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Thermal Friction Drilling: (A Review)

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Abstract: Thermal friction drilling is a novel nontraditional hole-making process. A rotating conical tool is applied to penetrate a hole and create a bushing in a single step without generating chips, providing a more solid connection for attachment than attempting to thread the original sheet. The amazing applications of thermal friction drilling in different industrial fields will lead to new era of joining process for different work materials, especially in the sheet metal applications. The aim of this work is to review the state of the art for researches performed on the friction drilling process as well as its applications considering its advantages and limitations. Thereby, to highlight the important and critical issues that should be tackled and investigated by researchers in the near future such as studying the optimal machining parameters of such process and evaluating their effects on the multiple performance characteristics.

Keywords: Friction drilling, Taguchi method, machining parameters, performance characteristics

1. Introduction

In 1923, the Frenchman Jean Claude de Valière tried making a tool that could make holes in metal by friction heat, instead of by machining. It has been recognized that if enough heat is generated it could melt and form a hole through the metal. With that thought in mind, he developed a special drill designed to increase friction. It was only a moderate success, because at that time the right materials were not yet available. Moreover, the right shape for this type of tool hadn't yet discovered till1980’s [1].

Increasing production of automobile industry, pipe industry, development of mechanical products, materials, design of joining in civil engineering force the producers to accelerate the production and to utilize new technologies.

Friction drilling, also known as thermal drilling, thermo-mechanical drilling, flow drilling, form drilling, or friction stir drilling, is a nontraditional hole-making method.

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Figure 1 shows a schematic illustration of the friction drilling steps. The tip of the conical tool approaches and contacts the workpiece, as shown in Fig. 1(a). Friction on the contact surface, created from axial force and relative angular velocity between tool and workpiece, produces heat and softens the workpiece material. As the tool is extruded into the workpiece, as shown in Fig. 1(b), it initially pushes the softened work-material sideward and upward. With the workpiece material heated and softened the tool is able to pierce through the workpiece, as shown in Fig. 1(c). Once the tool penetrates the workpiece, the tool moves further forward to push aside more workpiece material, as shown in Fig. 1(d), and form the bushing using the cylindrical part of the tool. As the process is completed, the shoulder of the tool may contact the workpiece to collar the back extruded burr on the bushing, as shown in Fig. 1(e). Then the tool retracts and leaves a hole with a bushing on the workpiece, as shown in Fig. 1(f). Finally thread forming is performed, as shown in Fig. 1(g). The drill consists of five regions as illustrated in Fig. 2.

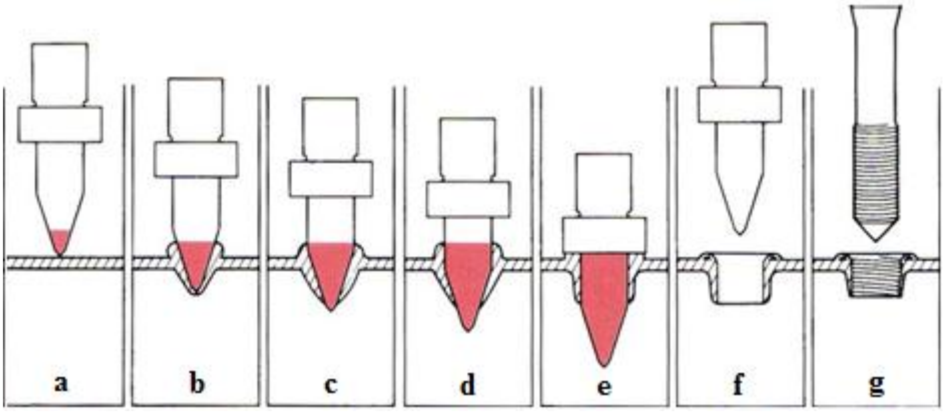

Fig. 1 Friction drilling steps: a- initial contact; b- tool-tip penetration to the material; c- material flow; d- tool-cylindrical region penetration; e- collar forming; f- tool withdrawal; g- thread forming [2]

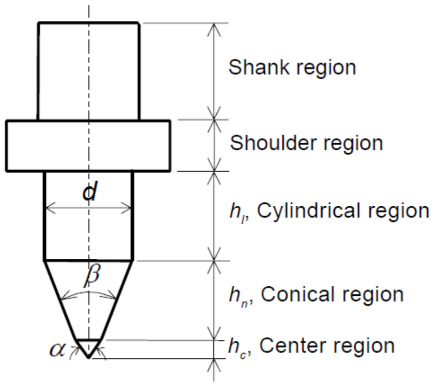

Fig. 2 Friction drilling tool geometry [3]

Friction drilling creates bushing on sheet metal, tubing, or thin walled profiles for joining devices in a simple, efficient way. The bushing created in the process is usually two to three times as thick as the original workpiece. This added thickness can be threaded, providing a more solid connection for attachment than attempting to thread the original sheet. Figure 3 shows some applications of friction drilling.

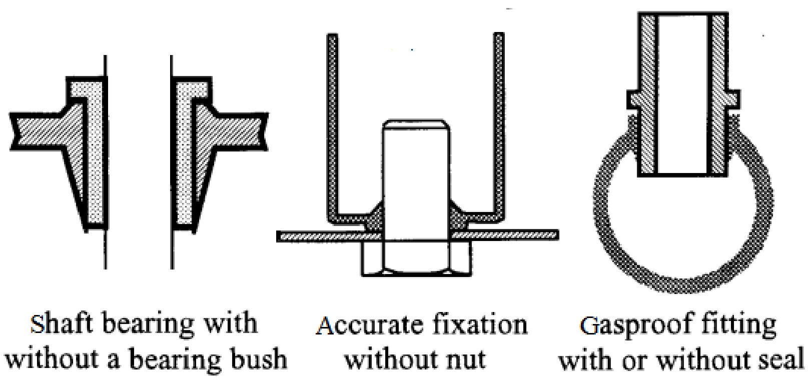

Fig. 3 Some applications of friction drilling [5]

The advantages of friction drilling compared to other methods of making fixing bushes are:

- High quality.
- Stronger joints.
- No need for special machines.
- High load capacity of bearing bushes.
- Suitable for automated manufacturing processes.
- Less material and lower weight due to the use of thin profiles.
- It is possible to produce bushes in blind sections because there is no need for support at the rear.
- No reinforcing welding, riveting down, or welding screw nuts necessary that are of a high integrity.
- Because there is no need for inspection, flow drilling can immediately be followed by thread forming.
- No cutting fluid or lubricant is necessary, which makes friction drilling a totally clean, environmentally friendly process.
- Reduces waste of material. All material from the drilled hole is transformed to create the bushing. This decreases chip cleaning and disposal cost, and no disturbances caused by chips (as in normal drilling).

