# Sensitivity Analysis and Optimization of the surface Roughness in the Incremental Forming of mild Steel Sheets

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## *Abstract*

Flexibility and simple tooling make the incremental sheet forming (ISF) a great process to create complex shapes from mild steel sheets. It is a significant issue to reduce the surface roughness (SR) which is a weakness in the manufacturing of the mild steel parts in ISF process. SR has an adverse effect on the esthetic aspects of the mild steel products or their painting appearance. The purpose of this study is to investigate the effects of the ISF process parameters on the SR of the mild steel sheets. Feed rate, tool diameter, vertical step and spindle speed are chosen as four input variables in the experimental tests. Taguchi design of experiment and the analysis of variance(ANOVA) are used to optimize the SR by investigating the parameters effects and their interactions. According to the obtained results, the vertical step reduction and increase in tool diameter, decrease the roughness on the surface of the mild steel sheets during the single-point incremental forming. In addition, the tool speed (rotation and feed) has little effect on the SR. The results of a validation test demonstrate that the Taguchi technique and the ANOVA, effectively optimize the level of each variable to ensure the best SR.

***Keywords:*** Mild steel sheet, Surface roughness, Single-point incremental forming, Taguchi technique, ANOVA.

## 1- Introduction

Incremental sheet forming is an innovative method of sheet forming. In this way, the sheets are formed without a need for punches and related dies, in spite of being utilized in typical stamping processes. Therefore, ISF is a competitive alternative for economically manufacturing of low-volume productions. For instance, one application of this process can be found in the automobile industry for producing car body panels of concept vehicles or special cars which are formed on the mild steel sheets. Other applications is in aerospace industry to manufacture the elements of an aircraft, and in medical industry to produce implants or medical devices. The process starts with incremental traveling of the hemispherical tool tip into the surface of sheet. The motion path is assumed to be characterized by G-codes in terms of Cartesian coordinates, derived from a computer-aided design and computer-aided manufacturing (CAD/CAM) software. Two methods of ISF are single-point incremental forming (SPIF) and two-point incremental forming (TPIF). SPIF (Figure 1(a)) was developed by Jeswiet [1], Leach [2], and Fratini [3] for the first time. In this type of ISF, a free, unsupported surface is detected on the back of the sheet that is being formed. Therefore, there would be just one point between the formed sheet and the tool tip. Powell and Andrew [4] and Matsubara [5] introduced the TPIF. In TPIF, as shown in Figure 2(b), there are two points to deform the sheet metal. One point, similar to the SPIF, is the forming tool that causes plastic deformation of the sheet. The other point is a supported die that locates under the blank to facilitate the plastic deformation procedure, especially in forming of complex shapes.

Mild steel or low-carbon steel blanks are the most typical form of steel and is commonly used in industry due to its low-cost constitutive materials and properties that are favorable for many applications. Surface roughness control of this kind of steel sheets is a critical requirement in the parts production by the SPIF process. Roughness in the surface of mild steel sheets causes the orange peel phenomenon which is a textured imperfection in the painting process. Esthetic aspects of the painted mild steel samples disfigure by this imperfection. Therefore, it is important to analysis and optimize the SR of the mild steel samples, formed by the SPIF. However, previous studies have investigated the surface roughness of materials rather than mild steel sheets. Hagan and Jeswiet [7] used a white light interferometry scan to implement surface roughness analysis of the SPIF test using the annealed Al3003 sheets. It was seen that the $R_z$ increased by increasing the step of the tool pitch. Cerro et al. [8] conducted some experimental tests and FEM simulations for the SR evaluation of the Al1050-0 sheets. As a result, they showed that the surface roughness decreased by reducing the axial step size. Durante et al. [9] evaluated the direction and speed of tool rotation in the ISF of the Al7075-T0 sheets. It was found that the roughness value differs, considering the influence of the rotation of the tool, both in terms of rotary speed and direction of the tool rotation. Hamilton and Jeswiet [10] studied the high rotational speed and feed rate effect of the tool on the SPIF processing of the Al3003-H14 sheets. Bhattacharya et al. [11] conducted an experimental research on the Al5052. They explained that the SR value decreased as the tool size and wall angle increased. Lu et al. [12] investigated the friction effect on the surface finish by using the traditional rigid tool and oblique roller-ball (ORB) tool. Four types of aluminum sheet, i.e., Al1100, Al2024, Al5052, and Al6111, were used in their study. It was demonstrated that the oblique tool could generate a better surface on the samples. Echrif and Hrairi [13] utilized the Al1050-O sheets in their SPIF tests. They used taguchi technique and ANOVA to investigate and optimize the quality of the surface of Al sheets. As a result, they proved that a large tool diameter, accompanied by a low vertical movement of the tool, made a smoother surface in the formed specimen. Gulati et al. [14] optimized both SR and formability of the Al6063 sheets. They performed some SPIF tests using the Taguchi's $L_{18}$ orthogonal array. Based on their findings, the lubrication followed by the feed rate, tool radius, step size, sheet thickness, and tool rotational speed affected the surface roughness positively. Yao et al. [15] studied the effects of tool diameter, step down, wall angle, and initial sheet thickness on the energy of deformation, SR, and dimensional errors of the Al1060 sheets. The results illustrated that the most important parameter that influenced the surface roughness was the step down. Taherkhani et al. [16], using the Al3105 sheets, performed four process parameters to model the Group Method of Data Handling (GMDH) as a sub model of artificial neural networks. Asghari et al. [17] studied the surface quality of Al1050 sheets during the TPIF process. By performing multi-objective optimization through grey relational analysis, they found the optimum condition to have  minimum thickness, surface quality, and springback. The above-reviewed papers failed to present a convincing and systematic method for analyzing and optimizing the whole process parameters on the SR of mild steel parts, produced in the SPIF process. Application of the mild steel is becoming prevalent in different forming methods, including the incremental forming, due to their interesting mechanical characteristics. Hence, surface roughness analysis and optimization seem necessary for these kinds of steel sheets in the SPIF.

