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# Experimental investigation of the ovality of holes on pre-notched channel products in the cold roll forming process

B. Shirani Bidabadi[a], H. Moslemi Naeini[b,*], R. Azizi Tafti[c], S. Mazdak[d]

[a] Department of Mechanical Engineering, Daneshpajoohan Higher Education Institute, Isfahan 84156, Islamic Republic of Iran
[b] Faculty of Mechanical Engineering, Tarbiat Modares University, P.O. Box, 14115-143 Tehran, Islamic Republic of Iran
[c] Department of Mechanical Engineering, Faculty of Engineering, Yazd University, P.O. Box 89195-741, Yazd, Islamic Republic of Iran
[d] Faculty of Mechanical Engineering, Tafresh University of Technology, Tafresh 39518, Islamic Republic of Iran

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ABSTRACT

Owing to the increasing use and demand of pre-notched sections in automotive and construction industries, cold roll forming is a suitable production process because of its high efficiency. However, some defects such as ovality in the holes might reduce the quality of the products. In this study, the conversion of pre-notched strips into channel section products was investigated experimentally during a cold roll forming process. The effects of a number of features such as the flower pattern (the forming angle increment), uphill and downhill strategies, the horizontal distance between the stands, the lubrication condition, the longitudinal distance between the holes, the distance between the holes and the product edge, the hole diameter, the width of the channel web and flange, and the strip thickness on the ovality are discussed. The results showed that the forming angle increment has the most significant influence on the hole ovality, whereas the web width and lubrication condition are of the least importance. Furthermore, comparing the results of the forming of the pre-notched strips with those of strips without holes showed that piercing the holes intensifies hole ovality.



## 1. Introduction

The cold roll forming process is a cost-effective, mass production process used to fabricate constant cross-section parts with desirable lengths. In recent years, the demand for semifinal pre-notched components has increased significantly. Therefore, much effort has been expended to produce high quality products using the cold roll forming process.

Generally, there are two common methods for producing pre-notched products. In the first method, after forming the initial strip into a product without perforations, the holes are punched at the predetermined positions. This method is slow and prevents locating the holes in positions with poor accessibility. In the second method, the holes are made by two punch rollers in the first stand of a cold roll forming line after which the pre-notched strip undergoes the forming operations. In this method, different holes can be mass produced at the desired positions. High production speed and reliability are the characteristics of this second method (Halmos, 2006). However, the ovality of the holes is a major issue in the products fashioned using this method.

### 1.1. Ovality

As shown in Fig. 1, the holes' ovality results from a hole being stretched in one direction and compressed in the other. Therefore, the ovality percent (O) can be calculated using Eq. (1):

$$O = \frac{d_1 - d_2}{d} \times 100 \quad (1)$$

where $d$ is the initial hole diameter before deformation and $d_1$ and $d_2$ are the largest and the smallest diameters after the deformation.

Many studies have been conducted to determine the parameters responsible for product quality in the cold roll forming process. Bhattacharyya et al. (1984) reported that the effect of the forming angle at the first and last stands is higher than that of the other stands to produce channel products with no buckled edges. They concluded that the deformation length depends on the geometry of the product section and the initial yield strength of the strip using an analytical and experimental study (Bhattacharyya and smith, 1984). McClure and Hanhui (1995) achieved consistent results with experimental samples by simulating the cold roll form-

* Corresponding author. Fax: +98 21 82886544.
*E-mail addresses:* Behrooz.shirani@modares.ac.ir, Behrooz.shirani@gmail.com (B. Shirani Bidabadi), moslemi@modares.ac.ir (H. Moslemi Naeini).

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ing process of a channel section product using the commercial finite element software, ABAQUS. Heislitz et al. (1996) found an appropriate approximation for the longitudinal strain distribution using a finite element simulation of the roll forming process of a channel product employing PAM-STAMP software. Panton et al. (1996) studied the normal strains in the longitudinal and the transverse directions, as well as the shear strain and developed analytical relations to estimate them. Hong et al. (2001) simulated a cold roll forming process in COPRA software and concluded that the roll diameter, the strip thickness, mechanical properties of the strip and the speed of the production line have a significant effect on the deformation length. They also reported that the risk of edge buckling was increased when a longitudinal edge strain, was higher than the yield strain. Han et al. (2001) simulated a hat shaped section using a B-spline finite strip and concluded that the horizontal distance between the stands, the forming angle increment, the strip yield strength, the width of the product web and the width of the outside flange had significant effects on the longitudinal edge strain. Furthermore, they reported that the angle of the first stand should be lower than a specified amount to avoid edge buckling (Han et al., 2002). Tajdari and Farzin (2002) found that the shear stress plays an important role in the elastic-plastic behavior of the strip. Tehrani et al. (2006) used ABAQUS software to study the edge buckling of a channel section. According to their results, to avoid edge buckling, the first forming angle should not exceed a specified value. They also introduced a limit for the forming angle to prevent edge buckling of the circular sections (Salmani Tehrani et al., 2006). Lindgren (2007) studied the longitudinal edge strain and the deformation length of a channel product using finite element analysis of the cold roll forming of a channel product employing MARC/MENTAT software. He concluded that the strip strength increased the longitudinal edge strain and decreased the deformation length. He also presented relationship for the longitudinal edge strain and the deformation length. Bui and Ponthot (2008) used METAFOR finite element code to investigate the effects of the production line speed, the horizontal distance between the stands, the friction coefficient between the strips and the rolls and the mechanical properties of materials of the strip on the longitudinal strain, the strip geometry and the bend angle along the deformation length. They found that the work hardening coefficient of the strip increased the longitudinal edge strain. Paralikas et al. (2008) simulated the roll forming process using ANSYS/LS-Dayna software and found that the rate of forming, the horizontal distance between the stands, the coefficient of friction, the gap between the upper and lower rolls and the rolls diameter increased the maximum longitudinal edge strain. They also reported that the horizontal distance between the stands had the most effect on the longitudinal edge strain, but the roll diameter and the forming speed were the least effective (Paralikas et al., 2009). Paralikas et al. (2011) concluded that the downhill strategy can greatly reduce the longitudinal edge strain in roll forming of V-shape and U-shape section products. Zeng et al. (2008) analyzed the edge buckling and the distribution of the strip thickness by simulating the roll forming process using ABAQUS software. They concluded that a strip material with a low work hardening coefficient and a high yield and ultimate strength decreased the edge buckling and the thinning defects. Zeng et al. (2009) used a hybrid method experimental design and finite element analysis to optimize the roll diameter and the forming angle increment so that the springback and the longitudinal edge strain were minimized. Park and Anh (2011), using a combined method of finite element simulation, neural networks and genetic algorithms produced U-shape and V-shape section products with the lowest possible stand number and the least number of buckling and springback defects. Wiebenga et al. (2013) attempted to reduce the longitudinal bow and the springback by setting the gap between the upper and the lower rolls at each stand, the horizontal distance between the stands and the downhill strategy.

