allotropic substance consisting of a cubic structure (α -Ti) and a compact hexagonal structure up to a temperature of 882°C (β -Ti). The truncated cone-specimens were formed from 98 x 98 mm² blank size sheets having a thickness of 1 mm. All test samples of sheet have been cut from annealed 1-mm-thick Ti6Al4V alloy sheets by water jet machining process. Before each experiment, OKS200 MoS₂ paste lubricant was applied on top surface of blank sheet, which prevent the oxidation of the specimen surface at higher temperature during forming process (Figure 2).

The truncated cone geometries with constant angle is formed with 46 mm top base diameter and vertical depth of 18 mm. The truncated con was employed to determine the SPIF formability of Ti6Al4V. The desired tool path to form the truncated cone specimen was generated using Microsoft Excel Software. All truncated specimens with constant angle have been formed using Z-level tool path. In Z-level tool path, first tool moves in XY- plane,

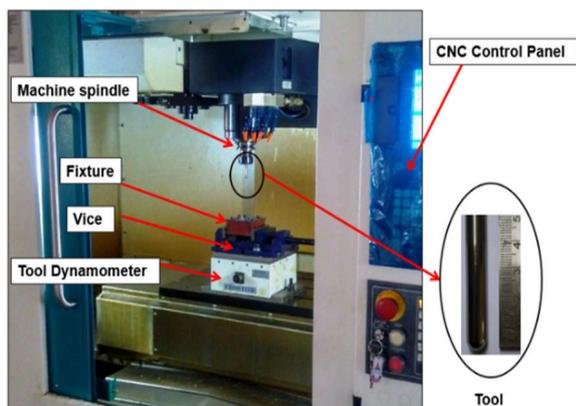


Figure 1. Experimental set for SPIF process with Jyoti PX20 CNC milling machine

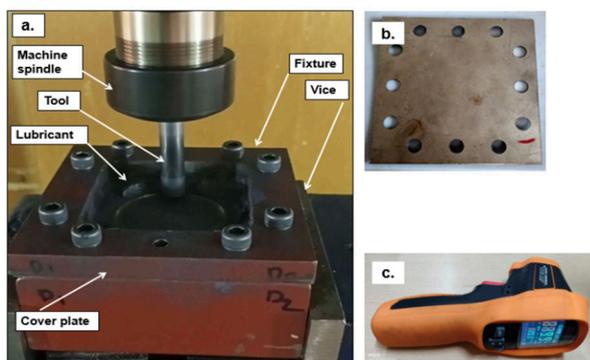


Figure 2. (a) The sheet during processing with OKS MoS₂ Paste Lubricant (b) The sheet provided with desired dimension (c) Infrared non-contact temperature measurement gun

reaches its starting point, then tool takes a step in the vertically (z-axis) downward with specified step size. This motion of tool continues till the complete specimen is formed. Figure 3 shows the CAD truncated cone specimen model with tool path.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The plan of experiments with process parameters are summarized in Table 1. In present study, there are four variables parameters such as speed, feed, step size and wall angle. The formability is one of the important response parameter of sheet metal forming process. Formability of sheet material in SPIF process is represented in different approach such as fracture forming limit, maximum formable angle and maximum forming depth.

In present work, maximum forming depth of specimen is measured as a formability of Ti6Al4V sheet material, which can be measured just before specimen part fractured during forming process. All specimens are formed till either design depth of 18 mm or the fractured of specimen during forming process. After the fractured the specimens are unloaded from the fixture and depth of fractured specimens are reported as the Z-axis coordinate on computer screen of the machine. The experimentation was carried out to investigate influence of various parameters such as speed, feed, step size and wall angle on formability.

3. 1. Influence of Wall Angle

The conical frustums specimens with diameter of 46 mm at the top and wall angle of 55°, 50°, and 45° are selected to evaluate the formability in the friction stir heat assisted SPIF process of Ti-6Al-4V alloy. The plan of experiments and the experiment results are shown in Table 1.