SR is a significant issue in quality of the mild steel balnks formed in the ISF process. This research investigates the effects of main process variables on the surface roughness of mild steel blanks, resulting from the SPIF process of an elongated cone. Feed rate, tool diameter, vertical step and spindle speed are the main parameters of the experiments. By using a surface profile meter, the arithmetic average roughness ($R_a$) parameter is considered to measure the surface roughness. Sixteen experimental tests are presented according to the Taguchi DOE and the analysis of variance

(ANOVA). The purpose is to study the effects of input factors to optimize the process parameters and obtain the lowest roughness of the mild steel sheet in the SPIF of an elongated cone. Finally, the specimen results with the optimized parameters are confirmed by a validation experiment.

## 2- Experimental Tests

The sheet metal used in this study is the *DIN St12*, a mild steel sheet. Dimensions and thickness of the initial blanks are $250_{mm} \times 160_{mm}$ and $1_{mm}$, respectively. This material has good formability and high tensile strength. Mechanical properties and chemical composition of the *St12* sheets are presented in Table 1.

An elongated cone is assumed to be the part created on the initial blank. The main dimensions of the shape are shown in figure 2(a). The Tungsten Carbide forming tool, as shown in Figure 2(b), is characterized by a hemispherical tip. During sheet forming in the SPIF, the tool tip wears and some small parts of the tool head may even become separated due to the local tool-sheet contact and the resulting friction between them. This has a negative effect on the forming surface quality. Hence, it is so important to choose an appropriate material with necessary strength for the tool to contact with the steel sheet. Generally, a Tungsten Carbide has a hardness value of about *1600 HV*, while the hardness value of mild steel is approximately *160 HV*. Consequently, Tungsten Carbide is approximately wear-resistant when contacting the steel sheet and exhibits enough strength against friction and temperature increase during the process of sheet deformation. The Tungsten Carbide tool follows a Z-level path to form the elongated cone based on the G-codes generated by the CAD/CAM software. During the movement of the tool, the SAE40 is applied as the lubricant. It is clear that the lubrication decreases the surface roughness because of the friction reduction in the interface of tool and the blank and better surface quality is obtained. The final formed blank is shown in Figure 2(c). As an engineering optimization method, Taguchi introduces a useful technique for optimization of the characteristics of a desired performance by combining the influenced parameters. To obtain the best design state in terms of efficiency, quality, and total cost, the Taguchi method represents an effective method for attaining the finest parameters, resulting in robust and high quality systemsThe tests are performed using a Taguchi design of experiments as a highly applicable technique for controlling the production quality [18-20]. Input variables are the feed rate, spindle speed tool diameter and vertical step. Surface roughness of the mild steel sheet is assumed as the output parameter which is presented by $R_a$. Levels of the considered parameters are shown in Table 2.

## 3- Method of the Surface Roughness Measurement

Surface integrity and surface topography are the two main aspects of the surface quality. Surface integrity describes metallurgical and mechanical changes of the surface, created by the machining operation. Surface topography is related to the geometry of the machined surfaces and includes the surface lay, roughness and waviness [21]. Main elements of the surface topography in the ISF process are the surface waviness and surface roughness. During the SPIF, when the tool moves on the sheet, certain areas on the blank remain as unforced regions because of the helical path of tool movement. Therefore, these sections lead to the surface waviness [22]. In addition, tool movement in a local zone on the blank during the SPIF results in the surface roughness. Roughness usually causes an orange peel phenomenon on the external surface of the specimens. It has a detrimental effect on the esthetic aspect of the products or the painting appearance. In this study, surface roughness is denoted by the arithmetic average surface roughness ($R_a$). This parameter is established as the average deviation of the surface irregularities over a specific length. In fact, $R_a$ is integral of the roughness height over the desired section of the part and is defined by the equation 1[23]:

$$R_{a=\frac{1}{L}\int_0^L |Y(x)| dx} \tag{1}$$

Where $Y$ is the ordinate of the roughness profile curve created on the formed blank during the process, and $L$ is the sampling length in the part (see Figure 3).

Microscopes, stylus instruments, or even a visual or feeling comparison with a standard comparator are used to assess the SR in the industrial manufacturing. In the present study, to determine the surface roughness of the formed blanks quickly and accurately, a Mahr M1, a stylus instrument, is applied, as shown in Figure 4.