The limitations of friction drilling are [1]:

- The target material must be able to withstand the added heat. Materials that have been painted, plastic coated, or galvanized are often unsuitable for this process.
- The friction drilling process is not possible in massive material. The melting metal must be able to flow somewhere. Yet it is possible to friction drilling holes in subjects up to 12 mm thick.

2. Literature Review

Streppel A.H. and *Kals H.J.J.* [4] performed a number of experiments in which some independent variables are introduced to study their effects on the resulted dependent variables. The considered independent variables are tool diameter (9, 12, and 16 mm), workpiece thickness (*md* = 2, 3, 4, and 5 mm), and workpiece material (mild steel C20, alfa-brass Cu63 Zn37, and stainless steel Cr18 Ni11.5). The considered dependent variables are: feed force, tool position, contact temperature, and the driving moment of the tool. Figure 4 shows the resulted characteristics of feed force (F_z), feed velocity (V_z), driving moment (M_z), and contact temperature (T_c), plotted against the traveled distance of the flow-drill in Z-direction.

For a better identification of the different phases of the process, the contour of the flow-drill is drawn along the Z-axis.

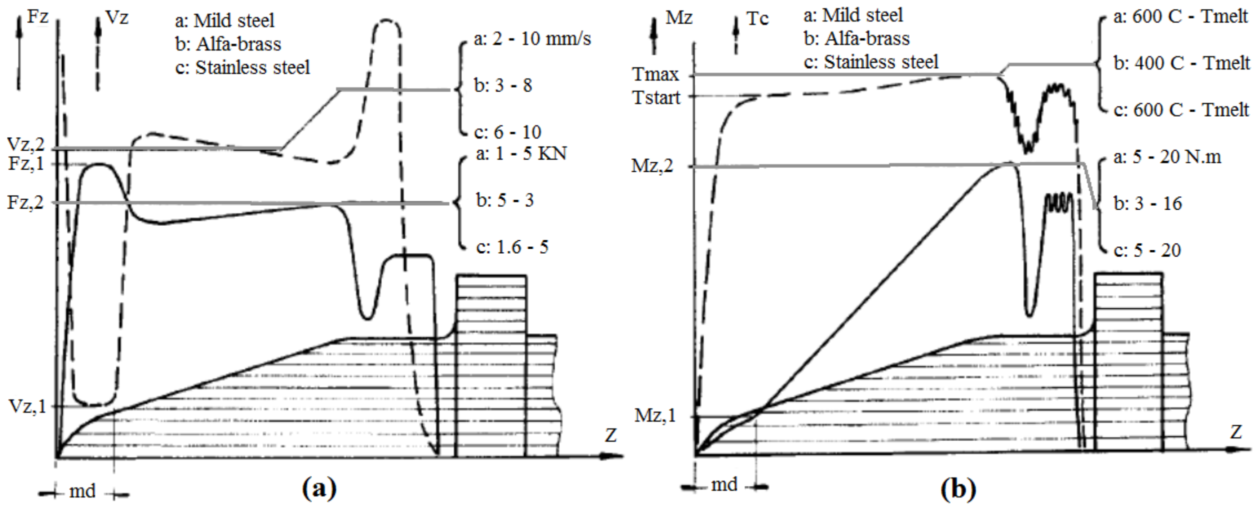

Fig. 4 (a) Feed force and feed velocity against flow-drill traveled distance;
(b) Driving moment and contact temperature against flow-drill traveled distance [4]

Kerkhofs M., *Stappen M.V.*, *D'Olieslaeger M.*, *Quaeyhaegens C.* and *Stals L.M.* [5] presented a comparison between machining by uncoated cemented carbide and (Ti,Al)N-coated flowdrills in AISI 304 stainless steel, to show the effect of coating on tool life depending upon the produced holes number. It was found that for the uncoated tools, the tool life was about 5000-15000 bushed holes, while for the (Ti,Al)N-coated flowdrills, tool lifetimes of about 100000-160000 bushed holes can be obtained. This occur because (Ti,Al)N forms, in an oxidizing environment and above 700 ^{o}C, a stable and protective Al_2O_3-type surface layer at the outer surface. The protective action of the Al_2O_3 film therefore inhibits further oxidation and can cause a reduction in the diffusion wear during high temperature machining.

Miller S.F., *Blau P.J.* and *Shih A.J.* [6] characterized the micro-structural alterations and subsurface micro-indentation hardness changes produced as a result of the friction drilling process of AISI 1020 steel, AISI 4130 steel, Al 5052, and commercially pure Ti by Co-bonded WC tools. Figure 5 shows the cross sections of friction-drilled holes. The steels had relatively smooth bore finishes, as shown in Fig. 5(a) and 5(b). However, the aluminum (Fig. 5c) and titanium (Fig. 5d) holes show severe tearing and scoring on the hole surface. Titanium was the most difficult of the four materials to friction drill. Its bushing shape, as shown in Fig. 5(d), is short and thick, compared with bushings of other work-materials. The light-colored deposit in the titanium hole is residue from the drilling lubricant.

Miller S.F., *Tao J.* and *Shih A.J.* [7] needed to generate a cylindrical shaped bushing without significant radial fracture or petal formation in brittle cast aluminum and magnesium alloys. Two ideas of pre-heating the workpiece and high speed friction drilling greater than 5500 rpm are proposed. It is well known that at elevated temperature the cast metal has increased plasticity, which can make the work-material conform to the tool and less likely to fracture. The highest workpiece temperature of Al380 was limited to 300 $^{\mathbf{o}}$C. Above this temperature, severe surface oxidization and bubble formation were observed in the workpiece. For magnesium alloy, the exothermic oxidation at elevated temperature is a problem. Therefore, friction drilling of magnesium alloy at elevated temperature was not performed. For Al380, the shape and quality of the produced bushing were observed to improve at higher workpiece temperature with less severe cracking and petal formation. But high spindle speed was detrimental on the bushing shape for both room temperature Al380 and MgAZ91D.