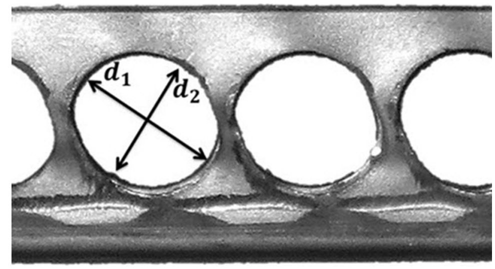


**Fig. 1.** Ovality defect in experimental tests.

There are a limited number of studies in the field of the cold roll forming process of pre-notched strips. Watari and Ona (1998) conducted experiments to investigate the influence of factors affecting the edge buckling, twist and the longitudinal bow of pre-notched channel and V-shaped products with square holes. They reported that the limited forming range of pre-notched strips depended on the hole size, the distance between the holes and the second moment of inertia of the cross section (Watari and Ona, 2001). Cavaguti and Ferreira (2010) analyzed the roll forming process of a channel product with rectangular holes in its web using SUPERFORM software. They reported that a small diameter of the lower roll together with application of a downhill strategy reduced the edge buckling of the web holes.

This review the literature showed that currently there is no research focused on the hole ovality defect in the pre-notched roll formed products. In the study reported in this paper, variables affecting the holes ovality in pre-notched channel section were studied. These factors included the flower pattern (the forming angle increment) of the profile, uphill and downhill strategies, the internal horizontal distance between the stands, the lubrication condition, the space longitudinal distance between the holes, the space distance between the holes and the product edge of the channel, the diameter of holes, the width of the channel web, flange size, and the strip thickness. Finally, the effects of each variable are discussed, and some recommendations for reducing the holes ovality defect are presented.

### 1.2. Geometry of a pre-notched channel product

The geometrical characteristics of a pre-notched symmetric channel section product are shown in Fig. 2.

As shown in Fig. 2, b is the distance between the holes and the product edge, a is the distance between the holes, d is the diameter of the holes, t is the strip thickness, h is the flange width, r is the inner radius of the corner, and w is the width of the web. These geometrical parameters can affect the holes ovality (Watari and Ona, 1998, 2001).

Groche et al. (2008) proposed using an inner corner radius that was equal to the strip thickness to reduce the springback phenomenon. On the other hand, if the inner corner radius is less than the strip thickness, crack occurrence will be unavoidable outside the bend (Suchy, 2006). Therefore, the inner radius was maintained equal to the strip thickness.

In the design process of a pre-notched channel product, some relationships between the flange width, the strip thickness, the holes diameter, the distance between the holes and the distance between the holes and the edge should be considered. Therefore, in order to generalize the results of this study to similar products with different sizes, three dimensionless variables were considered according to the results of some references (Watari and Ona, 1998, 2001) as given in Table 1. The levels of each parameter in the exper-

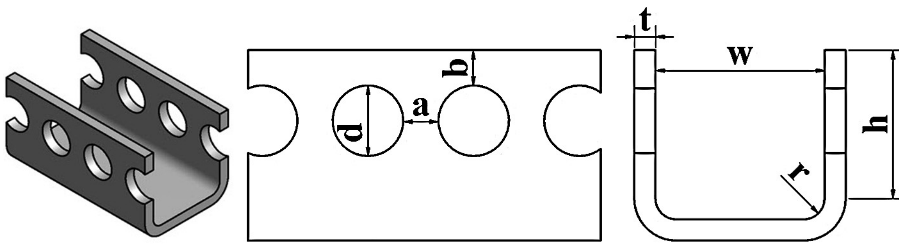


**Fig. 2.** the geometry of a pre-notched symmetric channel section.

**Table 1**
Geometric parameters of a symmetric pre-notched channeled product and their surveyed quantities.

| Geometric variables | Symbol | Quantities |
|---|---|---|
| Strip thickness (mm) | $t$ | 1,1.25,1.5 |
| Web width (mm) | $w$ | 20,30,40 |
| Ratio of holes distance from the edge to strip thickness | $b/t$ | 2,3.33,4.7,6 |
| Ratio of holes spacing to strip thickness | $a/t$ | 2,7.33,10.67,16,26 |
| Ratio of holes diameter to flange width | $d/h$ | 0.25,0.375,0.5,0.625 |