## 4- Results

$L_{16}$ Taguchi orthogonal array is adopted to investigate how the four input variables affect the SR of the mild steel sheets. The control factor values for each SPIF experiment are shown in Table 3. For each experiment, the SR is measured in three different points in the internal surface of the elongated cone and the average of all measured $R_a$ is reported in Table 3 as the specimen roughness.

### 4-1- Response Graph and Response Table

The effect of input parameters on the output factor is shown in the means response table. This table is one of the most important tools of the Taguchi technique to meet the objectives in an engineering design. The means response table can specify which process parameter has the largest impact on the response. In addition, the trend of each control factor can be observed. In other words, this table determines which level of the input variables is related to higher or lower response values. When the input parameters are changed, the response variations can be investigated using the main effect plot of the means. The means response table and the effect plot of means are illustrated in Table 4 and Figure 5. The ranks shown in Table 4 explain that the vertical step (Z), ranked first, is the most effective process parameter for the SR of the formed blanks. The tool diameter (D) has the second highest effect on the SR, which is followed by the tool rotational speed (W) and the feed rate (F), respectively.

An increase in the vertical step (Z) results in coarser surface roughness of the formed sheets. Table 4 depicts that $R_a$ increases from $1.327\mu m$ to $1.437\mu m$ over the step depth range of $0.5_{mm}$ to $1_{mm}$ (levels 1 to 4 in Table 1). By increasing the vertical step, the axial force of the tool increases and a deeper micro valley will occur on the interface of the tool and the mild steel sample. Moreover, analysis of the samples showed that some regions of the sheet partially remained as micro peaks between the successive contours of each step in the tool vertical motion. Thus, micro peaks and valleys of the surface increase and lead to rougher surface. Reduction of the tool vertical movement results in a more overlap among the neighboring contour paths, traced by the forming tool. Consequently, increasing the tool steps in the vertical dimension increases the SR in SPIF of the mild steel sheets; however, the process time reduces when the vertical step increases.

An increase in the diameter of the hemispherical tool (D) causes an appropriate effect on the SR of the mild steel blanks. When the tool diameter size increases, $R_a$ of the final parts decreases. By using a bigger tool diameter, the contact pressure in the interface of the tool and the blank decreases and flattens the patterns (micro peak and valleys). As a result, the surface roughness will decrease. Furthermore, surface roughness reduction, by means of a larger tool diameter, can be ascribed to an increase in the overlap zones between each contour of the tool path; this is due to the larger contact area of the tool and the blank. Therefore, using a smaller diameter for the forming tool makes the surface of the mild steel sheets rough; however, better formability occurs by means of an increase in the tool diameter size.

From Table 4 and Figure 5, it is inferred that by increasing the spindle speed (W), the surface roughness can be reduced (due to the selected range of the tool rotational speeds shown in Table 1). By speeding up the spindle, the sliding friction at the interface of the tool tip and the specimen surface increases. As a result, the heat treatment is increased in the forming process. In this way, contact area of the Tungsten Carbide tool and the mild steel sheet is changed from adhesive to abrasive type and better surface quality is obtained. Moreover, the rotation tool creates some veins on the blank, which is the asperity of the surface. Increasing the spindle speed creates smaller veins, and the surface becomes more polished which illustrates a reduction in SR of the mild steel sheets. As shown in Table 4, the spindle speed effect on the SR of the SPIF experiments is negligible.

When the feed rate increases in the SPIF, $R_a$ decreases. In fact, higher feed rates associated with the tool vibration in the experiments result in increasing wear rate, friction, and temperature. One reason is that when the feed rate increases, higher speed of the tool prevents the absolute formation of the lubricant film at the tool-blank interface. It can be concluded that the surface becomes rougher. However, in the present study, considering the specified feed rates, the results exhibit the contrary, showing that the lubricant film breakage occurs in the feeds more than those selected here. Increasing the feed rate in the selected range decreases the SR of the mild steel sheets. Similar to the spindle speed, Table 4 shows that the feed rate has low effect on the SR of this type of steel.

Taguchi designs are primarily intended to study main effects of factors. Occasionally, you might want to study some of the 2-way interactions. Figure 6, shows the 2-way interaction plots of the effect of process parameters on the SR. IT is clear that the larger tool diameter with the smaller vertical movement of the tool results in a better surface quality.

## 4-2- Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) is a statistical method that is used for testing the differences between two or more means. By using the analysis of variance, as well as the means response table, the most effective factor in the experimental tests can be determined. Moreover, the participation percentage of each variable (factor contribution) in the response can be evaluated. Table 5 depicts the ANOVA results of the samples. DF represents the degree of freedom, Seq.SS is the sequential sum of squares, Adj.SS is the adjusted sum of squares, and Adj.MS is the adjusted mean square. F-value is the ratio of the source variance to the error variance. P-value is used to evaluate the effect of each parameter on the output. The confidence level of *95%* is supposed here, regarding which corresponding analysis is carried out. The p-value less than *0.05* means that the output is considerably affected by the parameter. Moreover, the contribution, as shown in Table 5, indicates the participation percentage of each process variable in the SR of the mild steel sheets in the SPIF. As shown in Table 5, the vertical step is the most effective parameter for $R_a$ of the mild steel sheets in the experiments; its contribution is *55.88%*. The next effective parameter is the tool diameter size with the contribution of *33.13%*. The results are consistent with the factor ranking, shown in Table 4. Table 5 illustrates that the spindle speed and the feed rate have no considerable effect on the SR of mild steel sheets with the contribution of less than *10%*.