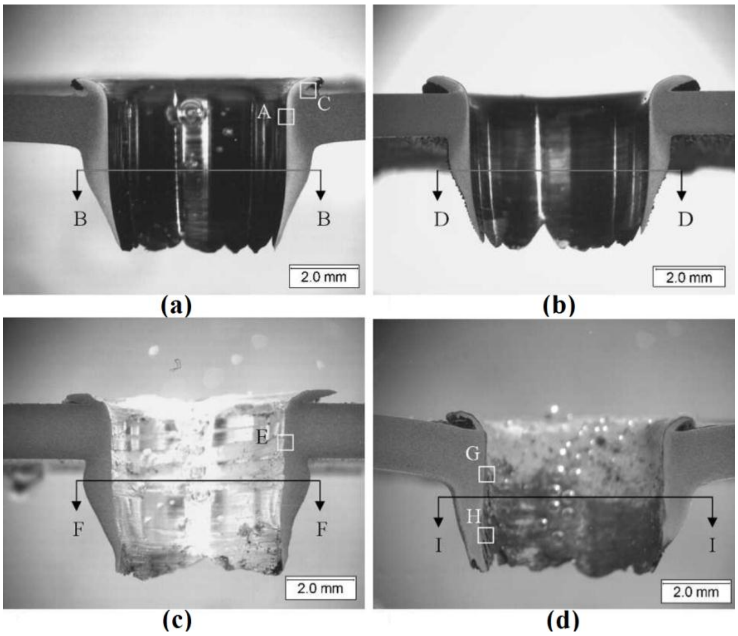

Fig. 5 Cross sections of friction-drilled holes in (a) AISI 1020 steel, (b) AISI 4130 steel, (c) Al 5052, and (d) commercially pure Ti [6]

Miller S.F., *Li R.*, *Wang H.* and *Shih A.J.* [8] developed an experimental analysis and modeling of friction drilling process. Experimentally measured thrust force and torque under constant tool speed were measured and analyzed. A mathematical model was proposed, based on the contact area between the undeformed workpiece of AISI 1020 cold-rolled carbon steel and the rigid unworn WC in a Co matrix tool, by applying ANSYS 7.0 finite element software package. The model predicted thrust force and torque had good correlation with experimental measurements as shown in Fig. 6. Some discrepancies still existed and showed the limitation of the simplified friction model used in this study.

Miller S.F., *Blau P.J.* and *Shih A.J.* [9] studied the wear of a conical tungsten carbide tool used for friction drilling of AISI 1015 steel workpiece. In addition, the thrust force and torque during drilling are measured periodically to monitor the effects of tool wear. Precise measurements of tool dimensions indicated that the wear was concentrated at the tool center region and at the intersection between the conical and cylindrical regions as shown in Fig. 7. The tool tip self-sharpened during friction drilling, which reduced the thrust force as tool wear progressed. The torque did not display any obvious changes at different stages of tool wear.

Miller S.F. and *Shih A.J.* [10] investigated 3D finite element modeling for friction drilling of Al6061-T6 work-material by A2 air hardening tool steel using ABAQUS/EXPLICIT finite element analysis software. The model is validated by comparing the resulted thrust force and torque to experimental measurements as shown in Fig. 8. The profiles of thrust force finite element modeling were shifted to the left of the experimental profiles due to the noticeable deflection of the sheet Al workpiece at the initial contact stage. This phenomenon was not accurately modeled by finite element modeling and led to the early peak of the thrust force. For torque, the discrepancy of modeling and experiment also improves at low tool feed rate. The model overestimated the torque in the initial contact stage, but underestimated the torque as it approaches its maximum. This demonstrates the limitation of the Coulomb’s friction model and the need to implement new friction models to achieve a more accurate prediction of the torque in friction drilling modeling.

