Effect of Tool Geometry, Feed Rate, and Rotational Speed of Thermal Friction Drilling Process on AISI 304 Stainless Steel

تأثير شكل العدة، معدل التغذية، وسرعة الدوران لعملية الثقب بالاحتكاك الحراري علي الاستانلس استيل AISI 304

Sara A. El-Bahloul*, Hazem E. El-Shourbagy**, and Tawfik T. El-Midany***
*Asst. Lect. (Prod. Eng.), **Lect. (Prod. Eng.), and ***Prof. (Prod. Eng.)
Prod. & Mech. Design Eng. Dept., Faculty of Engineering, Mansoura University, Egypt
*E-mail: elbahloul.sara@gmail.com, Tel.: +201007742266

الملخص العربي:- إن الغرض الرئيسي من هذا البحث هو دراسة تأثير معاملات عملية الثقب بالاحتكاك الحراري مثل شكل العدة، معدل التغذية، و سرعة الدوران، علي طول الجلبة الناتجة، القوى المحورية والعمودية علي المحور، الخطأ في أبعاد الثقب، وخطأ الاستدارة، أثناء ثقب الواح من الاستانلس استيل AISI 304 ذات سمكات مختلفة باستخدام عدد من كربيد التنغستن. أجريت التجارب علي طريقة تصميم التجارب. تم تصنيع جهاز الثقب في شركة شومان ـ مصر لأداء التجارب، ومنحت العدد من شركة Flow drill ـ هولندا. تم تطبيق تقنية المنطق الضبابي للنتائج المقاسة التي تم الحصول عليها لإيجاد حالة الثقب الامثل.

Abstract: - The main purpose of this research paper is to study experimentally the effects of the thermal friction drilling process parameters such as the tool geometry, feed rate, and rotational speed, on the resultant bushing length, axial and radial forces, hole dimensional error, and roundness error, while drilling AISI 304 stainless steel sheets with different thicknesses using tungsten carbide tools. The experiments were conducted based on the design of experiments method. A test rig was manufactured at Showman Company – Egypt to perform the experimental work, and the tools were offered by Flow drill Company – Netherlands. Also Fuzzy Logic technique is applied to the obtained results to find the optimal drilling condition.

1. INTRODUCTION

The product increasing of automobile industry, development of mechanical products, materials, or design of joining, force the producers to utilize new technologies [1, 2]. Friction drilling, thermal drilling, form drilling, flow drilling, or friction stir drilling is a nontraditional hole-making method that uses the heat generated from friction between a rotating conical tool and the work piece to soften and penetrate the work material and generate a hole [3, 4].

Friction drilling compared to other methods of making holes and joining, no coolant is needed, which makes friction drilling a totally clean and environment friendly process. Also friction drilling is the best solution for joining sheet materials in simple, efficient and most economical way. The generated bush can be threaded

with providing high strength load bearing surface due to more solid connection for attachment [4-9].

Since 1983, non-traditional hole-making methods were investigated [1-13]. Several authors studied the thermal friction drilling. *Streppel A.H.* and *Kals H.J.J.* [6], investigate the effect of tool diameter, workpiece thickness and material on the resulted feed force, contact temperature, and the driving moment. *Miller S.F.*, *Blau P.J.*, and *Shih A.J.* [9, 10] characterized the micro-structural alterations and subsurface micro-indentation hardness changes on several materials as a result of the friction drilling process. *Krasauskas P.* [11] performed a statistical five variable linear regression analysis to evaluate the influence of plate thickness, rotational speed, feed rate, and materials mechanical properties, on the axial force and torque. *Ozek C.* and *Demir Z.* [12] investigated the effect of spindle speeds and feed rates in friction drilling of aluminum alloys, that is on the generated frictional heat, surface roughness, and bushing length.

The main purpose of the present work is to investigate experimentally and analytically using Fuzzy Logic technique the optimal parameters of thermal friction drilling process; namely, tool diameter (d), friction angle (β), friction contact area ratio (FCAR), feed rate (FR), and rotational speed (RS). AISI 304 stainless steel work material is employed with 1, 2, and 3 mm

sheet metal thickness. The measured parameters are: bushing length (BL), axial force (AF), radial force (RF), hole dimensional error (DE), and roundness error (RE). Thus, the optimal performance could be ascertained to fit modern industrial requirements.