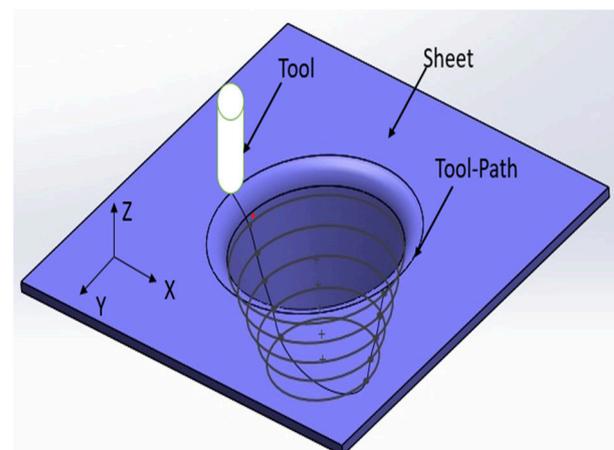


Figure 3. CAD model of truncated cone with Tool path

TABLE 1. Plan of experimental work and result

(a) Formability test results by varying the speed and step size with constant wall angle					
Exp. No.	Wall angle (α)-degree	Speed (s)-rpm	Feed (f)-mm/min	step-size (z)-mm	Depth of formed part (d)-mm
1	55	700	1000	0.25	6
2	55	1000	1000	0.1	5.5
3	55	1400	800	0.25	6.25

(b) Formability test results of wall angle			
Exp. No.	Wall angle(α)-degree	Depth of formed part (d)-mm	Constant parameters
3	55	6.25	speed 1400 rpm, feed 800 m/min, tool diameter 10 mm and step size 0.25mm.
4	50	7.25	
5	45	18	

(c) Formability test results of speed			
Exp. No.	Speed(s)-rpm	Depth of formed part (d)-mm	Constant parameters
6	700	7.50	wall angle 45°, feed 800 mm/min, tool diameter 10mm and step size 0.25mm.
7	1000	10.25	
5	1400	18	

(d) Formability test results of feed			
Exp. No.	Feed (f)-mm/min	Depth of formed part (d)- mm	Constant parameters
5	800	18	wall angle 45°, speed 1400 rpm, tool diameter 10mm and step size 0.25mm.
8	1000	6.25	
9	1200	5.5	

(f) Formability test results of step size with varying wall angle				
Exp. No.	Step size (z)-mm	Wall angle (α)-degree	Depth of formed part (d)-mm	Constant parameters
4	0.25	50°	7.25	speed 1400 rpm and tool diameter 10mm.
10	0.1	50°	7.25	
5	0.25	45°	18)	
11	0.1	45°	18	

In the first set of three specimens as shown in Table 1(a) with wall angle of 55° was formed with varying the speed and step size. All three specimens had early failed with poor surface finish as shown in Figure 4. It shows that wall angle is the most significant parameter for formability. In the second set of three specimens as shown in Table 1(b) with wall angle of 55°, 50° and 45° have been formed with considering other parameters as constant. As can be seen from the results and as shown in Figure 5, the specimen with wall angle of 45° has successfully formed at a depth of 18 mm and wall angle with 50° and 55° had early failed at a depth of 7.52 and 5.25 mm, respectively. The result showed that forming depth decreases with an increase in the wall angle as shown in Figure 6(a). The sheet metal had more stretching at higher wall angle, hence thinning of sheet metal increases with an increase in the value of wall angle based on cosine law.

3. 2. Influence of Speed In the third set of three experiments plan with varying the speed as shown in Table 1(c), the specimens have formed with varying the speed and keep other parameters constant.

The specimen formed successfully at forming depth of 18 mm with speed of 1400 rpm but specimens are failed at depth of 7.5 mm and 10.25 mm at lower

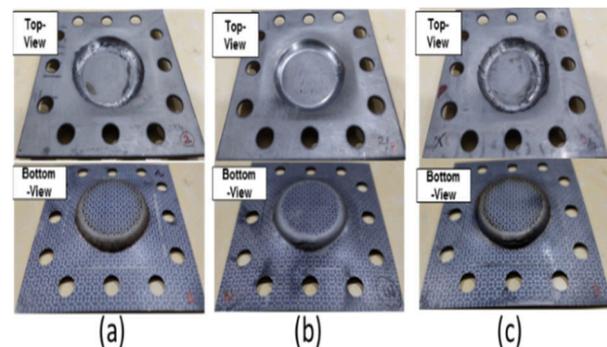


Figure 4. Specimens formed by varying the speed and step size with constant wall angle (a) exp no.1 (b) exp no.1 (c) exp no.3