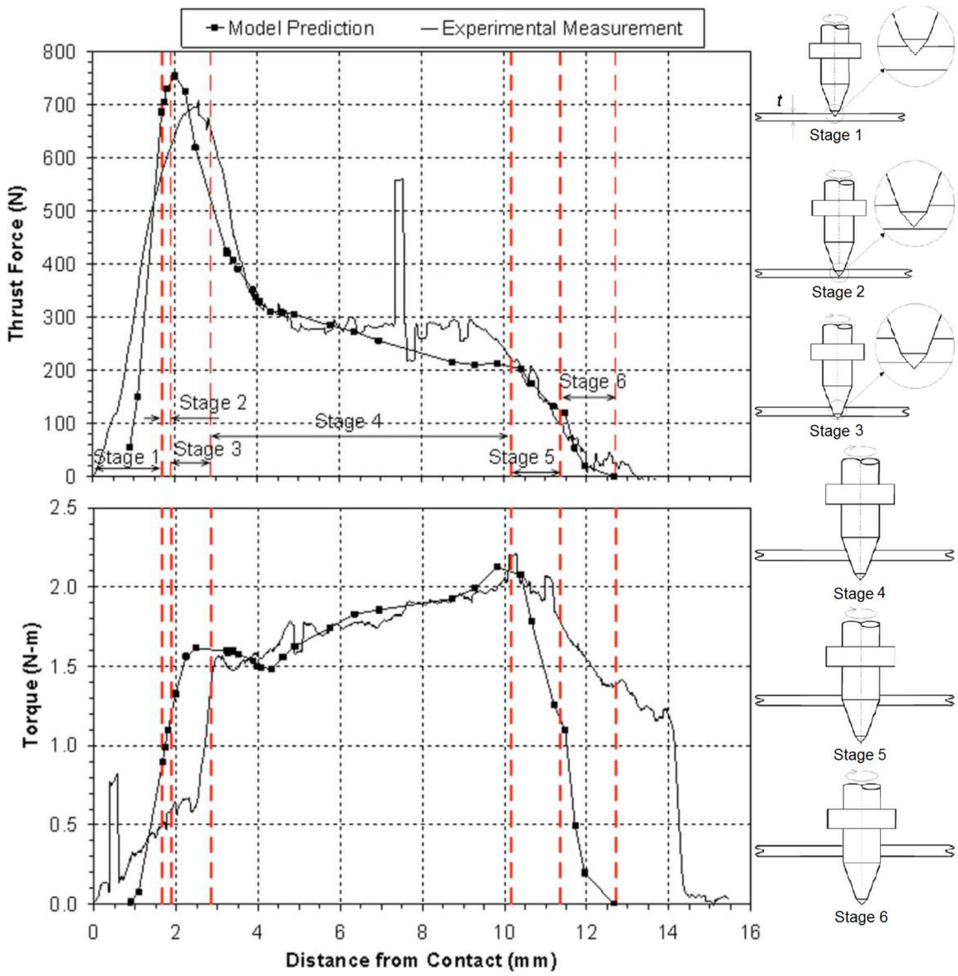

Fig. 6 Comparison of the experiment versus model predicted thrust force and torque [8]

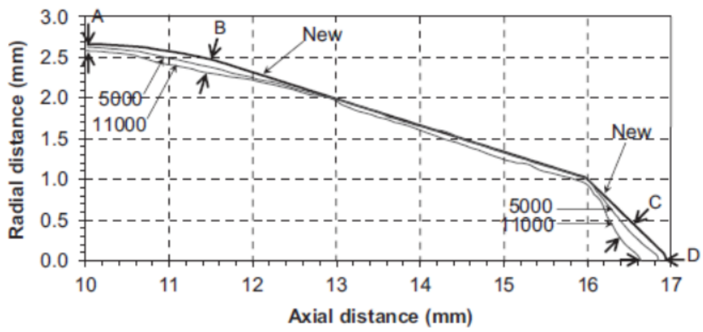

Fig. 7 Comparison of the lobe apex of the new tool and tool after drilling 5000 and 11,000 holes [9]

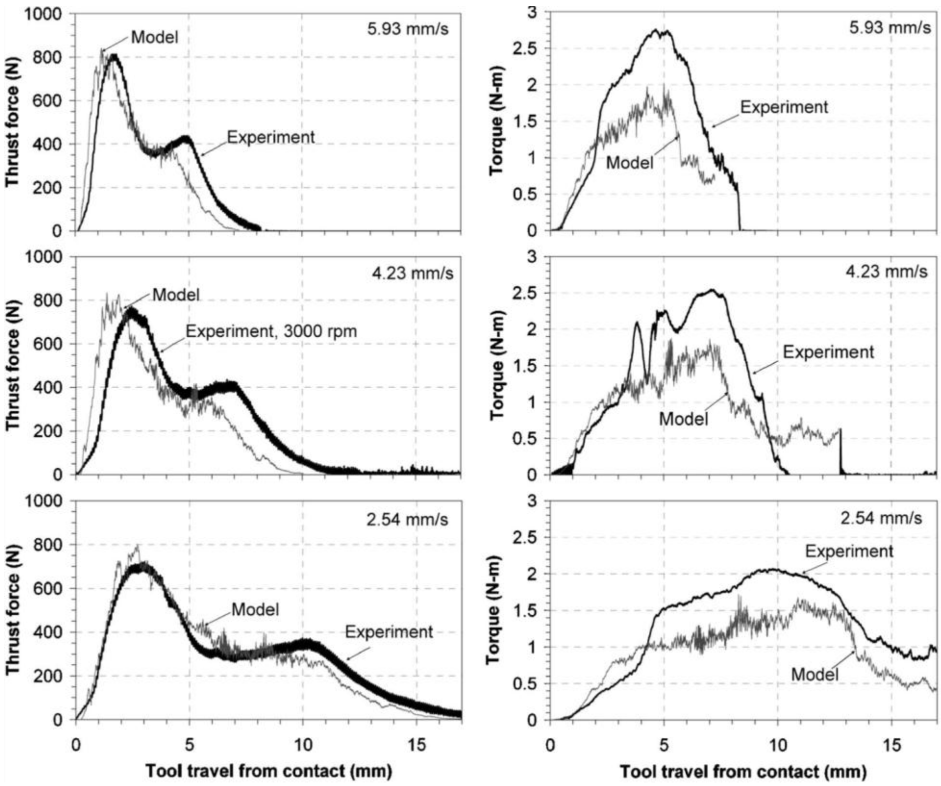

Fig. 8 Comparison of the experiment and model predicted thrust force and torque versus tool travel in friction drilling for 0.7 coefficient of friction and 3000 rpm spindle speed [10]

Chow H.M., *Lee S.M.* and *Yang L.D.* [11] applied Taguchi method to explore how different process parameters such as friction angle (30^o, 45^o, and 60^o), friction contact area ratio (50, 75, and 100 %), feed rate (75, 100, and 125 mm/min), and drilling speed (30, 60, and 90 m/min) would affect the produced hole surface roughness, while drilling AISI 304 stainless steel by sintered carbide drill. The optimal drilling conditions that produced the smallest surface roughness were: 30^o friction angle, 50 % friction contact area ratio, 100 mm/min feed rate, and 90 m/min drilling speed.

Qu J. and *Blau P.J.* [12] developed a new analytical model for thermal drilling useful for predicting the effective friction coefficient and shear stresses that occur during the process, based on the experimentally measured values of the instantaneous thrust force and torque of reference [5]. Figure 9 shows the produced profiles of coefficient of friction and shear stress.

Lee S.M., *Chow H.M.*, *Huang F.Y.* and *Yan B.H.* [13] used tungsten carbide drills with physical vapor deposition AlCrN and TiAlN coatings, and without coating to make holes in AISI 304 stainless steel. The presence of coating on drills suppressed the transfer of W and Co from the tungsten carbide base material to the drill surface and prevented the transfer of Fe and Cr from the stainless steel workpiece to the drill surface, both of which contributed to reduce tool wear. Experimental results reveal that lubricating effect of the coating and low thermal conductivity of AlCrN caused AlCrN coating drill to produce the highest surface temperature but the lowest axial thrust force with the least tool wear. However, the difference in performance between coated and uncoated drills diminished with increase in number of holes drilled.

