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Research Article

Fabrication of Saddle-Shaped Surfaces by Flame Forming Process

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ABSTRACT

The flame forming process is widely used to manufacture ship hull plates. The saddle-shaped surfaces have different curvatures in perpendicular angles of planes and the manufacturers face an anti-clastic curvature. In this article, the manufacturing of saddle-shaped surfaces utilizing the flame forming process is investigated. The spiral irradiating scheme is used for forming. In order to study the effects of process parameters (pitch of spiral path, number of irradiation passes, and the movement pattern (In-to-Out or Out-to-In)), several experiments have been carried out. Determining the effect of process parameters for fabrication of this type of sheet leads to the precise manufacturing with reduced costs and lower production time. After the implementation of the experiments, the displacement of the sheet is measured and the saddle-shaped surfaces are manufactured successfully by the spiral irradiating scheme. The final part has large deformations and the curvature can be clearly observed. The deformation of the saddle-shaped surface is noticeably increased by reducing the spiral path pitch (110% increase in height of the center point of the sheet). Also, it is proved that the Out-to-In spiral path movement pattern leads to larger deformations than In-to-Out ones. Besides, the deformations of manufactured saddle-shaped surfaces are increased by increasing the number of spiral passes.

1. Introduction

The flame forming process is introduced as a leading process to form thick sheets and plates. It is broadly used to fabricate ship hull pieces [1-5]. No regular technique exists for effective formation of the parts due to the exclusive nature and features of the flame forming process, hence the parts usually are made by the empirical intuition of the operators. The flame forming process has good automation characteristics such as reducing the irradiation time, higher productivity and proper repeatability. But the heating nature of the process and the uncertainties that exist in the flame forming prevents the expansion of the process productivity. The tooling cost decreases due to the replacement of the bending die and external punch with the flame torch and no external force exists in the flame forming process. The flame forming process consists of two stages: 1) the heating stage: in which the irradiated heat increases the temperature of a specified location of the sheet, 2) the cooling stage: in which a plastic strain is induced due to lateral tension of cold zones and the curvature is produced by local bending.

The number of researchers who focused on the subject of flame forming are few. Ueda et al. [6] developed a computer-aided process planning (CAPP) system and suggested a simple formula to find the

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curvature according to the selected flame forming process parameters. In another research, Ueda et al. [7] proposed a new formula using the finite element method (FEM) to predict the induced strain during the flame forming process. A good agreement has been obtained between the results and the proposed equation. Shin et al. [8], Clausen [9], Ishiyama et al. [10] and Yu et al. [11] published researches to comprehend the mechanism of the flame forming process numerically. However, they did not extract equations from their analysis results for the flame forming process. Jang and Moon [12] developed an algorithm to determine the curvature of plates due to line heating by using the flame gun during the forming. The algorithm calculates the curvature by assessing the location of some points along specified lines before and after heating. The method was only applicable to straight heating lines but was not able to calculate the curvature of complicated heat source movement strategies. The line heating method is a common way of bending plates in the flame forming process. Moshaiov and Vorus [13] and Moshaiov and Shin [14] investigated the mechanics of bending and forming by line heating in the flame forming process and finally, a model was presented based on a strip perpendicular to the heating line supported by springs. Also, some researches focused on finding the proper heating and cooling strategies to form complicated shapes based on the results of forming simple surfaces. Shao et al. [15] used the flame as a heating source for heat-treating (solution of the precipitated particles) and then forming and rapid quenching of aluminum alloys. The direct flame impingement (DFI) heating method can be used as a powerful tool for forming complicated shapes. Hemmati et al. [16] used finite element analysis with ANSYS software to investigate the material deformation as a key parameter of forming. The thermal analysis of the sheet is done using a Gaussian heat source and the results of large deformation thermos-elastoplastic analysis are compared with the analytical and experimental results. At last, it can be concluded that using the curvilinear irradiating schemes is necessary to form complicated shapes from a flat sheet. It is worth noting that several studies have been carried out on the two-dimensional flame forming process but, little research has been conducted in the field of the three-dimensional flame forming due to the extreme complexity of the process hitherto. In this article, the flame forming process of saddle-shaped surfaces from a flat rectangular sheet will be investigated. For this purpose, a new irradiating scheme (spiral path) is used for the forming of saddle-shaped surfaces. Also, the effects of irradiating scheme factors such as spiral path pitch, number of the irradiating passes and the movement patterns (Out-to-In and In-to-Out movement pattern) on the deformation of the saddle-shaped surface will, additionally, be studied.