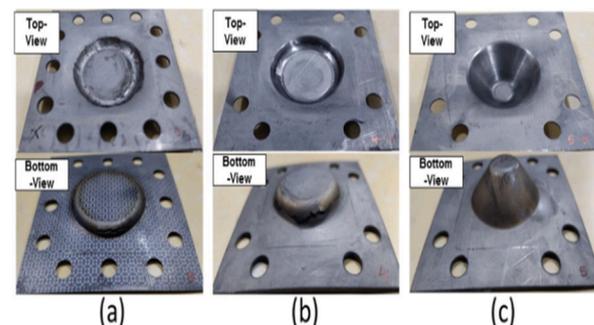
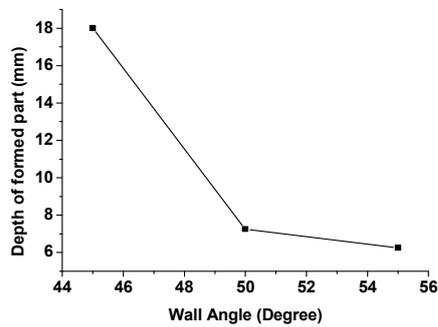
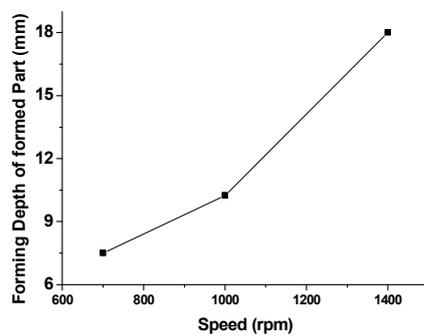


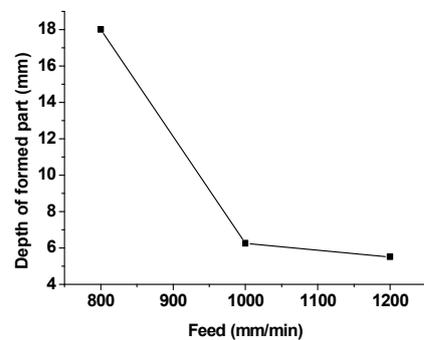
Figure 5. Specimens formed with varying the wall angle of (a) 55° (b) 50° (c) 45°



(a)



(b)



(c)

Figure 6. Effect of (a). Wall angle, (b). Speed, and (c). Feed-parameters on depth of formed part

speed of 700 and 1000 rpm, respectively as shown in Figure 7. It seems that forming depth is increases with an increase in tool rotation speed as shown in Figure 6 (b) because of thermal softening effect at tool-sheet interface. At the low rotations speed of 700 and 1000 rpm, the range of temperatures were lower at tool interface 60 to 90 °C observed by Infrared non-contact temperature measurement gun, as shown in Figure 2(a). At such low temperature, insufficient heat generated in the forming zone resulted in reduced formability of the part. In SPIF process, friction heat generation at tool-sheet interface is directly proportional to tool rotation speed [20].

3. 3. Influence of Feed In the fourth set of three experiments plan with varying the feed as shown in Table 1(d), the specimens have been formed with varying the feed of 800, 1000 1200 mm/min with keeping other parameters constant. Figure 8 (a) shows that specimen with feed of 800 mm/min was successfully formed but the specimens with feed of 1000 and 1200 mm/min had failed at depth of 6.25 and 5.5 mm, respectively as shown in Figure 8 (b, c). Further, as shown in Figure 6 (c) depth of forming specimens had increased with decreased in the value of feed.

At the lower feed, the more heat generated at interface between tool and work-piece due to slower rolling of the tooltip over the contact surface and rate of the heat dissipated is very slow. The metal is becoming ductile in nature and more straining occurred because of increasing the temperature at forming zone. Hence, the formability of sheet metal is increased. For higher feed, the formability decreased due to lower heat generation at tool interface, faster the tool tip rolls over the contact surface.

3. 4. Influence of Step Size In the fifth set of three experiments plan, the influence of step size with varying wall angle as shown in Table 1(f). As can be seen from results, the specimens had formed without any crack at the 45° wall angle in two 0.1 and 0.25 step sizes as shown in Figure 9 (c, d).

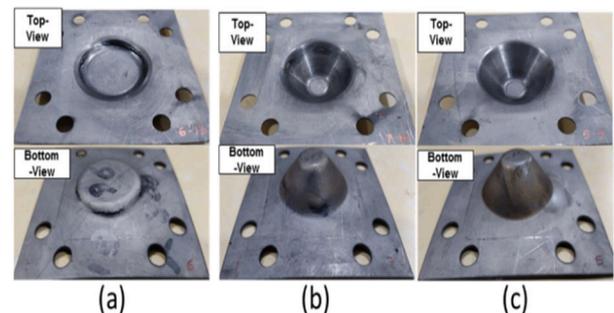


Figure 7. Specimens formed with varying the speed (rpm) of (a) 700 (b) 1000 (c) 1400