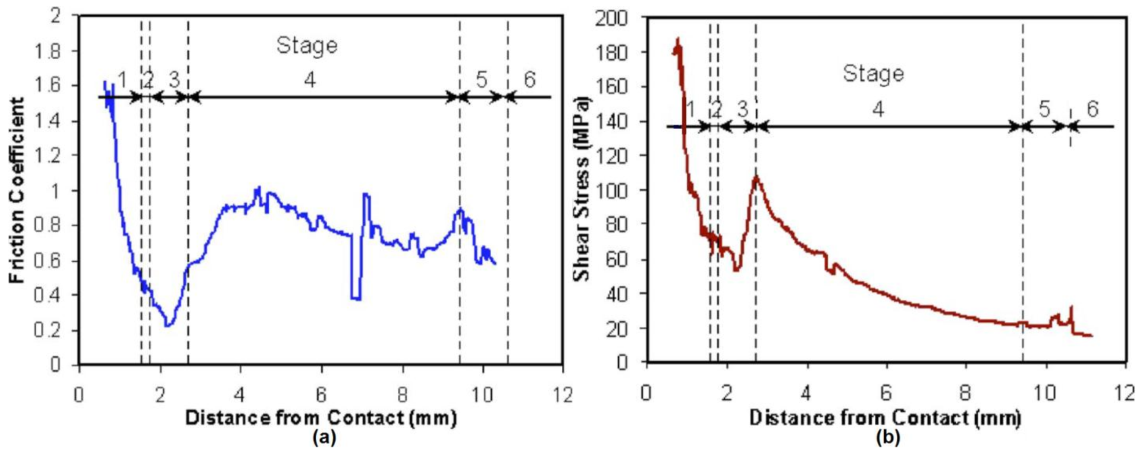

Fig. 9 Profiles of (a) friction coefficient and (b) shear stress [12]

Fernández A., *Lopez de Lacalle L.N.* and *Lamikiz A.* [14] analyzed, through controlled tests at different rotational speeds and feed rates, the friction drilling of austenitic stainless steel with different thicknesses by tungsten carbide with cobalt matrix tool. Experimentation shows that for higher spindle speeds, higher process temperature is produced. When the temperature of the workpiece increases, the form of the burr is more cylindrical with a greater depth. According to the feed rate, higher feed rate leads to a maximum temperature reduction, because the contact time between tool and workpiece decreases.

Krishna P.V., *Kishore K.* and *Satyanarayana V.V.* [15] designed an experimental layout and applied Taguchi method to evaluate the performance of high speed steel friction drill on AA6351 workpiece. The selected process parameters are rotational speed (2000−3000 rpm), feed rate (0.1−0.3 mm/rev), and friction angle (45^o-90^o). Figure 10 shows the variation of torque and thrust force according to the selected parameters.

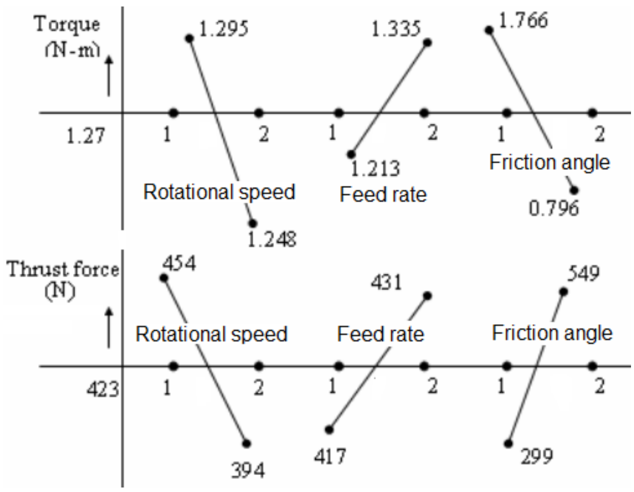

Fig. 10 Variation of torque and thrust force [15]

Somasundaram G., *Boopathy S.R.* [16] and *Palanikumar K.* [17] applied Response Surface methodology to develop a mathematical model for hole quality in terms of roundness error to correlate the important machining parameters in friction drilling of AlSiC metal matrix composite work piece by TIN coated high speed steel. The parameters considered are spindle speed (2000, 2500, 3000, 3500, and 4000 rpm), feed rate (40, 50, 60, 70, and 80 mm/min), workpiece thickness (2, 2.5, 3, 3.5, and 4 mm), and weight % of SiC (5, 10, 15, 20, and 25

%). Results showed that the hole quality in terms of roundness error increases with the increase in spindle speed, feed rate, and plates thickness, but it decreases with the increase in weight percentage of SiC.

Ku W.L., *Hung C.L.*, *Lee S.M.* and *Chow H.M.* [18] investigated the effects of friction angle (30^o, 45^o, and 60^o), friction contact area ratio (50, 75, and 100 %), feed rate (75, 100, and 125 mm/min), and spindle speed (1200, 2400, and 3600 rpm) while drilling SUS 304 stainless steel by tungsten carbide tool, on the two quality characteristics surface roughness and bushing length by using Taguchi method. Figure 11 shows the variation of surface roughness and bushing length according to the selected parameters. Results showed that friction angle and spindle speed were the significant machining parameters that most intensively affect surface roughness while friction contact area ratio was the only significant parameter for bushing length.