2. TEST RIG AND EXPERIMENTAL SETUP

Figure 1, shows the test rig, used in our previous work [13] that is designed to carry out the experimental work. The test rig is manufactured at Showman Company – Egypt, with rotational speed up to 4200 rpm, and feed rate up to 218.182 mm/min. Total of 18 thermal friction tools are used to perform all experiments. The tools are offered by Flow drill Company – Netherlands. They are made of uncoated tungsten carbide.
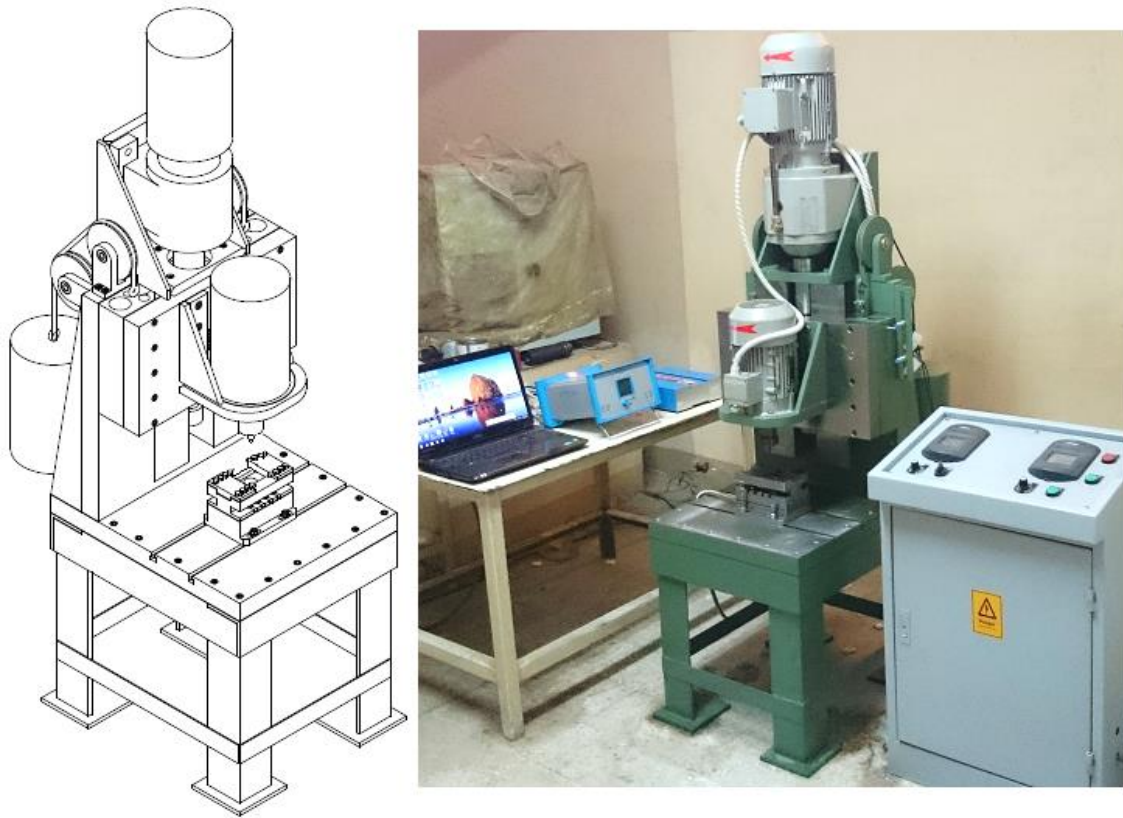

Fig. 1. The designed and manufactured test rig

An orthogonal array L18 [14] is applied to design the required experiments. Table 1, illustrates the investigated parameters and their values. Table 2, shows the obtained orthogonal array with 18 experiments' conditions, while each experiment was conducted three times. The orthogonal array is applied three times to work piece thickness (*t*) of 1, 2, and 3 mm, to study the effect of *t* variation.

The resultant bushing length (BL) was measured by a micro Vernier. The hole dimensional error (DE) and roundness error (RE) were measured by a coordinate measuring machine (Status CMM). The axial force (AF) and radial force (RF) were measured by a multi-component dynamometer (Kistler-Type 9257B).