**Table 2**
The quantities of cold roll forming line and tested values.

| Roll forming line variables | symbol | Quantities |
|---|---|---|
| Flower pattern (degree) | F.P | 0,45,80<br>0,30,60,80<br>0,15,30,45,60,75,80 |
| Inter-distance (mm) | I.D | 350,400,450,500 |
| Uphill-Downhill (mm) | U&D | −4, 0, +4 |
| Lubrication | Lub | Non-lubricated, with oil |

imental test were determined based on the punching limits (Suchy, 2006) and the capacity of the production line.

### 1.3. Variables of roll forming line

Roll forming variables including the flower pattern, the horizontal distance between the stands, the uphill and downhill strategies, and the lubrication type also effect the hole ovality defect (Halmos, 2006). The analyzed values for each variable are presented in Table 2 based on the limitations of cold roll forming lines (Bhattacharyya et al., 1984; Halmos, 2006) and the experimental line production being used in this study.

With respect to the oil lubrication, the initial strips were completely impregnated with an oil of viscosity 10 Pa.s, and a lubrication jet was used during the forming process to spray oil on the work.

## 2. Experiments

### 2.1. Roll forming machine specifications

Experimental tests were performed on a cold roll forming machine with seven stands (Fig. 3). Using this apparatus, it was possible to accurately position each stand in the horizontal and vertical directions.

In some cases, in order to feed the initial strip aligned to the production line, a series of side guide rolls were used. To produce channels with different web widths, three-piece upper and lower rolls were designed and fabricated in which a cylindrical spacer was placed between the two lateral rolls. The spacer thickness determines the web width. In Fig. 4 a pair of upper and lower rolls is shown in which the lower roll has a spacer (B) and two lateral rolls (A).

The line speed was set at 0.1 m/sec. Filler gauges were used to adjust the roll gap to the strip thickness at each stand. As shown in Fig. 5, the first stand, which fed the strip smoothly into the next

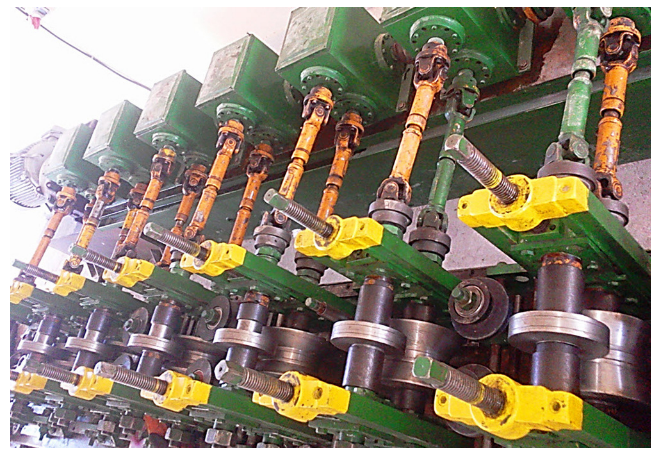

**Fig. 3.** Cold roll forming line.

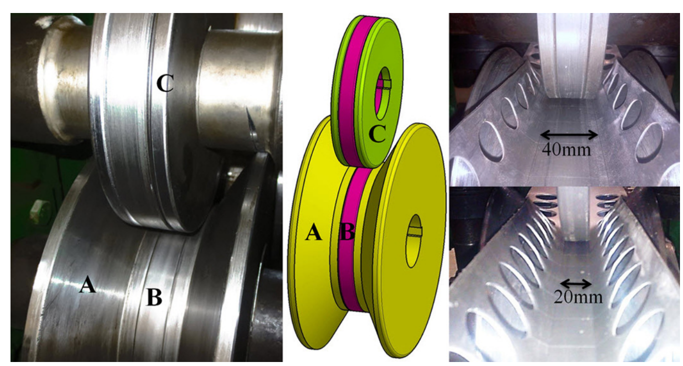


**Fig. 4.** Three-piece rolls used in the experimental tests (right) to produce different web widths (left) and their rolls schematics (middle).