## 4-3- Determination of the Optimum Surface Roughness

In the Taguchi design, the signal-to-noise (S/N) ratio is employed in the optimization of the input variables. Optimum conditions are represented by determining every level of the process parameters effect on the response. The optimum level of the factors has the largest S/N ratio. The S/N ratio is divided into three groups: (1) nominal is the better case, (2) smaller is the better one and (3) larger is the better case [24]. This study aims to minimize the surface roughness; hence, the-smaller-the-better method is utilized based on equation 2 [25]:

$$S/N\ ratio\ =\ 10log_{10}(\frac{1}{n}\sum_{i=1}^{n} y_i^2) \qquad (2)$$

Where $y_i$ is $R_a$, measured by the stylus instruments (see Figure 4), and $n$ denotes the number of observations on a particular product. According to Table 6, the optimum level of the input variables (the largest S/N ratio), considering lower $R_a$ and therefore, SR on the formed mild steel sheets, is $D_4F_4W_4Z_1$. It means the minimum $R_a$ as the optimum condition takes place when the fourth level of the tool diameter ($D_4$), the fourth level of the feed rate ($F_4$), the fourth level of the spindle speed ($W_4$), and the first level of the vertical step ($Z_1$) are selected. Based on Table 4, surface roughness rates at the levels of $D_4$, $F_4$, $W_4$, and $Z_1$ are *1.343*, *1.371*, *1.367*, and 1.327 $\mu m$, respectively. The optimum $R_a$ is predicted [26] as in the equation 3:

$$\boldsymbol{R_a = D_4 + F_4 + W_4 + Z_1 - 3T = 1.343 + 1.371 + 1.367 + 1.327 - 3 \times 1.384 = 1.206\mu m}$$

(3)

Where T is the average of the surface roughness responses (see Table 3).

## 4-4- Confirmation Test

To determine the error between the experimental tests and the mathematical modeling, a validation test was performed at a determined level. Accordingly, the best quality of the surface with the minimum roughness(optimum comdition) was determined based on the following conditions: the tool diameter of $20_{mm}$ ($D_4$: the fourth level of the tool diameter), feed rate of $250_{mm/min}$ ($F_4$: the fourth level of the feed rate), spindle speed of $1000_{rpm}$ ($W_4$: the fourth level of the spindle speed), and vertical step of $0.5_{mm}$ ($Z_1$: the first level of the vertical step). Respecting these input parameters, $R_a$ of the experiment with factors of the optimum condition is $1.264_{\mu m}$ and less than *5%* difference between the experiment and the optimum predicted one is achieved. Hence, the optimum state can be verified because of the small error between the experimental results and numerical prediction.

Figure 7 shows the surface quality of two different samples, including the optimized formed blank. The results illustrate that the SR of the mild steel sheets is decreased considerably under the optimal condition. In addition, better surface quality and smoother surface result from a decrease in the vertical step size and an increase in the tool diameter.

## 5- Conclusion

In this paper, the SR of the mild steel sheets wasinvestigated, using the Taguchi $L_{16}$ orthogonoal arrey and ANOVA. The effect of the process parameters, i.e., the feed rate, tool diameter, vertical step and spindle speed, was studied through the SPIF process of forming an elongated hole. Arithmetic average roughness ($R_a$) was employed to evaluate the effect of input variables on the roughness of the final formed blanks. The results of this study are as follows:

- Tool vertical movement has the highest important effect on the SR of the mild steel sheets. Increasing the vertical step results in the increase of $R_a$ and a rough surface appears on the formed specimens.
- Increasing the tool diameter leads to reduction of $R_a$ and smoother surface of the mild steel sheets in the SPIF.
- The ANOVA approved that the speed of the spindle and the feed rate have no significant effect on the SR of the mild steel sheets.
- According to the graphs, tables and the provided experimental results, it was found that a better surface quality can be achieved with a lower vertical movement and a larger tool diameter.
- The tool optimum condition characterized by the diameter of $20_{mm}$, feed rate of $250_{mm/min}$, rotation speed of $1000_{rpm}$ and step size of $0.5_{mm}$ is achieved by the Taguchi technique and

was validated experimentally.

## References

[1] Jeswiet, J. and Hagan, E., “Rapid proto-typing of a headlight with sheet metal”, 9th International conference on sheet metal forming, Leuven, Belgium, pp. 165-170 (2001).

[2] Leach, D., Green, A. J. anf Bramley, A. N., “A new incremental sheet forming process for small batch and prototype parts”, 9th International conference on sheet metal forming, Leuven, Belgium, pp. 211-218 (2001).

[3] Filice, L., Fratini, L. anf Micari, F., “Analysis of material formability in incremental forming”, CIRP Annals- Manufacturing Technology, **51**(1), pp. 199-202 (2002).