2. Materials and Methods

The initial blanks are cut and prepared from a plate of as-received mild steel. The dimensions of the rectangular blanks are 400 mm (Length) × 300 mm (Width) × 12 mm (Thickness). The flame forming is carried out using an oxy-acetylene flame torch installed on a 2-axis computer numerical control (CNC) machine. In Fig. 1, the experimental set-up and a manufactured saddle-shaped sample by the spiral irradiating scheme are shown. Table 1 describes the heating conditions of the flame forming process for the manufacturing of the saddle-shaped surfaces.

Fig. 1. a) The heat irradiation set-up b) sample of flame formed saddle-shaped surfaces with the spiral irradiating scheme c) schematic illustration of the spiral path movement.

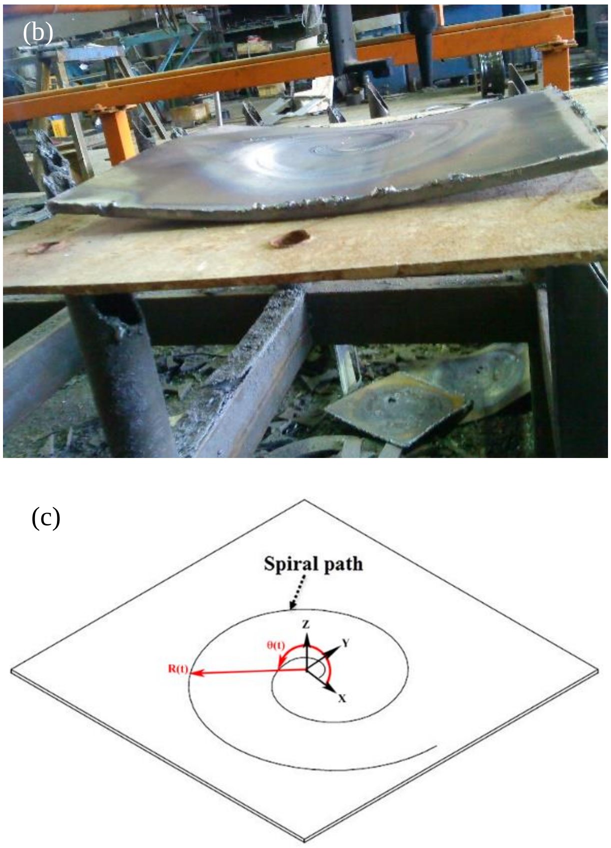

Fig. 1. Continue

Table 1. Flame forming conditions for the fabrication of saddle-shaped surface

Oxygen flow rate (Liter per minute)	70 lpm
Oxygen pressure	700 kPa
Acetylene flow rate (Liter per minute)	20 lpm
Acetylene pressure	100 kPa
Distance between the torch tip and the workpiece (stand-off distance)	45 mm
Feed Speed (mm/s)	18 mm/s

The spiral irradiating scheme is used for the fabrication of the workpiece. Fig. 1(c) shows a schematic view of the process outline. The location of the torch can be determined using equation 1.

$$r(t) = r_0 + \frac{at}{T} \qquad (1)$$

$$\theta(t) = \frac{2\pi t}{T}$$

r_0 is the radius of starting circle (75 mm), a is the spiral pitch (20 mm), t is time and T is the time of traveling the torch 2π radian. $r(t)$ and $\theta(t)$ are the radial and angular coordinations of the torch in the 2D polar coordinate system. The feed speed of torch in the CNC machine is constant (18 mm/s), so, the angular velocity ($\dot{\theta}(t) = \omega(t) = \frac{2\pi}{T}$) is not constant.

The heat transfer in flame forming is important. The basic equation of heat transfer can be written as Equation 2 [17].