Table 1. Process parameters and their levels

Process Parameters	Symbol	Unit	Level 1	Level 2	Level 3
Tool diameter	*d*	Mm	5.4	7.3	9.2
Friction angle	*β*	Degree	30°	45°	60°
Friction contact area ratio	FCAR	—	50 %	75 %	100 %
Rotational speed	RS	Rpm	2500	3000	3500
Feed rate	FR	mm/min	60	100	140

Table 2. Five three-levels factors L18 orthogonal array

Exp. No.	d (mm)	b (degree)	FCAR	FR (mm/min)	RS (rpm)
1	5.4	30	50	60	3000
2	5.4	30	75	100	2500
3	5.4	45	50	140	3500
4	5.4	45	100	140	2500
5	5.4	60	75	60	3500
6	5.4	60	100	100	3000
7	7.3	30	100	60	3500
8	7.3	30	100	140	3000
9	7.3	45	50	100	3500
10	7.3	45	75	100	3000
11	7.3	60	50	60	2500
12	7.3	60	75	140	2500
13	9.2	30	50	100	2500
14	9.2	30	75	140	3500
15	9.2	45	75	60	3000
16	9.2	45	100	60	2500
17	9.2	60	50	140	3000
18	9.2	60	100	100	3500

3. RESULTS AND DISCUSSION

As mentioned above and illustrated in Table 2, each plotted point of the following results is the average of six experiments, each of them repeated three times. Figure 2, shows the effect of the tool operating parameters on the resultant BL. There is no pronounced effect of β, FCAR, FR, and RS, on the BL. Therefore, the tool with $\beta = 30^o$ is recommended because its ability to higher penetration into work material. It has been reported that, the minimum bushing length to be threaded based on ISO 898, is calculated according to the following Equations (1 and 2) [15].

$$L_e \text{ (min)} = \frac{2 A_t}{0.5\,\pi\,(D - 0.64952\,p)} \qquad (1)$$

$$A_t = \frac{\pi}{4}\,(D - 0.938194\,p)^2 \qquad (2)$$

Where L_e is the length of the thread engagement, A_t is the screw thread tensile stress area, D is the basic diameter, and p is the thread pitch. The minimum L_e for M6, M8, and M10 threaded hole are 4.79, 6.48, and 8.18 mm respectively. Almost all the values of the BL produced lies within the permissible range according to the calculated L_e.
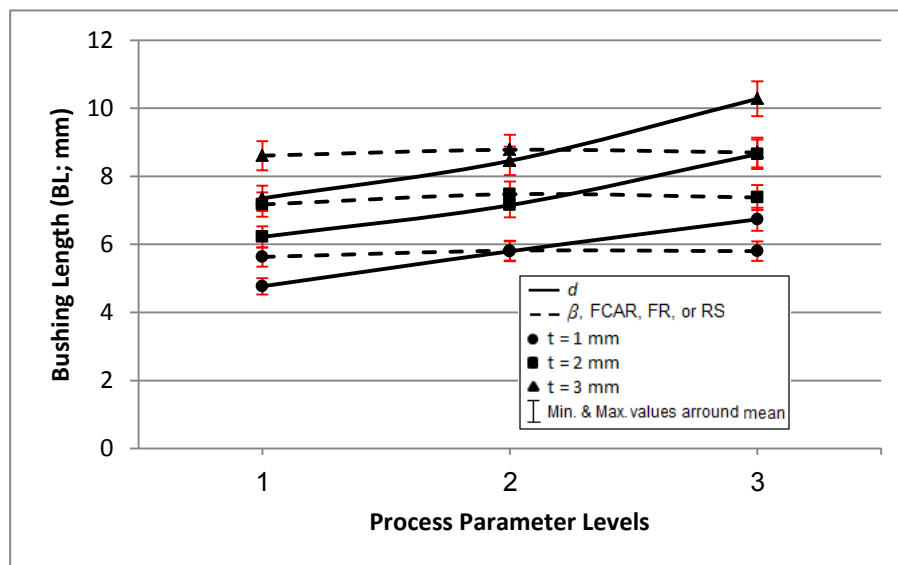

Fig. 2. Effect of the considered process parameters on the bushing length

Figures (3 to 7), show the effect of the tool operating parameters on the resultant forces. Generally, the values of the RF are very small compared to the AF. Figure 3, shows the effect of d on the resultant forces. The lowest AF achieved at $d = 7.3$ mm. However, for the material thickness under investigation, the AF varies with maximum of 20%. Increasing β increases the AF, as shown in Fig. 4. Its effects are pronou nced with increasing t. For all material thickness under investigation, the lowest AF achieves at $\beta = 30^o$. Increasing the FCAR increases the AF as shown in Fig. 5.