[4] Powell, N. and Andrew, C., “Incremental forming of flanged sheet metal components without dedicated dies”, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, **206**(1), pp. 41-47 (1992).

[5] Matsubara, S., “Incremental backward bulge forming of a sheet metal with a hemispherical tool”, Journal of the Japan Society for Technology of Plasticity, **35**(406), pp. 1311-1316 (1994).

[6] Silva, MB. and Martins, PA., “Two-point incremental forming with partial die: theory and experimentation”, Journal of Material Engineering Performance, **22**(4), pp. 1018-1027 (2013).

[7] Hagan, E. and Jeswiet, j., “Analysis of surface roughness for parts formed by computer numerical controlled incremental forming”, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, **218**(10), pp. 1307-1312 (2004).

[8] Cerro, I., Maidagan, E., Arana, J., et al., “Theoretical and experimental analysis of the dieless incremental sheet forming process”, Journal of Materials Processing Technology, **177**(1-3), pp. 404-408 (2006).

[9] Durante, M., Formisano, A., Langella, A., et al., “The influence of tool rotation on an incremental forming process”, Journal of Materials Processing Technology, **209**(9), pp. 4621-4626 (2009).

[10] Hamilton, K. and Jeswiet, J., “Single point incremental forming at high feed rates and rotational speeds: Surface and structural consequences”. CIRP Annals- Manufacturing Technology, **59**(1), pp. 311-314 (2010).

[11] Bhattacharya, A., Maneesh, K., Venkata Reddy, N., et al., “Formability and surface finish studies in single point incremental forming”, Journal of Manufacturing Science and Engineering, **133**(6): pp. 061020–1-061020–8 (2011).

[12] Lu, B., Fang, Y., Xu, D.K., et al. “Mechanism investigation of friction-related effects in single point incremental forming using a developed oblique roller-ball tool”, International Journal of Machine Tools & Manufacture, **85**, pp. 14-29 (2014).

[13] Echrif, S.B.M., Hrairi, M., “Significant parameters for the surface roughness in incremental forming process”**,** Materials and Manufacturing Processes, **29**(6), pp. 697-703 (2014).

[14] Gulati, V., Aryal, A. and Katyal, P., “Process Parameters Optimization in Single Point Incremental Forming”, Journal of the Institution of Engineers (India): Series C, **97**(2), pp. 185-193 (2016).

[15] Yao, Z., Li, Y., Yang, M., et al., “Parameter optimization for deformation energy and forming quality in single point incremental forming process using response surface methodology”,

Journal of Advances in Mechanical Engineering, **9**(7), pp. 1-15 (2017).

[16] Taherkhani, A., Basti, A., Nariman zadeh, N., “Achieving maximum dimensional accuracy and surface quality at the shortest possible time in single-point incremental forming via multi-objective optimization”, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, **233**(3), pp. 900-913 (2018).

[17] Asghari, A., Sarband, A. and Habibnia, M., “Optimization of multiple quality characteristics in two-point incremental forming of aluminum 1050 by grey relational analysis”, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, **203**, pp. 1989-1996 (2017).

[18] Khalkhali, A., Noraie, H. and Sarmadi, M., “Sensitivity analysis and optimization of hot-stamping process of automotive components using analysis of variance and Taguchi technique”, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, **231**(4), pp. 732-746 (2016).

[19] Tanga, L., Maa, Y., Wanga, J., et al., “Robust parameter design of supply chain inventory policy considering the uncertainty of demand and lead time”, Scientia Iranica, pp. 1-34 (2018). DOI: 10.24200/sci.2018.5205.1217.

[20] Roy, R.K.,” A primer on the Taguchi method”, Society of Manufacturing Engineers (SME), Michigan, USA (2010).

[21] Malkin, S. and Guo, C., “Grinding Technology-Theory and Applications of Machining with Abrasives”, Industrial Press, New York, USA (2008).

[22] Shojaeefard, M.H., Kalkhali, A. and Shahbaz, S.O., “Analysis and optimization of the surface waviness in the single-point incremental sheet metal forming”, Proceedings of the Institution of

Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 233(4), pp. 919-925 (2018).

[23] Moghaddam, M. and Kolahan, F., "Using combined artificial neural network and particle swarm optimization algorithm for modeling and optimization of electrical discharge machining process", Scientia Iranica, pp. 1-22 (2019). DOI: 10.24200/sci.2019.5152.1123.

[24] Mohammadi, S., Cheraghalikhani, A. and Ramezanian, R., "A joint scheduling of production and distribution operations in a fow shop manufacturing system", Scientia Iranica, Transactions E: Industrial Engineering, **25** (2), pp. 911-930 (2018).

[25] Hemmati Far, M., Haleh, H. and Saghaeia, A., "A fexible cell scheduling problem with automated guided vehicles and robots under energy-conscious policy", Scientia Iranica, Transactions E: Industrial Engineering, **25**(1), pp. 339-358 (2018).

[26] Ross, P.J., "Taguchi Techniques for Quality Engineering", McGraw-Hill, New York, USA (1988).