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + q_v = \rho c_p \frac{\partial T}{\partial t} \qquad (2)$$

Where k is material conductivity coefficient, q_v is the rate of energy generation per unit volume, ρ is the density and c_p is the specific heat capacity of the sheet. The irradiated heat by the flame is the q_v term of the heat transfer equation. It is a moving heat source. Part of the received heat is transferred in the sheet according to the material conductivity coefficient (k) and the remain increases the temperature of the sheet according to the value of ρc_p coefficient. The increase in temperature of the sheet causes a decrease in yield and ultimate tensile strength of the sheet and also phase transformation. The effect of work hardening is eliminated and the density of dislocations is reduced. After traveling the torch, the cooling process starts and the heat decreases based on the heat conduction of the sheet. Phase transformation begins again and tensile stress is produced between the irradiated line and the solid material at the vicinity of the irradiated line. This tension causes the sheet to bend.

3. Results and discussion

Based on observations made during the experimental tests, it can be concluded that the spiral irradiation movement of the torch on a square or rectangular plate will create a saddle-shaped surface. The curvature value of the formed saddle-shaped surface can be used as a key parameter to assess the flame forming process. In Fig. 2, two main selected paths for measuring the displacement of the saddle-shaped surface are shown. The vertical displacements of defined paths A and B are measured by an Easson ENC-565 coordinate measuring machine (CMM). The vertical displacement is associated with the Z direction in Fig. 1(c). Fig. 3 shows the vertical displacement measurement along the two main paths, namely A and B, for the flame formed sample with the spiral irradiating scheme (spiral pitch=20 mm, Spiral irradiating pattern= In-to-Out, Number of spiral passes=1). The center point of the sheet (point H) is important in this investigation. The curvature of the saddle-shaped surfaces is different in perpendicular axis of the planes. As can be seen in Fig. 2, the sheet is deformed with a positive curvature regarding path A and negative curvature regarding path B. Point H is the intersection of the paths and the height of sample point H increases by decreasing the curvature radius. In this article, rather than standing for curvature radius, the displacement of sample point H represents the variation of curvature. The curvature can be calculated by knowing the width of the sheet and the difference of height between the sample point H and the lateral edge of the sheet.

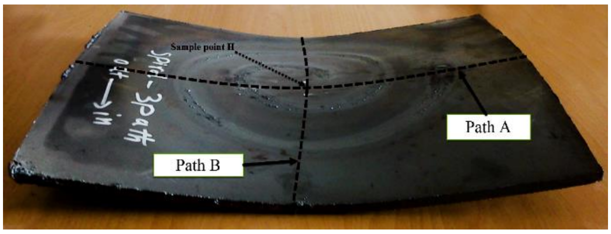

Fig. 2. Two main paths for measuring the values of curvatures for obtained saddle-shaped surface (Spiral path pitch= 10 mm, Spiral irradiating pattern= Out-to-In, Number of the spiral passes=3).

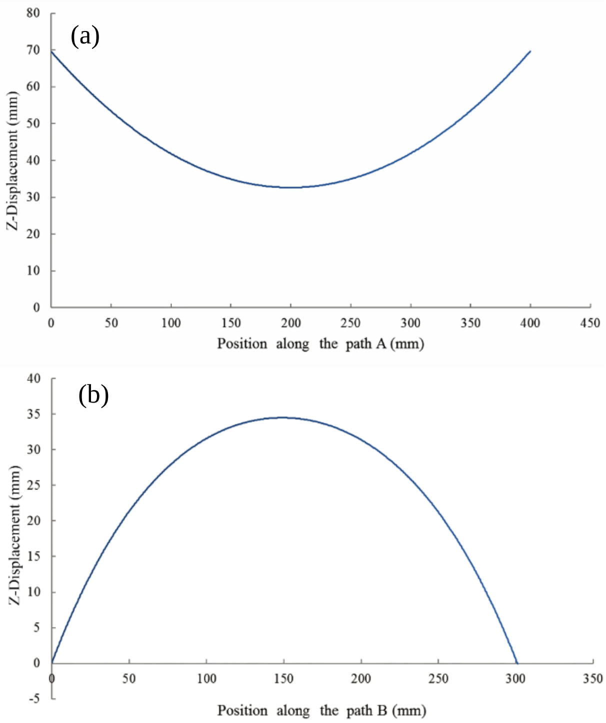

Fig. 3. Vertical displacements along two main paths for flame formed sample a) path A, b) path B (Spiral path pitch=20 mm, Spiral irradiating pattern= In-to-Out, Number of the spiral passes=1).