Therefore 50% FCAR shows the lowest AF. Increasing the FR increases the AF as shown in Fig. 6. Its effect is pronounced with increasing t to maximum percentage of 23% of the AF at $t = 3$ mm. In general, FR of 60 mm/min gives the lowest values of the resultant AF. It has been noticed in Fig. 7 that, increasing the RS decreased the resultant forces not more than 17%, and by increasing t, the resultant AF will be increased by 52 % when the material thickness is form $t = 1$~2 mm, while it is 40% from $t = 2$~3 mm, and 70% from $t = 1$~3 mm.
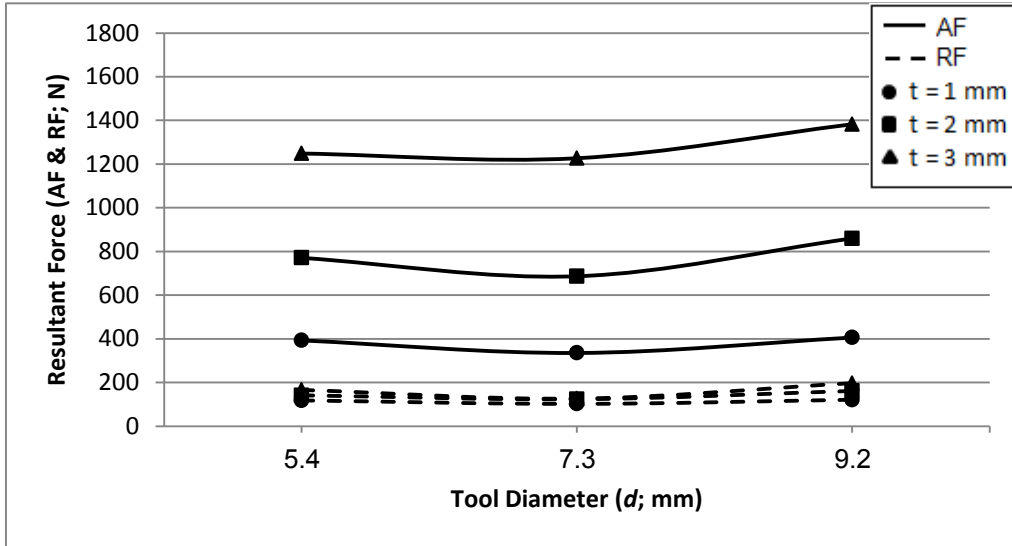
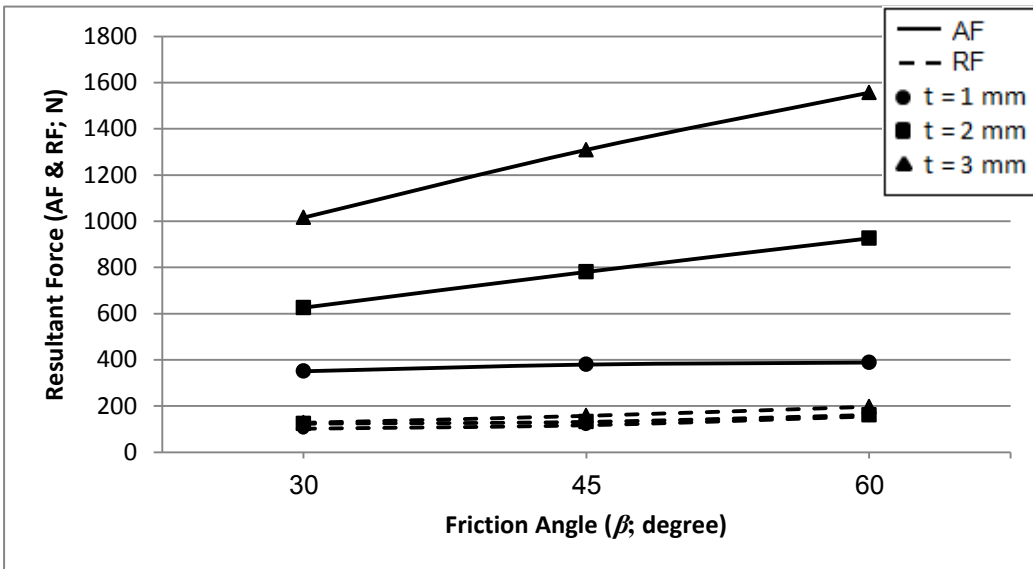Fig. 3. Effect of tool diameter on the resultant force