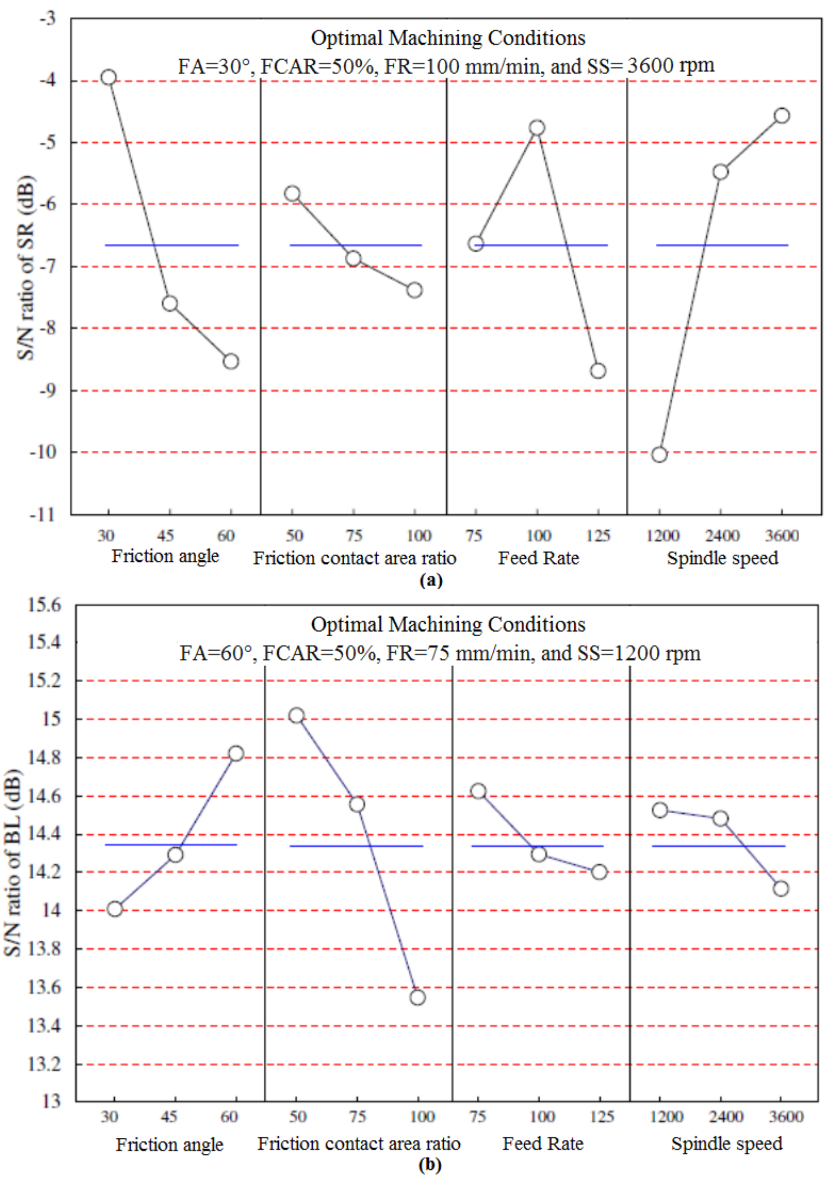

Fig. 11 Response graph of (a) surface roughness and (b) bushing length [18]

Ku W.L., *Chow H.M.*, *Lin Y.J.*, *Wang D.A.* and *Yang L.D.* [19] studied the optimal machining parameters for thermal friction drilling of SUS 304 stainless steel by tungsten carbide tool.

The experiments were conducted based on Taguchi method and grey relational analysis, which produce a multiple performance characteristics correlated with surface roughness and bushing length. The considered machining parameters are spindle speed (1200, 2400, and 3600 rpm), feed rate (75, 100, and 125 mm/min), friction angle (30^o, 45^o, and 60^o), and friction contact area ratio (50, 75, and 100 %). The statistically analysis results show that friction contact area ratio and the spindle speed were the significant machining parameters that affect the multiple performance characteristics. The optimal combination levels of machining parameters were: 30^o friction angle, 50 % friction contact area ratio, 100 mm/min feed rate, and 2400 rpm spindle speed.

Krasauskas P. [20] performed a statistical five variable linear regression analysis in order to evaluate the influence of plate thickness (1.5, 2, and 2.5 mm), rotational speed (2000, 2500, and 3000 rpm), feed rate (60, 100, and 140 mm/min), and materials mechanical properties, by choosing three different materials (hot rolled 5235 steel, AISI 4301 stainless steel, and Al5652 alloy), on axial drilling force and torque. The analysis of spindle rotational speed and feed rate influence on axial force variation showed that minimal spindle speed calls bigger drilling force, while bigger the feed bigger the axial force.

Pantawane P.D. and *Ahuja B.B.* [21] applied the Response Surface method to investigate the effect of friction drilling input parameters such as rotational speed (2086, 2500, 3500, 4500, and 4914 rpm), feed rate (71.36, 90, 135, 180, and 198.64 mm/min), and tool diameter (7.3 and 9.2 mm) on the responses dimensional error and surface roughness of AISI 1015 bush by using tungsten carbide in a cobalt matrix drilling tools. Optimization using Desirability Function has been used to optimize the machining conditions. The optimum setting which results in maximum desirability found to be as 4500 rpm speed, 71.36 mm/min feed, and 7.3 mm tool diameter. The low desirability M10 tool indicates its poor performance, hence this tool is not recommended.

Sobotová L., *Kmec J.* and *Bičejová L.* [22] developed thermal drilling of three types of materials: aluminum (AlMgSi, Slovak standard STN 42 4401, thickness 2 mm); copper (STN 42 3001, U profile, thickness 2 mm); and steel (S2356JR, STN 11 373, thickness 2 mm) by short and short flat conical drills. The best quality of bushing and collar was created from steel, also the strength properties was the best for this material. For copper and brass sheets, the bushings and collars were not so smooth; the bottoms were wrapped with comparison of steel ones, but are satisfied for mechanical screw non-permanent joints. The worst material was aluminum from used materials, where the following creating of threads shows the most deviation from defined shape and there were occurred more fractures on the bottom border of bushing.

Engbert T., *Heymann T.*, *Biermann D.* and *Zabel A.* [23] developed flow-drilling and thread-forming of steel-wire-reinforced and non-reinforced aluminum profiles by cemented carbide tools. The considered influencing factors are flow drill peripheral speed (v_c) and feed (f), as well as the position of the reinforcing elements (RE) relative to the centre of the hole. Figure 12 shows variation of maximum feed force during flow drilling with different parameter combinations. To examine the effect of the reinforcement on the thread-forming result, the threads are stressed with a defined tensile load until failure. Figure 13 shows the maximum tensile force transmitted by differently produced threads.