The vertical displacement of the plate in Fig. 3 shows that the curvatures of the flame formed section that has a spiral irradiation scheme are remarkably large. The curvature along path A is positive while the curvature along path B is negative (anti-clastic curvature). So, the spiral irradiation scheme is an appropriate heating strategy for the fabrication of saddle shape surfaces with large curvatures.

Three main process parameters are the spiral path pitch, number of spiral passes, and movement patterns (In-to-Out and Out-to-In spiral paths). These parameters affect the vertical displacement (Z direction) of the surface manufactured with the flame forming process. The effect of flame forming process parameters on the vertical displacement of formed plates will be investigated in the following sections.

3.1. Effect of spiral path pitch

To investigate the effect of spiral path pitch on the vertical displacement of formed saddle-shaped parts, some experiments with different spiral path pitches, such as 10 mm, 20 mm and 30 mm ones, are performed. The vertical displacement of sample point H in Fig. 2 is selected as an independent variable. Fig. 4 shows the Z-displacement of sample point H for saddle-shaped surfaces obtained by spiral paths with different pitches. As it is seen, with an increase in the spiral path pitch, the vertical displacement of sample point H decreases. In other words, flame forming of spiral paths with smaller pitches leads to forming saddle-shaped surfaces with larger deformations. The smaller spiral path pitch applies more heat flux on the surface of the plate due to more irradiation length and curvature increase. So, the area of the plastic deformation zone, due to heating increases for smaller spiral path pitches. By decreasing the spiral pitch from 30 mm to 10 mm, the height of sample point H increases from 20 to 42 mm (110% increase).

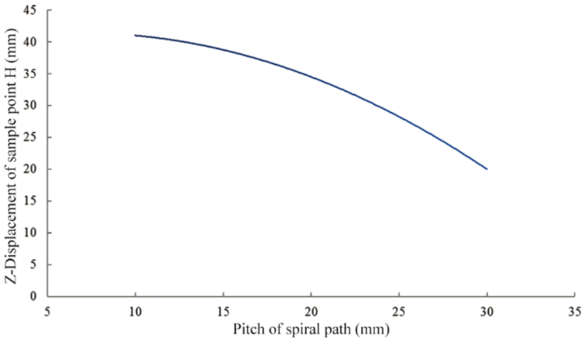

Fig. 4. Vertical displacements of sample point H for flame formed samples by different spiral path pitches (Spiral irradiating pattern= In-to-Out, Number of the spiral passes =1).

3.2. Effect of movement pattern

Two different movement patterns can be defined according to the torch movement. The flame torch may start the spiral path from the inside towards the outside of the plate (In-to-Out) or start the spiral path from the outside towards the inside (Out-to-In) of the plate. Fig. 5 shows the vertical displacement of the sample point H for the flame formed saddle-shaped surface for In-to-Out and also Out-to-In spiral pattern movements.

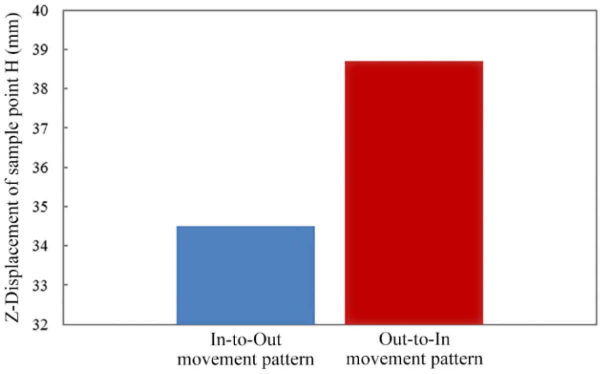

Fig. 5. Vertical displacements of sample point H for In-to-Out and Out-to-In spiral movement patterns (Spiral path pitch=20 mm, Number of the spiral passes =1).