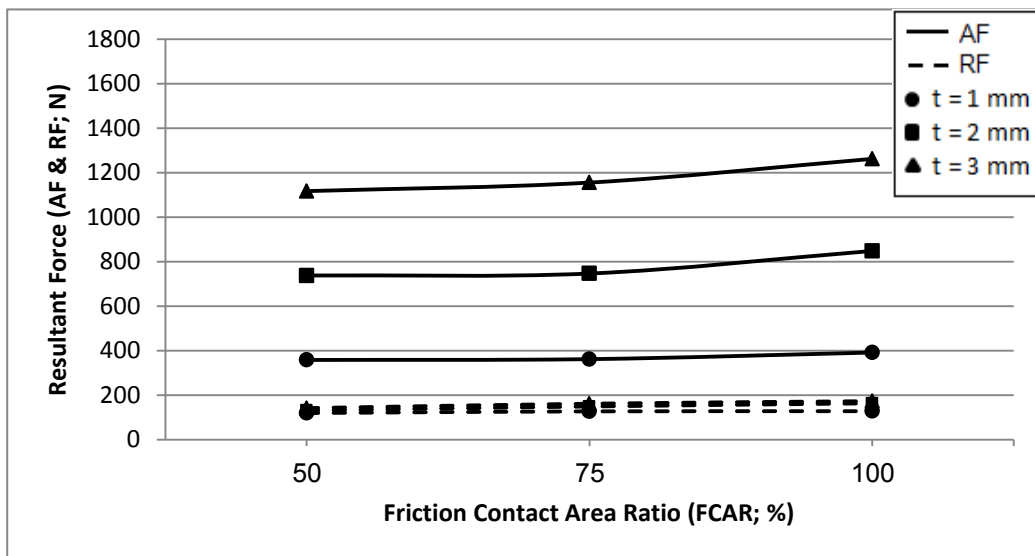Fig. 4. Effect of friction angle on the resultant force

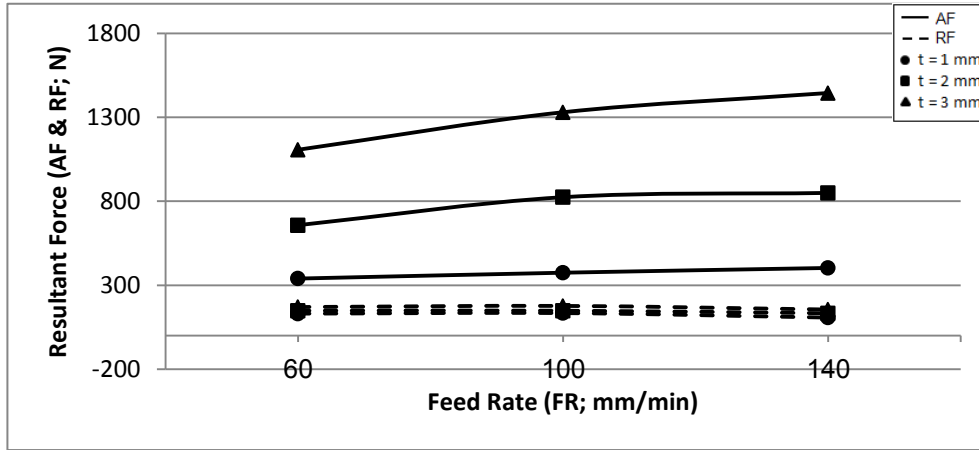Fig. 5. Effect of friction contact area ratio on the resultant force