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## Figure captions:

Figure 1. (a) Single-point incremental forming (SPIF); (b) Two-point incremental forming (TPIF) [6]

Figure 2. (a) The main dimension of the elongated hole, used as the shape of the process(*mm*); (b) Tungsten Carbide hemispherical forming tools used in the forming process of the mild steel sheets (*mm*); (c) Final elongated cone formed on the mild steel sheet during the SPIF

Figure 3. Surface roughness profile and average surface roughness ($R_a$) definition [13]

Figure 4. Mahr M1 used for Ra measurement

Figure 5. Main effect plots for means of $R_a$ of the mild steel sheets in the SPIF experiments

Figure 6. 2-way interaction plots of the effect of process parameters on the SR

Figure 7. Surface quality of two different specimens of mild steel sheets formed in the SPIF process: (a) D=10mm, Z=1mm; (b) specimen with the optimum condition: D=20mm, Z=0.5mm

## Table captions:

Table 1. Chemical composition and mechanical properties of St12 sheets utilized in the SPIF process

Table 2. Input parameters and their levels in the Taguchi design of experiments (4 factors in 4 levels)

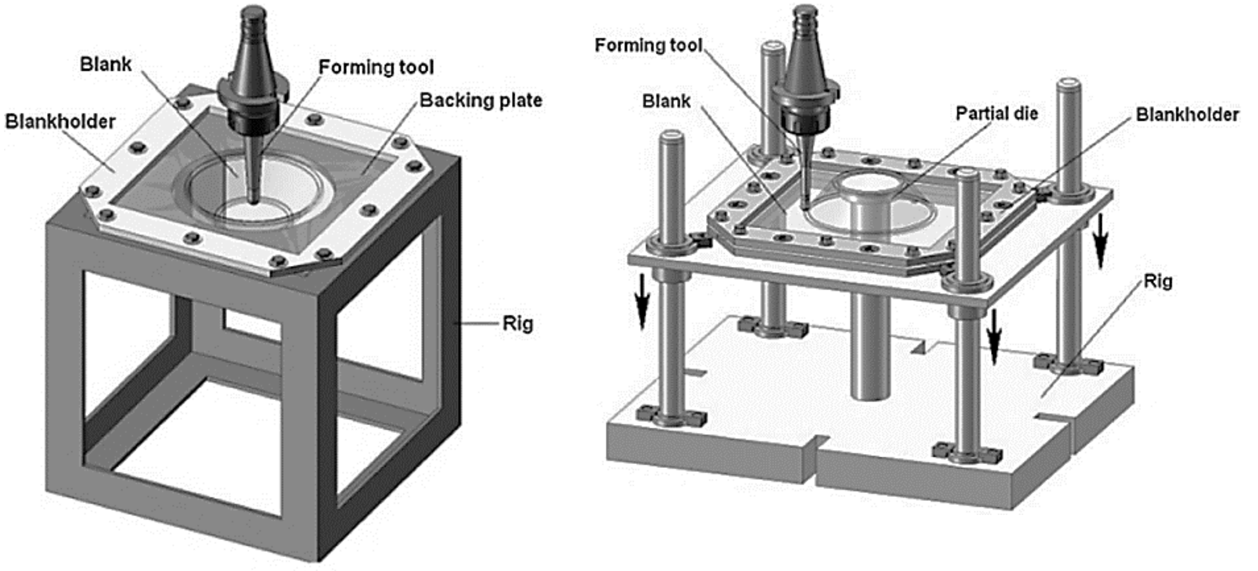
Table 3. L16 Taguchi orthogonal array designed for the roughness measurement on the mild steel sheets

Table 4. Table of responses for means of Ra in the SPIF process of mild steel sheets

Table 5. Analysis of variance of Ra of the mild steel sheets in the SPIF experiments of forming the elongated cone

Table 6. Table of Responses for the signal-to-noise ratios in the-smaller-the-better case

# Figures



(a) (b)

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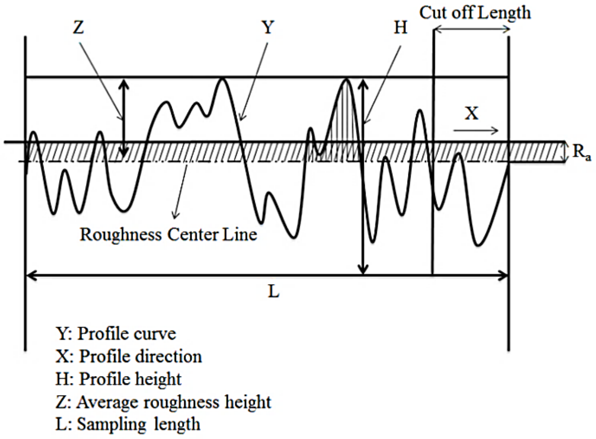