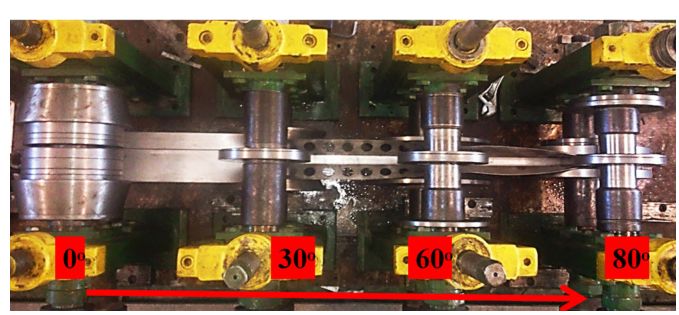


**Fig. 5.** A sample being formed by three stands.

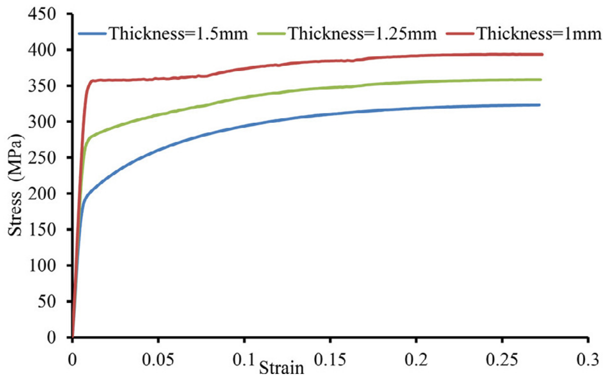


**Fig. 6.** The true stress-strain curves of three strip thicknesses formed in the experiments.

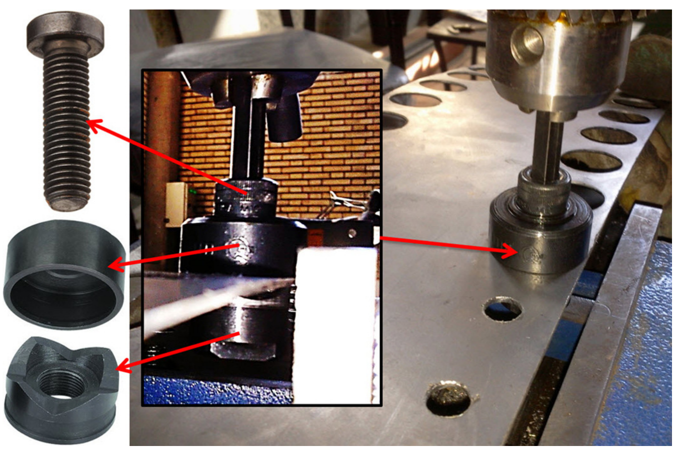

**Fig. 7.** Punching the strip with a knockout punch.

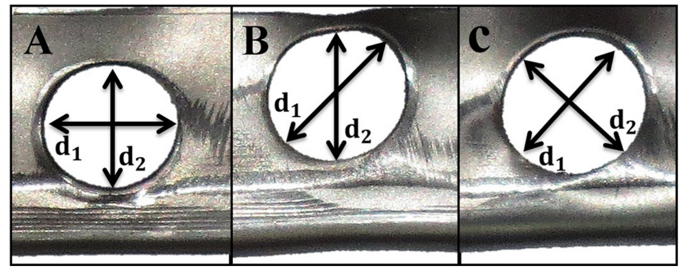


**Fig. 8.** Three general types of holes ovality.

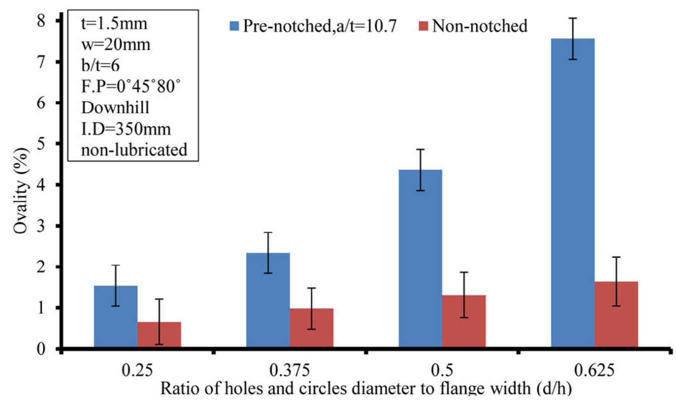


**Fig. 9.** Comparing the ovality in pre- notched and non-notched products.

stand, had cylindrical rolls and was not dedicated to forming samples.

### 2.2. Sample preparation

The strips used in the experimental tests were prepared from ASTM A283 Grade-C steel sheets whose stress-strain curves are presented in Fig. 6 for thicknesses of 1, 1.25, and 1.5 mm.

The length of the strips was three times longer than the horizontal distance between the stands. The holes with diameters of 10, 15, 20, and 25 mm were punched at the middle third length of the strip with the given distance from the strip edge and distance from each other (Fig. 7).

To determine the effects of holes on the strip deformation, circles with specific diameters were scratched on non-notched strips at specified distances from the edge.

### 2.3. Ovality measurement

After forming a strip, the largest and the smallest diameters of the middle holes on both sides (flanges) of channel were measured using a digital micrometer with a resolution of 0.001 mm, and the ovality was specified by Eq. (1). For each experimental model two channels were prepared, formed and their middle holes were measured. If the ovality results were approximately close, the average value was considered as the ovality. But if the ovality difference was significant (more than 10%), a third sample was tested. Hence, for each result, the measured ovality was based on the measured results of four holes a minimum. Using this method, 181 channels were prepared, formed and measured which comprised 8 non-notched and 173 pre-notched channel sections.

## 3. Results and discussion

As a result of roll forming of pre-notched strips, three general types of hole ovality were observed as shown in Fig. 8.