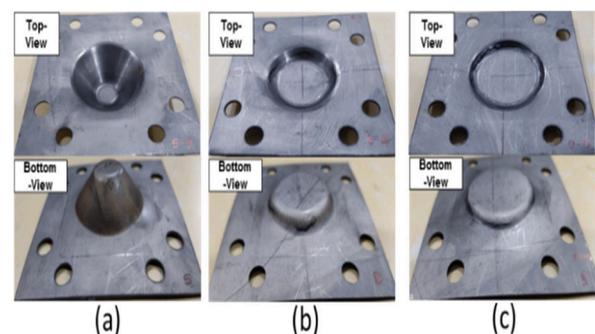


Figure 8. Specimens formed with varying the feed (mm/min) of (a) 800 (b) 1000 (c) 1200

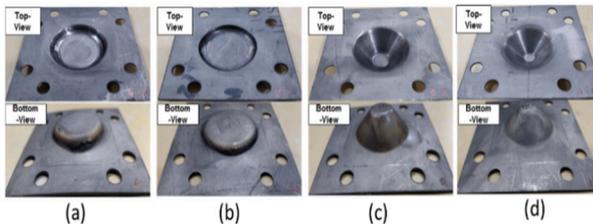


Figure 9. Specimens with varying the step size (mm) with wall angle (a) 0.25, 50° (b) 0.1, 50° (c) 0.25, 45° (d) 0.1, 45°

On the other hand, the specimens with wall angle of 55° early failed at depth of 7.25 mm as shown in Figure 9 (a, b). This shows that wall angle is more significant parameter than step size and, there is no significant effect is found on formability with varying the step size of 0.1 mm and 0.25 mm.

4. CONCLUSIONS

In this study, experimental investigation of single point friction stir incremental forming process of Ti-6Al-4V is performed. The results of the study can be summarized as follows:

- Process parameters, such as wall angle, speed and feed have influence on the formability of sheet metal blank. Formability is increased with a decrease in the wall angle from 55° to 45° and the highest formability is obtained in term of maximum forming depth of 18 mm at wall angle of 45° due to lower the stretching of material. It has been found that the wall angle has significant influence on the formability of sheet metal.
- With an increase in the speed from 700 to 1400 rpm, the formability of sheet metal is increasing of 7.5 mm to 18 mm in term of maximum forming depth. The sheet metal shows higher formability at higher temperature cause of higher rubbing action at contact surface due to increases speed. While formability decreases from 18 mm to 5.5 mm in term of forming depth as the feed increasing from 800 to 1200 mm/min. At higher feed rate, formability is lower due to poor accumulation of heat at contact surface, causes more rate of heat dissipated.
- Furthermore, step size of 0.1 and 0.25 mm did not have any significant effect on formability.
- The most influencing parameters in this process are wall angle followed by tool rotation speed and feed. So with correct combination of these parameters, it can come up to safe forming of the Ti6Al4V blank sheet without additional heat assisted equipment.

In this approach, the present study helps to user to get recommendations about, parameters with their range should be select to form the hard to form material of Ti-6Al-4V by friction stir SPIF process at room temperature.

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Persian Abstract

چکیده

فرآیند شکل دهی افزایشی تک نقطه ای (SPIF) یک رویکرد جدید از روش شکل دهی فلزی انعطاف پذیر است که در آن می توان به اجزای سه بعدی اجازه شکل گیری داد. این فرآیند با قالب کمتر انعطاف پذیر، زمان هدایت کمتر و شکل پذیری بالاتر در مقایسه با فرآیند مهر زنی معمولی مشخص می شود. کار حاضر شامل مجموعه ای از آزمایشات ورق Ti6Al4V به ضخامت ۱ میلی متر با استفاده از فرآیند SPIF اصطکاکی در دمای اتاق و بررسی تأثیر زاویه دیوار، سرعت، تغذیه و اندازه پله بر شکل پذیری ورق است. نتایج نشان داد که حداکثر شکل پذیری نمونه مخروط فروستوم در زاویه دیواره ۴۵ درجه به دست آمد و زاویه دیوار مهم ترین پارامتر است. با افزایش زاویه دیوار و تغذیه، شکل پذیری ورق خالی کاهش می یابد در حالی که با افزایش سرعت چرخش ابزار، شکل پذیری افزایش می یابد. علاوه بر این، همچنین مشاهده شد که اندازه پله تأثیر معنی داری بر شکل پذیری ورق نداشت.