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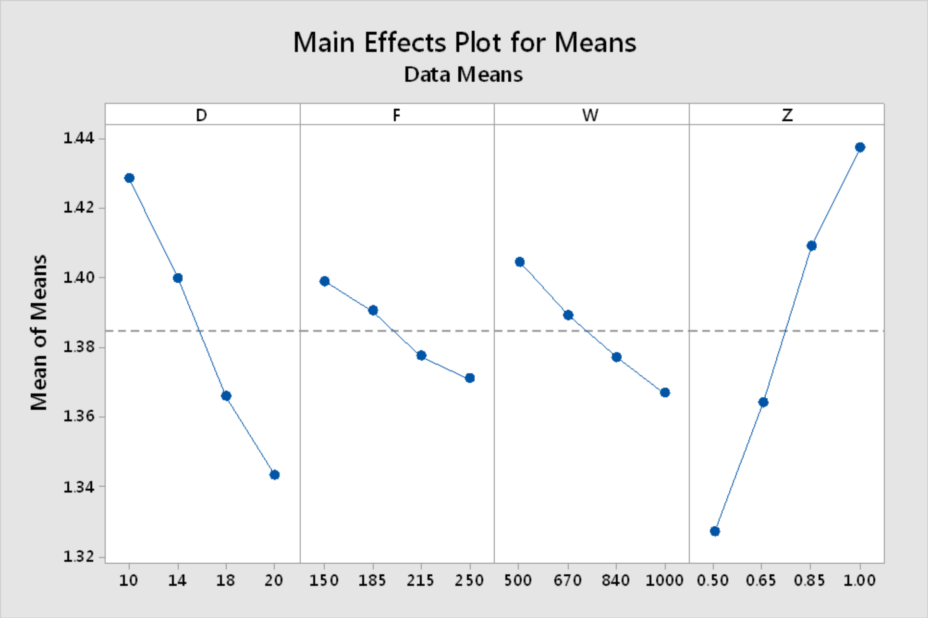


Figure 5. Main effect plots for means of $R_a$ of the mild steel sheets in the SPIF experiments

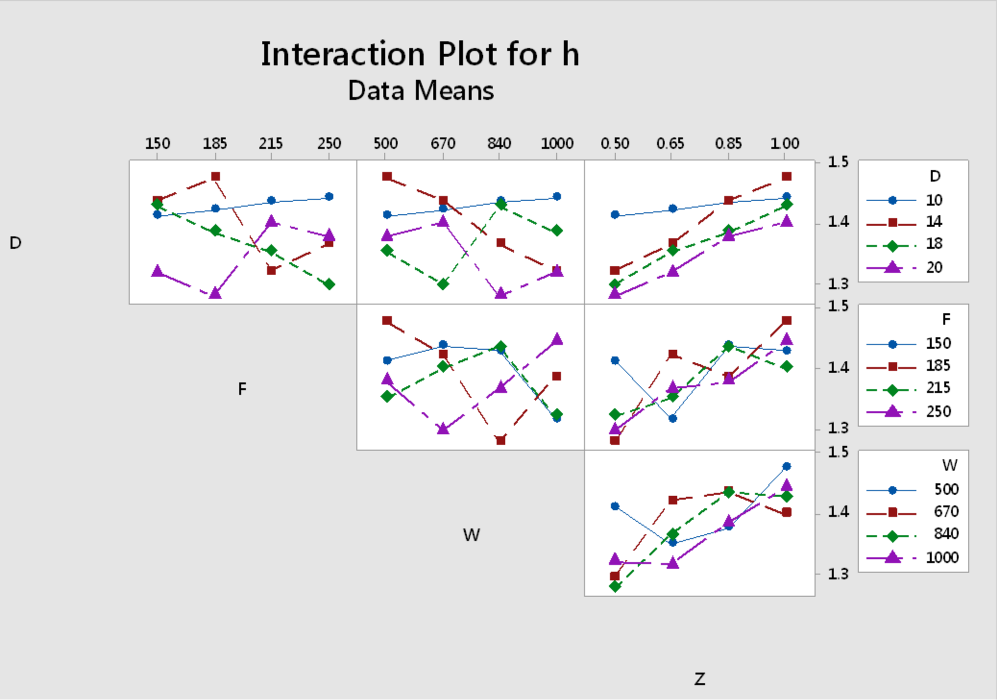
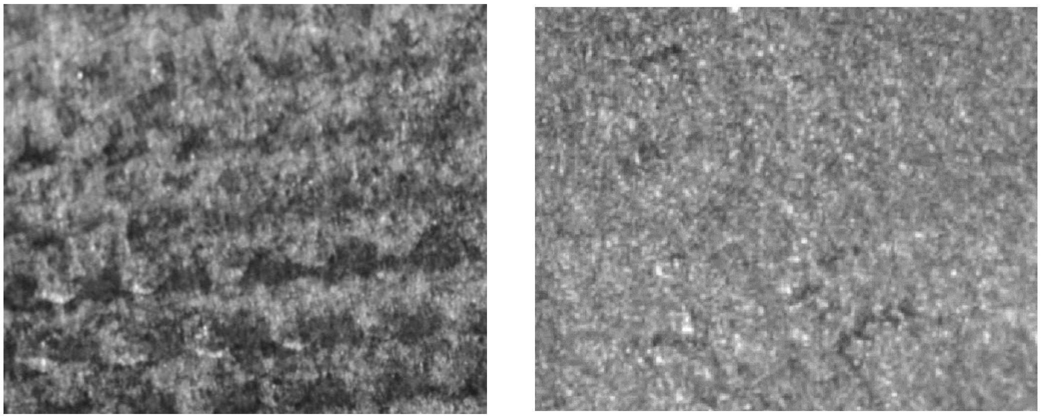