The type A ovality was observed in samples whose holes were close to the bend line and the distance between the holes was long. Therefore, according to the deformation of two areas, (the area between the holes and the area between the holes and the strip edge) it can be concluded that the difference between the longitudinal and the transverse strains had a significant effect on the hole ovality type A. In cases where the holes were close to the strip edge and the distance between the holes was long, type B ovality occurred. Hence, it appeared that the longitudinal strain between the holes and the strip edge and the shear strain between the holes dictated the type B ovality. The type C ovality was found in cases where the holes were close together. It appeared that the shear strain between the holes had a major influence on the type C ovality.

### 3.1. The effect of holes on the ovality

The ovality of pre-notched and non-notched samples at different ratios of holes and circle diameter to flange width is displayed in Fig 9. This exhibits the influence of the holes themselves on the ovality.

According to Fig. 9, increase of the ratio of holes and circles diameter to flange width increased the ovality in both pre-notched and non-notched products respectively. It was also observed that the hole ovality of the pre-notched products was higher than the circle ovality of non-notched products, because the holes reduced the strip resistance to deformation. The ovality of non-notched products was caused by different strains in the longitudinal and the transverse directions. Since the hole ovality is more sensitive to the ratio of the hole diameter to flange width, compared to the

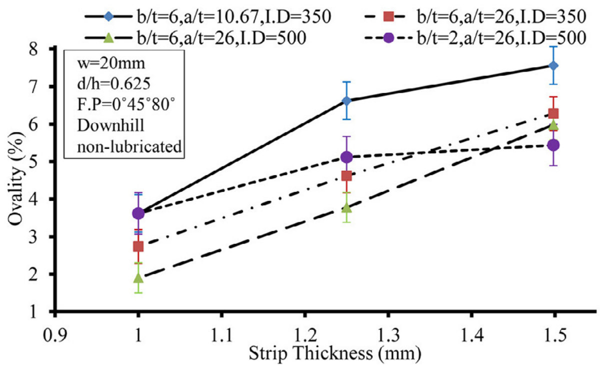


**Fig. 10.** Diagram of the effect of the thickness on ovality.

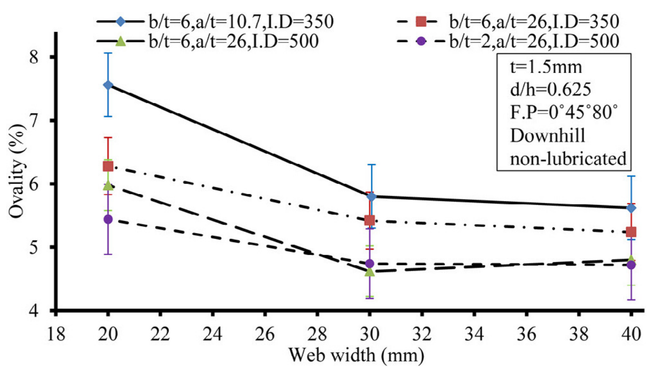


**Fig. 11.** Diagram of the effect of the web dimension on ovality.

circle ovality (Fig. 9), it can be concluded that the holes in the pre-notched strips enhanced the strain between the longitudinal and the transverse directions.

### 3.2. Strip thickness effects on holes ovality

In Fig. 10 the influence of the strip thickness on the holes ovality is shown.

As can be seen in this figure, the strip thickness increased the ovality, because an increase in strip thickness caused an increase in the peak longitudinal membrane strain of the flange (Han et al., 2001), which directly affected the longitudinal and the transverse strains between the holes.

### 3.3. Web width effect on the hole ovality

The effect of the web width on the hole ovality is represented in Fig. 11.

As shown in Fig. 11, increasing the web width will lead to a slight decrease in the hole ovality. Although the web width does not have a significant effect on the flange strains, increasing the web width reduces the peak longitudinal membrane strain (Han et al., 2001) and the flexural rigidity of the section, thereby decreasing the hole ovality by reducing the bowing of the channel.

### 3.4. The effect of the ratio of holes spacing to strip thickness on the hole ovality

Fig. 12 shows how the spacing of the holes to strip thickness affects the hole ovality.

As it can be seen in Fig. 12, in strips with a fixed thickness, increasing the distance between the holes reduces the holes ovality initially, and then, this effect is diminished. Analyzing the hole ovality types revealed that with an increase of the hole spacing,

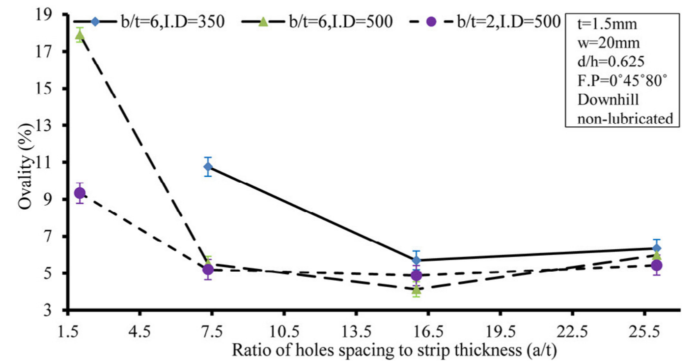


**Fig. 12.** The effect of hole distance to strip thickness on the holes ovality.


**Fig. 13.** Transition from type C to type A ovality with increasing hole spacing.

**Fig. 14.** Sample failure resulting from hole spacing that was too tight.

the ovality type C converts into the type A in samples with $b/t = 6$ (Fig. 13). But type C changes into the type B in samples with a $b/t = 2$. Due to these ovality type conversions, the ovality initially decreased and then gradually increased with increase of the hole spacing.