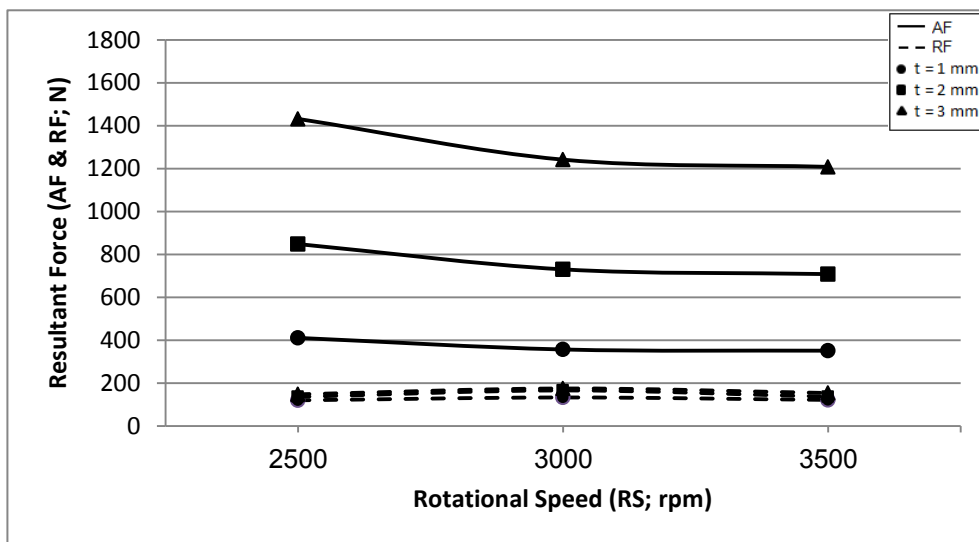Fig. 6. Effect of feed rate on the resultant force

Fig. 7. Effect of rotational speed on the resultant force

The effect of the tool operating parameters on the resultant whole diameter errors was also studied. Generally, the values of the RE are very small compared to the DE. According to ISO 286-2 grade E13 for nominal hole size 6~12 mm [16], all the obtained measured DE and RE values are within the permissible standard values, so the effect of the operating parameters are neglectable with respect to the DE and RE. For example, Fig. 8 shows the effect of d on the DE and RE at different t values.
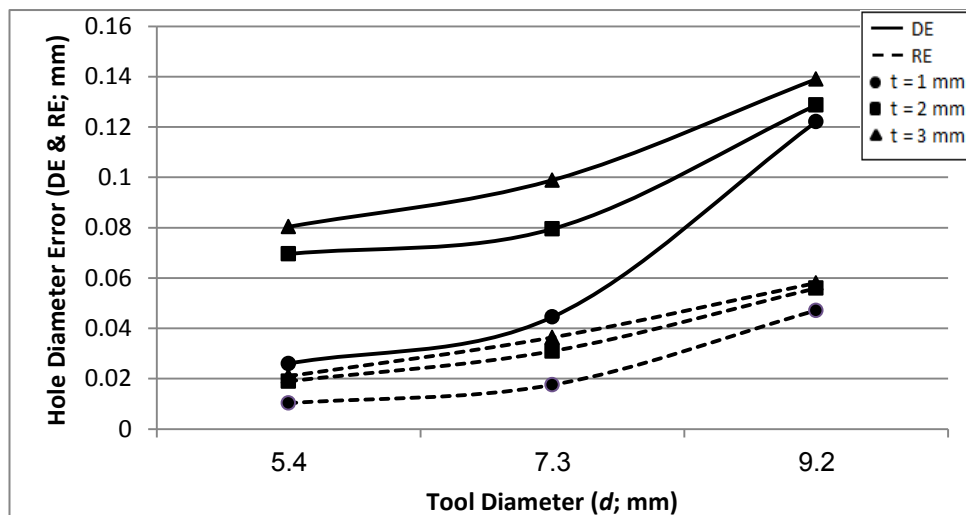

Fig. 8. Effect of tool diameter on the hole diameter error

From the above discussion, the tool operating parameters have significant effects on the AF and BL. To study the effect of the parameters on both the AF and BL together analytically, Fuzzy Logic technique and ANOVA are used.