The results of Fig. 5 show that the vertical displacement created by the Out-to-In spiral pattern leads to higher curvature than the In-to-Out movement patterns. This is due to the geometrical constraints while deformation. When formed by Out-to-In spiral pattern movements, the lateral edges of the plate are free and can distort more easily than its interior zone. The inner area of the plate is constrained by peripheral material and the plastic deformations of the heated zone make a limited displacement on the plate. In the In-to-Out movement patterns, the torch moves from inner zones to outer zones. When inner zones heated up, the deformations of the inner zones of plate affected the total deformation of the plate and the total stiffness of the plate was increased. But, the portion of plastic deformation of outer zones on total curvature decreased due to an increase in the total stiffness of the plate in the In-to-Out movement patterns. Conversely, in the Out-to-In movement pattern, the torch moved from the outer zones of the plate to their inner zones. The plastic deformation of the outer zones of the plate has little effect on the total stiffness of the plate and the total stiffness of the plate is not noticeably increased by the Out-to-In movement patterns. So, the portion of the plastic deformation of the inner zones of the plate is substantial and the total deformation of the plate in the Out-to-In movement patterns will increase in comparison with the In-to-Out ones.

In order to further investigate the effects of stiffness on forming behavior in flame forming process, an experimental study was performed. For this purpose, two plates were flame formed with two different spiral paths. In these spiral paths, the irradiating scheme was the same as the In-to-Out movement patterns, the spiral pitch and the end point of the paths were similar but the radius of the starting circle was different. In other words, two spiral paths with the radius of starting circle as 55, 75 mm, similar pitch of spiral path as 20 mm and the same end point of spiral path were employed. The results of Z-displacement of sample point H for saddle-shaped surfaces obtained by spiral paths with starting circle that have different radiuses are shown in Fig. 6. As is seen in Fig. 6, the maximum value of Z-displacement of sample point H is obtained for the spiral path with radius of starting circle at 75 mm. In other words, although the Z-displacements of sample point H for spiral scheme with radius of starting circle of 55 mm are expected to be higher, due to more heating length, more induced heat flux, and consequently more plastic deformations, however, more displacements for sample point H in spiral path with radius of starting circle of 75 mm are observed. Hence, it is concluded that the effects of stiffness of inner areas are more than the increase of heating length and this proves that the stiffness created in the plate considerably decreases the Z-displacement of sample point H.

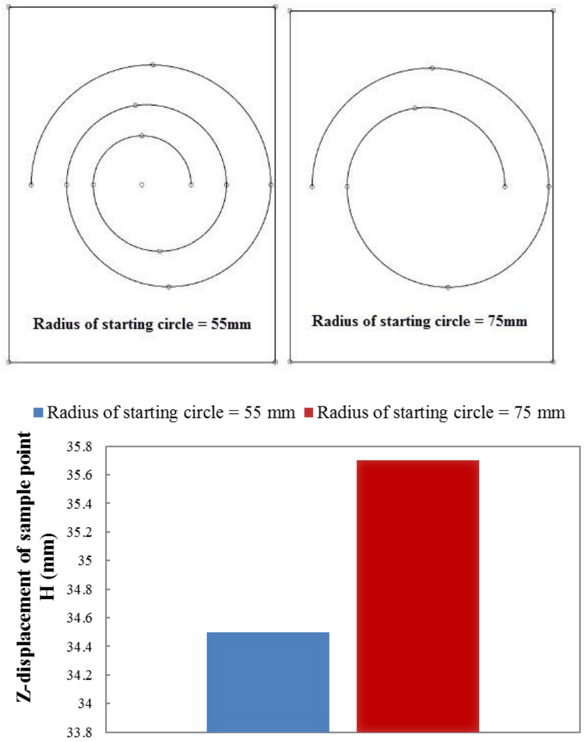

Fig. 6. The Z-displacement of sample point H for saddle-shaped surfaces obtained by spiral paths with different radius of starting circles.

3.3. Effect of number of spiral passes

Figure 7 shows the effect of the number of spiral passes on the vertical displacement of the sample point H in flame formed saddle-shaped surfaces.

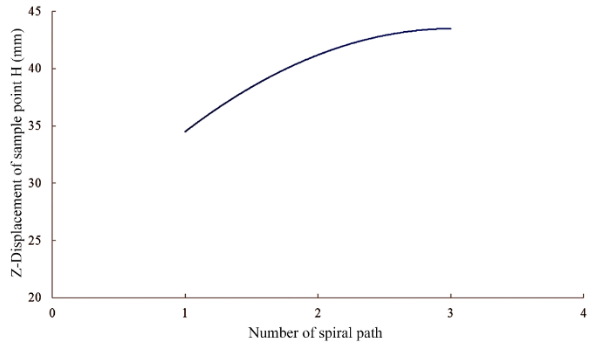

Fig.7. Vertical displacements of sample point H by varying the number of spiral passes of flame formed saddle-shaped surface (Spiral path pitch=20 mm, Spiral irradiating pattern= In-to-Out).