Figure 6. 2-way interaction plots of the effect of process parameters on the SR



(a) (b)

Figure 7. Surface quality of two different specimens of mild steel sheets formed in the SPIF process: (a) $D=10_{mm}$, $Z=1_{mm}$; (b) specimen with the optimum condition: $D=20_{mm}$, $Z=0.5_{mm}$

# Tables:

Table 1. Chemical composition and mechanical properties of *St12* sheets utilized in the SPIF process

| **Material** | **Chemical Composition (wt%)** | | | | **Mechanical Properties** | | |
|---|---|---|---|---|---|---|---|
| | *C* | *Mn* | *P* | *S* | *YS(MPa)* | *UTS(MPa)* | *Elong.(%)* |
| ***St12*** | *0.10* | *0.50* | *<0.05* | *<0.05* | *186* | *306* | *48* |

Table 2. Input parameters and their levels in the Taguchi design of experiments (4 factors in 4 levels)

| **Parameters** | **Notation** | **Unit** | **levels** | | | |
|---|---|---|---|---|---|---|
| | | | $L_4$ | $L_3$ | $L_2$ | $L_1$ |
| **Feed rate** | F | *mm/min* | *150* | *185* | *215* | *250* |
| **Tool diameter** | D | *mm* | *10* | *14* | *18* | *20* |
| **Vertical step** | Z | *mm* | *0.5* | *0.65* | *0.85* | *1* |
| **Spindle speed** | W | *rpm* | *500* | *670* | *840* | *1000* |

Table 3. $L_{16}$ Taguchi orthogonal array designed for the roughness measurement on the mild steel sheets

| **Experment** | **F** *(mm/min)* | **D** *(mm)* | **Z** *(mm)* | **W** *(rpm)* | $R_a$ *(μm)* |
|---|---|---|---|---|---|
| **1** | *150* | *10* | *0.5* | *500* | *1.413* |
| **2** | *185* | *10* | *0.65* | *670* | *1.422* |
| **3** | *215* | *10* | *0.85* | *840* | *1.436* |
| **4** | *250* | *10* | *1* | *1000* | *1.443* |
| **5** | *150* | *14* | *0.85* | *670* | *1.437* |
| **6** | *185* | *14* | *1* | *500* | *1.476* |
| **7** | *215* | *14* | *0.5* | *1000* | *1.321* |
| **8** | *250* | *14* | *0.65* | *840* | *1.366* |
| **9** | *150* | *18* | *1* | *840* | *1.429* |
| **10** | *185* | *18* | *0.85* | *1000* | *1.386* |
| **11** | *215* | *18* | *0.65* | *500* | *1.352* |
| **12** | *250* | *18* | *0.5* | *670* | *1.297* |
| **13** | *150* | *20* | *0.65* | *1000* | *1.317* |
| **14** | *185* | *20* | *0.5* | *840* | *1.278* |
| **15** | *215* | *20* | *1* | *670* | *1.401* |
| **16** | *250* | *20* | *0.85* | *500* | *1.378* |

Table 4. Table of responses for means of $R_a$ in the SPIF process of mild steel sheets

| Level | F | D | Z | W |
|---|---|---|---|---|
| **1** | *1.399* | *1.429* | *1.327* | *1.405* |
| **2** | *1.390* | *1.400* | *1.364* | *1.389* |
| **3** | *1.377* | *1.366* | *1.409* | *1.377* |
| **4** | *1.371* | *1.343* | *1.437* | *1.367* |
| **delta** | *0.028* | *0.085* | *0.110* | *0.038* |
| **rank** | *4* | *2* | *1* | *3* |

Table 5. Analysis of variance of $R_a$ of the mild steel sheets in the SPIF experiments of forming the elongated cone

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|---|---|
| **D** | *3* | *0.016798* | *33.13%* | *0.016798* | *0.005599* | *36.20* | *0.007* |
| **F** | *3* | *0.001910* | *3.77%* | *0.001910* | *0.000637* | *4.12* | *0.138* |
| **W** | *3* | *0.003201* | *6.31%* | *0.003201* | *0.001067* | *6.90* | *0.074* |
| **Z** | *3* | *0.028331* | *55.88%* | *0.028331* | *0.009444* | *61.06* | *0.003* |
| **Error** | *3* | *0.000464* | *0.92%* | *0.000464* | *0.000155* | - | - |
| **Total** | *15* | *0.050704* | *100.00%* | - | - | - | - |

Table 6. Table of Responses for the signal-to-noise ratios in the-smaller-the-better case

| Level | D | F | W | Z |
|---|---|---|---|---|
| **1** | *-3.097* | *-2.911* | *-2.947* | *-2.453* |
| **2** | *-2.914* | *-2.851* | *-2.849* | *-2.695* |
| **3** | *-2.704* | *-2.777* | *-2.771* | *-2.978* |
| **4** | *-2.559* | *-2.735* | *-2.708* | *-3.149* |
| **Delta** | *0.538* | *0.177* | *0.240* | *0.697* |
| **Rank** | *2* | *4* | *3* | *1* |