4. FUZZY LOGIC TECHNIQUE AND ANALYSIS OF VARIANCE

To construct the inference model of the multiple performance characteristic index (MPCI) correlated with the resultant AF and BL, MATLAB software has been used. The inputs are the AF and BL means normalized values for each experiment, and the output is the MPCI.

Since the experimental design is orthogonal, so it is possible to separate out the effect of each process parameter at different levels [17]. For example, the MPCI mean for the d parameter at levels 1, 2 and 3 can be calculated by averaging the MPCI for experiments 1-6, 7-12, and 13-18, respectively as illustrated in Table 2, so the mean of the MPCI for each level of the other process parameters can be computed in a similar manner. Then the results are summarized in a table called the response table. Table 3, shows the resultant response table at t = 1, 2, and 3 mm.

Table 3. MPCI mean response table

Process Parameter	MPCI Mean								
	t = 1 mm			t = 2 mm			t = 3 mm		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
d	0.258	0.537	0.654	0.331	0.562	0.621	0.369	0.544	0.688
β	0.528	0.488	0.434	0.561	0.516	0.437	0.609	0.532	0.461
FCAR	0.491	0.485	0.473	0.521	0.498	0.495	0.586	0.584	0.431
FR	0.541	0.480	0.428	0.590	0.466	0.458	0.615	0.508	0.478
RS	0.394	0.490	0.565	0.472	0.506	0.536	0.468	0.554	0.579

However, the relative importance amongst the process parameters for the performance characteristic still needs to be known, so that the optimal combinations of the process parameter levels can be determined more accurately. The statistical analysis of variance (ANOVA) is used to investigate which process parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the multi performance characteristics indexes, which is measured by the sum of the squared deviations from the total mean of the MPCI, into contributions by each of the process parameter and the error. The sum of the squared deviations due to each process parameter k (SS_k) can be calculated according to the following Equation (3) [18].

$$SS_k = m \sum_{i=1}^{n} (MPCI\ Mean_i - \eta_m)^2 \qquad (3)$$

where m is the number of each level appearance for each factor in the orthogonal array, and n is the level number

for each parameter. The percentage contribution by each of the process parameter in the total sum of the squared deviations can be used to evaluate the importance of the process parameter change on the performance characteristics.

Table 4, shows the results of ANOVA. It indicates that the tool diameter is the most significant process parameter in affecting the AF and BL together.

From the experimental and analytical analysis, the optimal results obtained at β = 30°~45°, FCAR = 50~75 %, FR = 60 mm/min, and RS = 2500~3500 rpm, regardless the workpiece thickness and the tool diameter. Due to the achieved results at the obtained optimal ranges of β, FCAR, FR, and RS are very close to each other within 5~10 %, and these parameters are not significant, then the optimal process parameters combination will be: β = 30°, FCAR = 50%, FR = 60 mm/min, and RS = 3500 rpm at any work piece thickness or tool diameter, for the proposed experimental levels.

Table 4. Result of ANOVA

Process Parameters	t = 1 mm		t = 2 mm		t = 3 mm	
	Sum of square	Contribution (%)	Sum of square	Contribution (%)	Sum of square	Contribution (%)
d	0.495	72.328	0.281	59.661	0.306	48.374
β	0.027	3.951	0.047	9.929	0.066	10.374
FCAR	0.001	0.152	0.002	0.525	0.095	15.068
FR	0.038	5.555	0.066	13.975	0.062	9.877
RS	0.088	12.873	0.012	2.591	0.041	6.429
Error	0.035	5.142	0.063	13.320	0.062	9.880
Total	0.685	100.00	0.470	100.00	0.632	100.00

5. CONCLUSIONS

This paper has studied the effect of changing the thermal friction drilling process parameters such as the tool geometry, feed rate, and rotational speed, on the resultant bushing length, axial force, radial force, hole diameter dimensional error, and roundness error, while

drilling AISI 304 stainless steel sheets with different thickness by uncoated tungsten carbide tools. Experimental results show that by increasing the work piece thickness the resultant measured parameters increased. Also the tool diameter is the most significant parameter affecting the AF and BL together comparing to

the other considered parameters. This study can be applied on the friction drilling of various malleable metals including mild steel, stainless steel, copper, brass, and aluminum to generate precision holes. Also different machining conditions can be considered, so as to build a computer aided process planning expert system of thermal friction drilling process with the goal of automation.