Reddy V.D., *Krishnaiah G.*, *Chand G.* and *Indumathi* [24] applied Taguchi method to evaluate the performance of high speed steel form drill on AA1100 work piece, by measuring the thrust force and torque during the process. The process parameters considered are rotational speed (700−760 rpm), feed rate (0.15−0.2 mm/min), and R_2/R_1 (0.11−0.44). Figure 14 shows the variation of thrust force and torque according to the selected parameters.

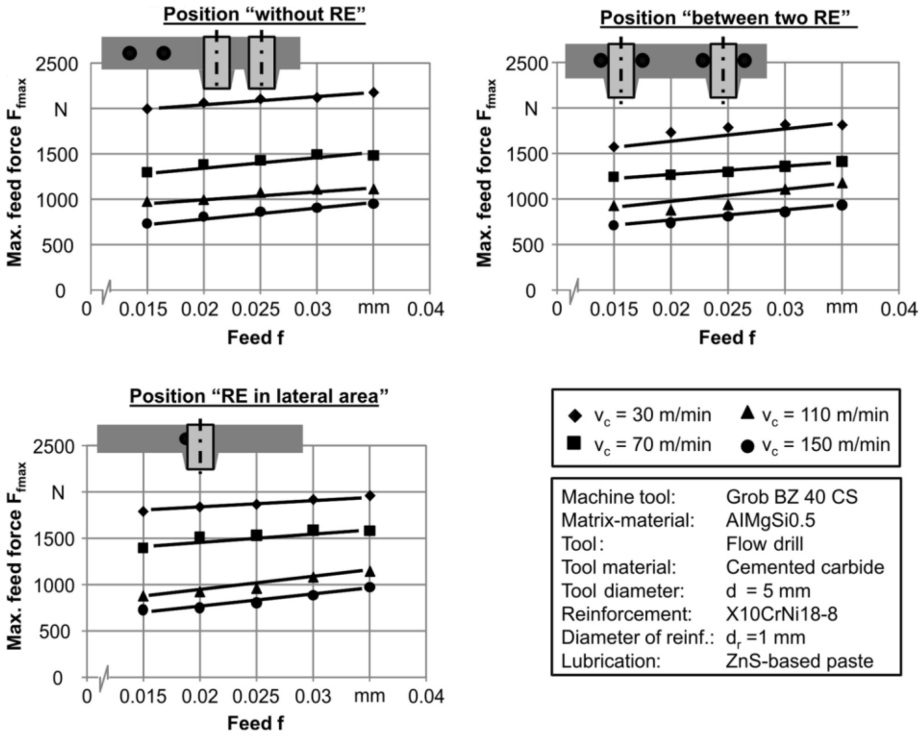

Fig. 12 Variation of maximum feed force during flow drilling with different parameter combinations [23]

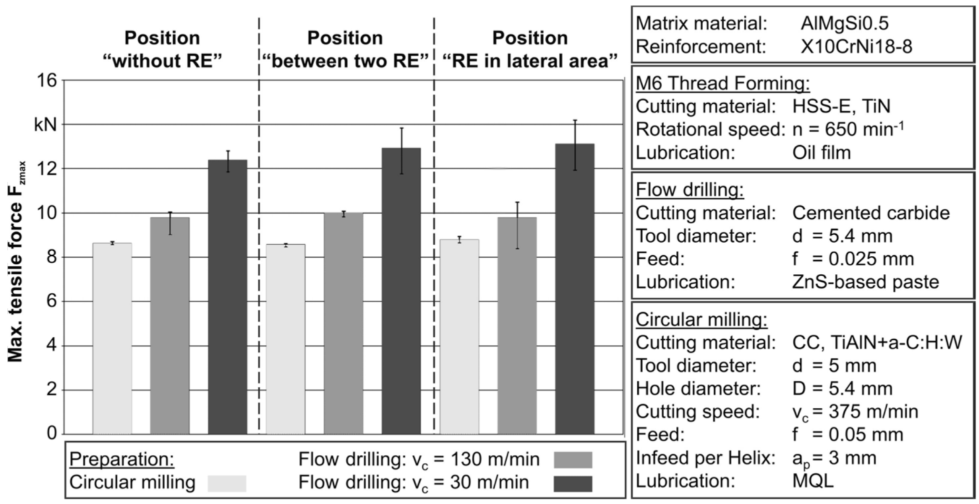

Fig. 13 Maximum tensile force transmitted by differently produced threads [23]

Sobotová L. [25] verified the suitability of thermal drilling of anti-corrosive steel (STN 17 240) by short and short flat conical drills. The produced samples were tested by Vickers hardening test. The hardening of material was changed in dependence of measuring distance from the heat influenced places. The testing places are shown in Fig. 15, while their measured hardness values are shown in Table 1 for drilling at 1470 rpm.

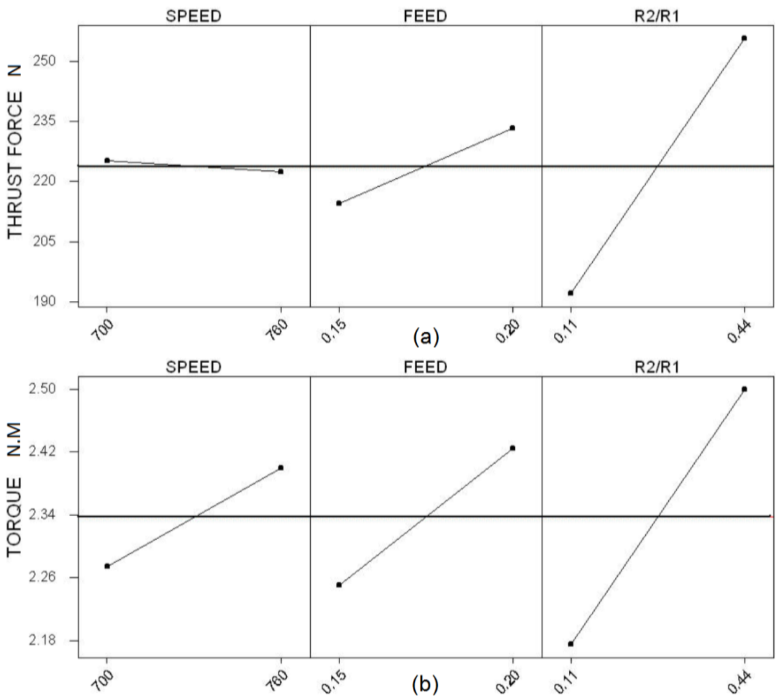

Fig. 14 Variation of (a) thrust force and (b) torque [24]