It was not possible to form a sample with $b/t = 6$ and $a/t = 2$ using three stands with the horizontal distance of 350 mm, because the flange was torn between stands at 45 and 80 degrees (At the beginning of 80 degree stand as shown in Fig. 14.

This phenomenon probably resulted from the high transverse and shear strains between the holes. In other words, when the holes are very close together, the hole ovality becomes significant, and metal rupture may be unavoidable. On the other hand, punching the holes Far from each other causes the increasing stress concentration between holes and strip edge. As a result of both these phenomena the ovality in both situations increases.

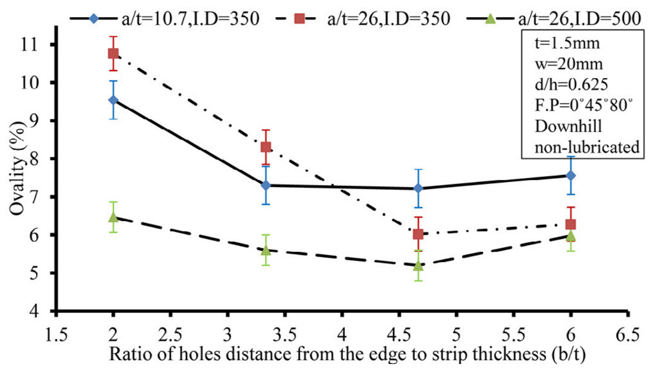


**Fig. 15.** The effect of ratio of holes distance from the strip edge to strip thickness on the holes ovality.

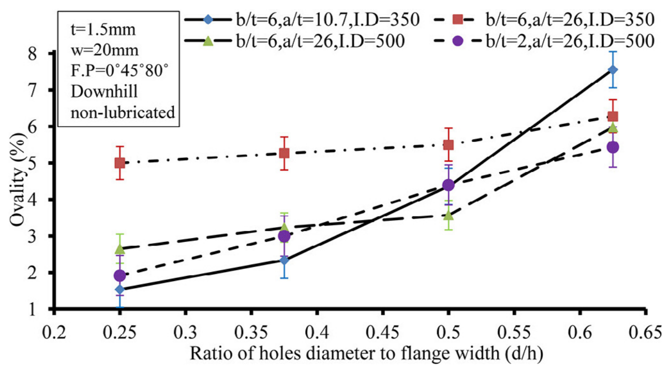


**Fig. 16.** The effect of ratio of holes diameter to flange width on the holes ovality.

### 3.5. The effect of ratio of hole distance from the strip edge to strip thickness on the hole ovality

Fig. 15 shows how the ratio of the distance between the holes and the strip edge to the strip thickness affects the hole ovality.

As can be seen in Fig. 15, in pre-notched strips with a constant thickness, the hole ovality decreased when the distance between the holes and the strip edge increased. On the other hand, by decreasing the distance between the holes and bend zone the hole ovality also increased. This means that a hole close to the bend zone and strip edge experienced a high ovality.

An accurate inspection of the experimental samples showed that the ovality type B is converted into the type A as the distance between the holes and the strip edge increases.

### 3.6. The effect of the ratio of holes diameter to flange width on the hole ovality

Fig. 16 shows the effect of the ratio of the hole diameter to the flange width on the hole ovality.

As the results shown in Fig. 16 dictate, with a fixed flange width, an increase in the hole diameter leads to a higher ovality, because a larger hole causes the metal to be less resistant to deformation in comparison to a smaller hole. It should be emphasized that increasing the hole diameter, holding all other variables constant, will decrease the distance between the holes and the bend line. It has been previously detailed that this phenomenon will increase the hole ovality.

It was observed that in samples with $b/t = 2$ the hole ovality was type B, while samples with $b/t = 6$ exhibited type A ovality for all hole diameters. Furthermore, increasing the holes diameter of samples with $a/t = 10.7$ converted the hole ovality from type A to type C and showing a significant increase in holes ovality.

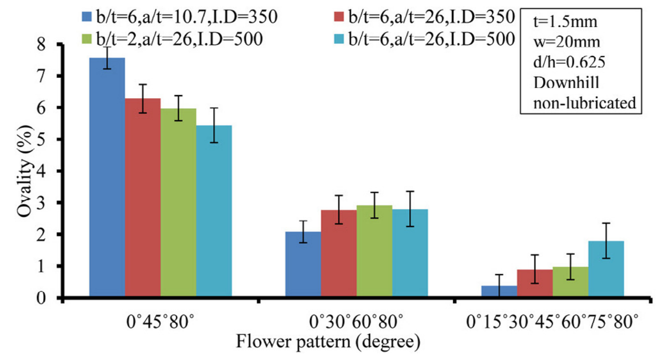


**Fig. 17.** The effect of flower pattern on the holes ovality.

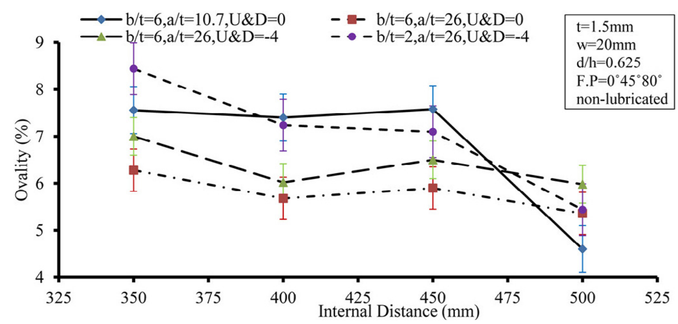


**Fig. 18.** The effect of the horizontal distance between the stands on hole ovality.

### 3.7. The effect of the flower pattern on holes ovality

The angle increment in consecutive stands is referred to as the flower pattern and its effect on ovality is summarized in Fig. 17.