REFERENCES

[1.] Sobotová L., Kmec J. and Bičejová L., "*Thermal Drilling – New Progressive Technology*," Annals of Faculty Engineering, Hunedoar-International Journal of Engineering, pp. 371-373, 2011.

[2.] Sobotová L., "*The Creation of Joinings by Thermal Drilling Method*," Ministry of Education of the Slovak Republic, pp. 80-82, 2012.

[3.] Wu C.D., Fang T.H., and Kuo C.H., "*Atomistic simulation of nanodrilling mechanics and mechanism on Cu substrates*," Applied Physics A, Materials Science and Processing, © Springer-Verlag Berlin Heidelberg, DOI 10.1007/s00339-014-8732-5, August 2014.

[4.] Prabhu T. and Arulmurugu A., "*Experimental and Analysis of Friction Drilling on Aluminum and Copper*," International Journal of Mechanical Engineering and Technology (IJMET), pp. 123-132, Volume 5, Issue 5, ISSN 0976 – 6359 (Online), May 2014.

[5.] http://www.flowdrill.com/.

[6.] Streppel A.H. and Kals H.J.J., "*Flowdrilling: a Preliminary Analysis of a New Bush-Making Operation*," Annals of the CIRP, pp. 167-171, Vol. 32/1, 1983.

[7.] Qu J. and Blau P.J., "*A New Model to Calculate Friction Coefficients and Shear Stresses in Thermal Drilling*," Journal of Manufacturing Science and Engineering, pp. 014502/1-014502/4, Vol. 130, February 2008.

[8.] Fernández A., Lopez de Lacalle L.N. and Lamikiz A., "*Friction Drilling of Stainless Steels Pipes*," International Conference on Advances in Materials and Processing Technologies, pp. 1187-1192, 2010.

[9.] Miller S.F., "*Experimental Analysis and Numerical Modeling of the Friction Drilling Process*," PHD thesis (Mechanical Engineering), University of Michigan, 2006.

[10.] Miller S.F., Blau P.J. and Shih A.J., "*Microstructural Alterations Associated With Friction Drilling of Steel, Aluminum, and Titanium*," Journal of Materials Engineering and Performance, Vol. 14(5, pp. 647-653), October 2005.

[11.] Krasauskas P., "*Experimental and Statistical Investigation of Thermo-Mechanical Friction Drilling Process*," Mechanika, Vol. 17(6), pp. 681-686, 2011.

[12.] Ozek C. and Demir Z., "*Investigate the Friction Drilling of Aluminum Alloys According to the Thermal Conductivity*," TEM Journal, Volume 2, Number 1, 2013.

[13.] El-Bahloul S.A, El-Shourbagy H.E, and El-Midany T.T, "*Optimization of Thermal Friction Drilling Process Based on Taguchi Method and Fuzzy Logic Technique*," International Journal of Science and Engineering Applications, Volume 4, Issue 2, ISSN-2319-7560 (Online), 2015.

[14.] Tsai P., Gilmour, S.G., and Mead R., "*Some New Three-Level Orthogonal Main Effects Plans Robust to Model Uncertainty*", Statistica Sinica 14(2004), PP.1075-1084, 2004.

[15.] Oberg E., Jones F.,, Horton H., Ryffel H., McCauley C., "*Machinery's Handbook 29th Edition–Toolbox*", ISBN: 9780831129002, January 2012, http://www.roymech.co.uk/ Useful_Tables/ Screws/Thread_Calcs.html.

[16.] http://www.iso.org/iso/home/search.htm?qt=iso+2 86,http://www.cobanengineering.com/Tolerances/I SOHoleTolerances3mmTo400mm.asp.

[17.] [17] Hsiang, S., and Lin Y., "*Optimization of the extrusion process for Magnesium alloy sheets using the fuzzy based Taguchi method*", the Arabian journal for science and engineering, volume 34, number 1c, 2009.

[18.] Athreya Srinivas and Venkatesh Y.D., "*Application of Taguchi Method for Optimization of Process Parameters in Improving the Surface Roughness of Lathe Facing Operation*", International Refereed Journal of Engineering and Science (IRJES), ISSN (Online) 2319-183X, (Print) 2319-1821, Volume 1, Issue 3, PP.13-19, November 2012.