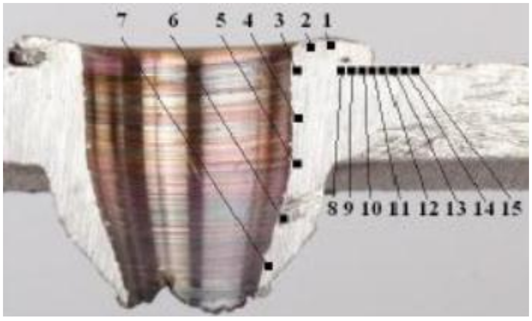

Fig.15 The measuring points of Vickers hardening test on the testing sample [25]

Table 1 Measured values of hardness [25]

Point	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Micro-hardness (HV 0.1)	267	298	275	298	298	240	225	309	307	291	312	307	293	307

Krasauskas P., *Keselys T.* and *Kilikevicius S.* [26] performed a simulation of the thermo mechanical drilling process using ABAQUS/EXPLICIT finite element analysis software. The axial force variation during the penetration of tungsten carbide tool in AISI 304 steel plate was obtained and a comparison to the experimental data was carried out as shown in Fig. 16.

Yang L.D., *Ku W.L.*, *Chow H.M.*, *Wang D.A.* and *Lin Y.C.* [27] applied thermal friction drilling on three types of Ni-based superalloys (Mar-M247, Haynes-230, and Inconel-718) using different spindle speeds and feed rates. The experiment results showed that material strength and mechanical features are the most significant factors. As Inconel-718 has the highest strength of the three materials so its destructive and yield strength is the highest, so during friction drilling it has the highest axial force to run through the workpiece and obtain the shortest bush length and worst surface roughness. Haynes-230 has the smallest destructive and yield strength of the three materials, therefore, it needs small axial force to run through the workpiece and forms the longest bush length and best hole surface roughness.

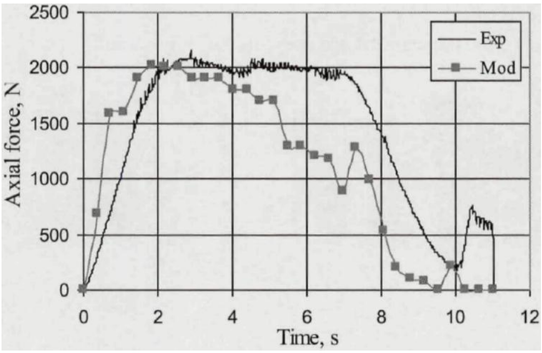

Fig. 16 Comparison of experimentally measured and simulated axial force variation at spindle rotation speed of 2000 rpm and tool feed rate of 60 mm/min [26]

Raju B.P. and *Swamy M.K.* [28] investigated the finite element modeling for friction drilling of AL6061 work-material by tungsten carbide tool, using DEFORM-3D software. The resulted effective stress and effective strain at various speeds and feed rates are shown in Fig. 17.

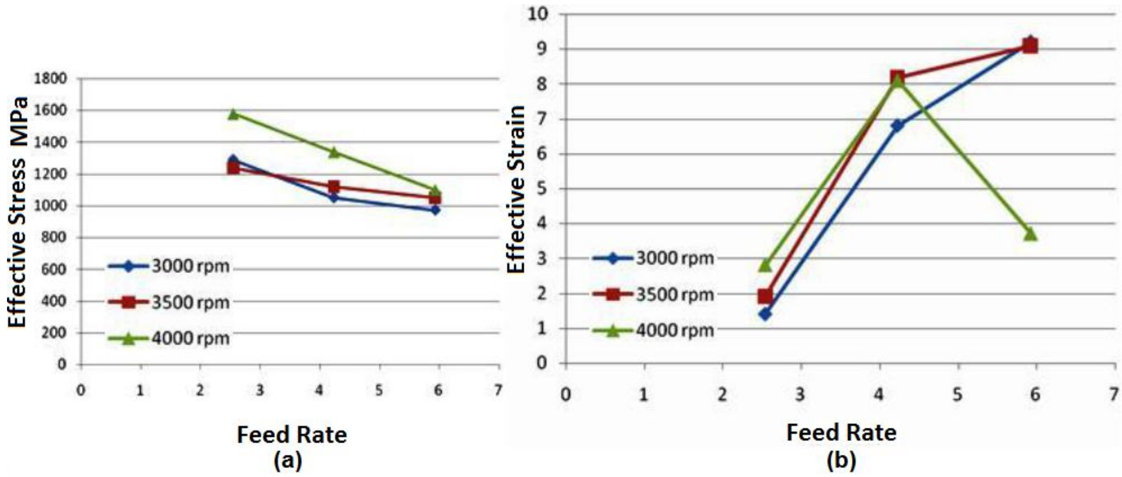

Fig. 17 (a) Effective stress vs. feed rate; (b) Effective strain vs. feed rate [28]

3. Conclusions

Friction drilling is a rapid, economical and revolutionary technique for holes making in sheet metals. This review has identified the need for future studies in the following areas:

- Optimization of friction drilling process, considering important machining parameters, using means of Artificial Intelligence techniques such as Fuzzy Logic, Neural Networks, Genetic Algorithms, etc.
- The finite element modeling can be extended to study the temperature and stress in the tool during friction drilling. This can be beneficial for the tool geometry design and tool material selection. A better tool geometry can also help to reduce the thrust force and deflection and improve bushing formation in the workpiece.

- New ideas to improve the quality of bushing are still necessary for brittle cast metals. The deformation and fracture of work-material to form petals are not well understood. Practically, different ways to heat the workpiece need to be investigated, such as using the induction heating to locally raise the temperature on the spot of drilling or the tool, ultrasonic vibration of the workpiece, or designed tool features that cause frictional heating prior to drilling.

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