In the roll profile design, the forming angle increment between two stands is a key parameter that determines maximum edge membrane longitudinal strains (Zeng et al., 2009). The larger the fold angle, the higher the strain rate (Nefussi and Gilormini, 1993). According to Fig. 17, a higher number of forming stands significantly reduces the hole ovality by forming the strip more slightly and producing more uniform strains in the longitudinal and the transverse directions.

### 3.8. The effect of horizontal distance between stands on holes ovality

Fig. 18 shows the effect of that the horizontal distance between the stands has on the hole Ovality.

Since the horizontal distance between the stands increases the deformation length, the strip is formed smoothly, which lowers strains that are uniformly distributed (Paralikas et al., 2009). Therefore, increasing the horizontal distance between the stands decreases the holes ovality (Fig. 18).

### 3.9. The effect of uphill and downhill strategies on holes ovality

In Fig. 19 shows the effect of uphill and downhill strategies on the holes ovality.

According to Fig. 19, the Down-hill state has reduced ovality compared to the leveled and Up-hill states. Since in the Downhill state longitudinal strain is not focused on the strip edges, but is evenly spread in the flange, the ovality is reduced (Paralikas et al., 2011).

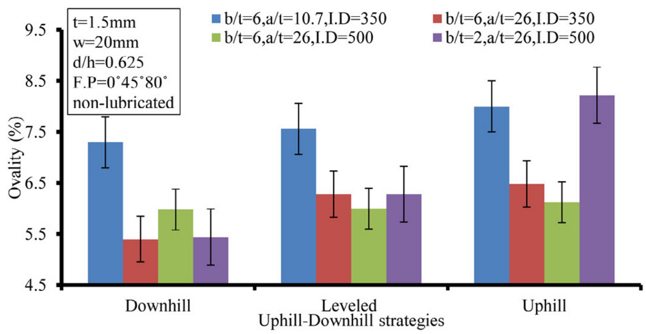


**Fig. 19.** The effect of uphill and downhill strategies on the holes ovality.

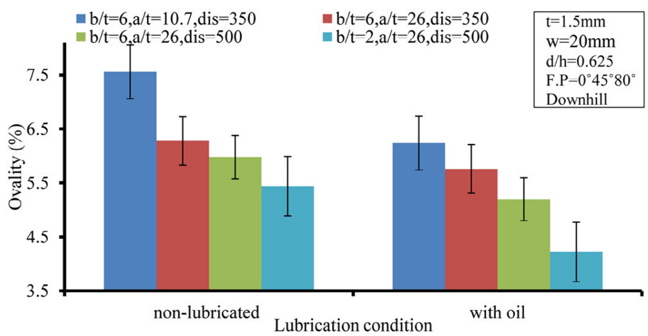


**Fig. 20.** The effect of lubrication on the holes ovality.

### 3.10. The effect of lubrication on holes ovality

Fig. 20 shows the effect that lubrication between the strip and the rolls has on hole ovality.

As shown in Fig. 19, use of lubricants in the fabrication process reduced the ovality by reducing tangential frictional forces between the rolls and the strip. Since these forces play a major role in pulling the strip into the stands, the strip was fed more easily through the forming line with lower tangential forces.

Analyzing samples produced in the presence of the lubricant showed that the lubrication improves the flange surface finish by decreasing the scratch marks. On the other hand, in many cases, the lubrication was used to increase the rolls lifetime by reducing their temperature and by decreasing abrasion.

### 3.11. Evaluation of the effective variables

To evaluate the influence of each variable including the flower pattern, lubrication, horizontal distance between stands, uphill and downhill strategies, the distance between the holes and the strip edge, the distance between the holes, the holes diameter, the strip thickness, the flange width, and the web width on the holes ovality, the experimental data were analyzed using a non-linear regression method employing Minitab software. Results of estimated effects are provided in Table 3 where non-significant factors were ignored. Unlike positive *T*-values, a negative *T*-value indicates a reduced effect of the corresponding factor on the hole ovality.

Since the P-Value for the web width, lubrication, the horizontal distance between stands, the uphill and the downhill strategies, and the distance from edge plate ratio is greater than 0.05, it can be concluded that these factors do not significantly affect the holes ovality directly. The *R*-Sq value indicates that approximately 85% of the entire experimental test values were estimated accurately (Navidi, 2011). Fig. 21 shows a Pareto chart that depicts the standardized effect of the main factors on the hole ovality.