Figure 7 shows that the vertical displacement of sample point H increases by increasing the number of spiral passes. Additionally, an increase in the number of spiral passes, causes a decrease in the vertical displacement and the graph reaches the plateau line which can be called the saturation line of induced plastic strain and total curvature. This is due to increasing the forming stiffness of the plate after each step of flame forming has been conducted.

4. Conclusions

In this article, the flame forming of a saddle-shaped surface was experimentally explored with a spiral irradiation scheme pattern. The results of the current study can be listed as follows:

- The experimental results show that the spiral movement of the torch is a suitable scheme for manufacturing a saddle-shaped surface with large amounts of deformations.
- It was shown that sheets with higher curvatures can be obtained by implementing the spiral path with smaller pitches due to inducing more heat fluxes into the sheet because of longer irradiation length.
- The vertical deformation of the saddle-shaped surface increased by increasing the number of spiral passes. The rate of increase in the vertical displacement decreases by increasing the number of spiral passes.
- Using the Out-to-In movement pattern leads to the manufacturing of a saddle-shaped surface with larger deformations.

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ساخت قطعات زینی شکل با کمک شکل دهی شعله ای

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چکیده

فرآیند شکل دهی شعله ای یکی از فرآیندهای مورد استفاده در ساخت قطعات بدنه های کشتی بخصوص قطعات با انحنای مشخص می باشد. از جمله مهمترین ویژگی های سطوح زین اسبی می توان به وجود دو شعاع انحنای متضاد در صفحات عمود بر ورق اشاره نمود که سازندگان را با مشکلات فراوانی روبرو نموده است. در این مقاله به بررسی ساخت قطعات زینی شکل با استفاده از روش شکل دهی شعله ای پرداخته خواهد شد. بدین منظور از حرکت مارپیچ (اسپیرال) شعله جهت شکل دهی استفاده شده است و اثر پارامترهای فرآیند شامل گام مارپیچ، تعداد دفعات تابیدن شعله و طرح حرکتی تابش (حرکت شعله از شعاع داخل به سمت شعاع بیرونی ورق و یا حرکت از شعاع بیرونی به سمت شعاع داخلی) مورد بررسی قرار گرفته است. تعیین اثر پارامترهای فرآیند می تواند کمک شایانی به ساخت دقیق تر قطعات زین اسبی با هزینه کمتر و زمان تولید پایین تر بنماید. کلیه آزمایش‌ها به شکل تجربی انجام شده و پس از شکل دهی میزان ارتفاع قسمت میانی ورق بعنوان نماینده ای از انحنای ایجاد شده در ورق اندازه گیری شده است. قطعات زینی شکل با کمک حرکت مارپیچ شعله با موفقیت ساخته شده و قطعات نهایی دارای تغییر شکل بالا بوده اند به گونه ای که به آسانی انحنای قطعه شکل دهی شده قابل مشاهده می باشد. میزان تغییر شکل سطح ورق زین اسبی (ارتفاع نقطه میانی ورق) با کاهش گام مارپیچ و افزایش تعداد دفعات تابش شعله به شکل قابل توجهی افزایش یافته است. با کاهش شعاع مارپیچ ارتفاع نقطه میانی ورق تا ۱۱۰ درصد افزایش یافت که تغییر قابل توجهی در انحنا می باشد. همچنین نتایج تجربی نشان می دهند که استفاده از طرح حرکت شعله از سمت شعاع بیرونی به سمت شعاع داخلی موجب دست یابی به تغییر شکل بالاتر در نقطه میانی ورق می گردد که نشان دهنده شعاع انحنای پایین تری می باشد.

واژه‌های کلیدی: فرآیند شکل دهی شعله ای، سطوح زین اسبی، طرح تابش مارپیچ (اسپیرال)، گام مارپیچ