**Table 3**
Estimated effects and coefficients for ovality.

| Term | Coef | SE coef | *T*-value | *P*-value |
|---|---|---|---|---|
| Constant | 0.997348 | 0.0296752 | 33.6088 | 0 |
| F.P | −0.010674 | 0.0014721 | −7.2508 | 0 |
| $t$ | −0.000497 | 0.0001143 | −4.3506 | 0 |
| $d/h$ | 0.101413 | 0.0278939 | 3.6357 | 0.001 |
| $a/t \times d/h$ | −0.002475 | 0.0008097 | −3.0569 | 0.003 |
| F.P × I.D | 0.000011 | 0.0000042 | 2.6636 | 0.01 |
| $a/t$ | 0.002577 | 0.0010248 | 2.5145 | 0.014 |
| $a/t$ × U&D | 0.000049 | 0.0000228 | 2.1602 | 0.034 |
| $b/t \times a/t$ | −0.000062 | 0.0000289 | −2.1463 | 0.035 |
| $a/t$ × F.P | 0.000071 | 0.0000377 | 1.8909 | 0.063 |
| $b/t$ | 0.003714 | 0.0020906 | 1.7766 | 0.08 |
| U&D | −0.000895 | 0.0005433 | −1.6472 | 0.104 |
| I.D | −0.000108 | 0.0000661 | −1.6352 | 0.107 |
| $b/t \times d/h$ | −0.004871 | 0.0031134 | −1.5644 | 0.122 |
| $w \times a/t$ | −0.000466 | 0.0004261 | −1.0937 | 0.278 |
| $w$ × I.D | 0.000035 | 0.0000336 | 1.039 | 0.302 |
| Lub | 0.004187 | 0.0079145 | 0.529 | 0.599 |
| $w$ | −0.001946 | 0.0119308 | −0.1631 | 0.871 |

$S$ = 0.00300465, R-Sq = 85.91%, R-Sq(adj) = 82.39%

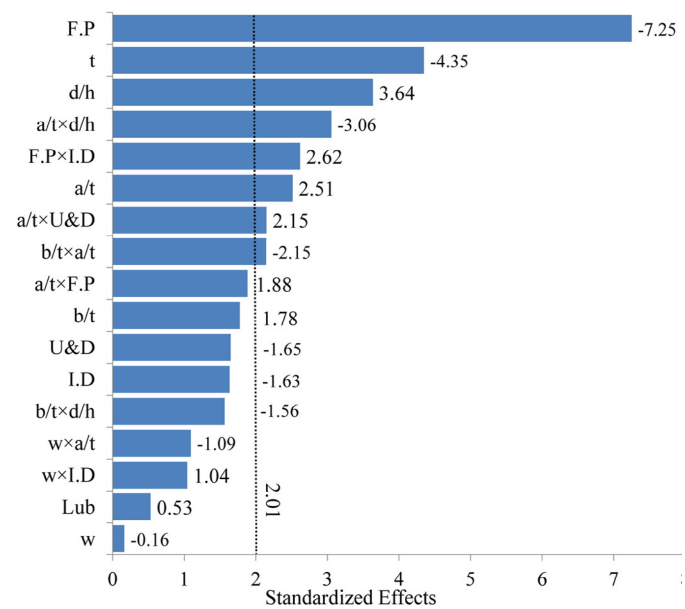


**Fig. 21.** Pareto chart of the standardized effects on the holes ovality.

According to Fig. 21, all the factors beyond 2.01 (*P*-value > 0.05) have a significant effect on the ovality. Furthermore, the flower pattern has the greatest impact on the ovality, while the strip thickness and the ratio of holes diameter to strip thickness are in the next rankings. Also, after the web dimension, lubrication, internal distance between stands, Uphill and Downhill, and distance from edge plate ratio had the least effect on ovality. According to the Pareto chart, although many factors do have a great direct impact on ovality, some of them have an indirect effect by interacting with the other factors.

## 4. Conclusions

In this study, the influence of the geometrical variables of pre-notched channel products and the roll forming variables on ovality of holes in the U-shaped sections were studied experimentally. The results led to the following conclusions:

- In the cold roll forming process, several factors affect the hole ovality of a symmetrical pre-notched channel product by producing non-uniform strains distribution around the holes.
- Considering the hole ovality appearance, three types of ovality were observed in the experiments. The distance between the holes and the distance between the holes and the strip edge (or the bend line) determined what type of ovality occurred.
- The Flower pattern or bending angle increment at each stand in the forming process exerts the most effect on the hole ovality. An excessive forming angle produces high strain with a non-uniform distribution, thereby increasing the hole ovality. The experimental results showed that increasing the number of forming stands from 2 to 6 reduces the ovality 25 times.
- Increasing the diameter of the holes reduces the strip resistance against the deformation and produces a non-uniform strain distribution, which causes significant hole ovality.
- While the web width is the least effective variable in reducing the hole ovality compared to the other variables, lubrication, the horizontal distance between the stands, the uphill and the downhill strategies, and the hole distance from the strip edge are next in the rankings.
- By increasing the number of stands and the horizontal distance between the stands and by using the downhill strategy and the lubrication, it is possible to reduce the hole ovality of the pre-notched channel products.
- In addition to the variables that directly affect the hole ovality, other variables have significant indirect effects by interacting with the primary variables.
- Generally speaking, geometrical variables of a pre-notched channel product show a higher influence on hole ovality compared to the roll forming process variables.

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