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Review

Thermal drilling processing on sheet metals: A review

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Abstract

Thermal drilling is a sheet metal hole making technique and which is the most cost-effective and extremely high productivity technique in sheet metal fastenings. Especially, the fastening or joining of sheet metals is generally used in all manufacturing and industrial applications. But, by reason of thin sheet metal thickness, these fastenings are seen as a tremendously big problem in production. Different traditional methods are available such as welding of a nut to sheet metal, insert rivet & swelling nuts in the drilled hole, which is generally employed for the applications of screw fastening in order to produce a safe and secure screw fastening situation. Those methods revealed some undesirable effects like lifting & twisting of rivets and nuts, thermal distortion at the welding of nut. These difficulties are entirely eliminated in the thermal drilling process. In this review, the basic working principle of the thermal drilling process, merits, the described experimental setup, used thermal drill tools and different applications for various sheet metals are stated clearly.

Keywords

Thermal drilling; Applications; Thermal drill tools; Sheet metals

1. Introduction

Nowadays, in numerous industrial applications, the fixing of thin sheet metal with the thin walled section and pipe-shaped profiles fitting are widely used. Moreover, due to the development of modern design in the automobile industry, the requirement of lightweight structures is high to increase the efficiency of automotive vehicles. As stated above, for the fastening of sheet metals, three important conventional methods for mechanical fastening have existed. They are i) joining by bolt and nuts, ii) welding of nut and iii) inserting of rivets [1].

Fig. 1 shows the comparison of conventional methods with a novel method. The first method is bolt fastening method which is commonly using fastening method in fastening of sheet metal constructions [3], since it needs a single hole drilling only and threading in the sheet metals to be connected and hence it is the very easy and cheapest method.

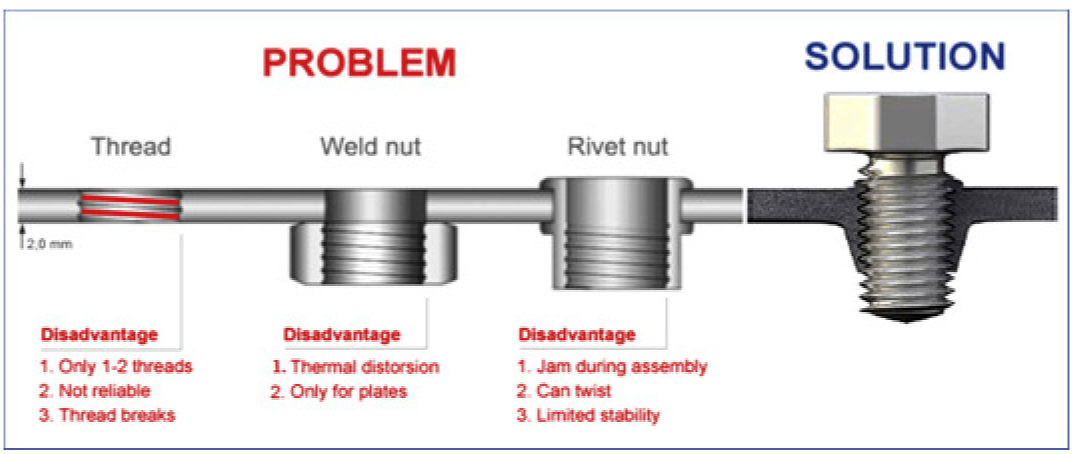

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Fig. 1. Sheet metals joining methods [2].

However, during fastening of thin sheet metals to each other, the strength problem of the joint is attained by inadequate screwing length. Next two methods are developed to increase the strength of joint such as welding of nuts and inserting of rivets by increasing of screwing length. But those methods also some disadvantages such as thermal distortion, jamming and twisting during assembly and limited stability. Thermal drilling is the only process which provides the solution of ensured adequate screwing length without twisting by the way of formation of bush and threading [4]. Table 1 gives the various criteria of drilling methods.

Table 1. Comparison of different fastening methods.

Sl. No	Criteria	Conventional fastening methods		Thermal drilling
		Weld nut	**Rivet nut**	
1	**Necessity of previously drilled holes and burring**	Yes	Yes	No
2	**Complex features**	Time consuming	Time consuming	**Fast in less time**
3	Requirement of special attachment	Yes	Yes	No
4	Error rate	Very high	Very high	Very low
5	Automation	Conditionally possible with high effort	Conditionally possible with high effort	Easily possible with high flexibility
6	**Machining of closed frames**	Conditionally possible	Possible on circular tubes	Simply possible
7	Reliability	High	Low	High
8	Torque level	High	Low	High
9	Type of connection	Partly joining of microstructure by spot welding	Mechanical and Keyed press connection	Uniformly closed joining of microstructure
10	Distortion problem	Distortion due to heat input by welding process	Distortion of thread and risk of slipping	No distortion

The thermal drilling process is described as sleeve or bush forming in a single processing step by using rotating thermal drill tool without removal of the chip [5]. This process uses the frictional heat produced by a rotating tool to form a bush. This frictional heat, which is happened by friction or rubbing between the tool and sheet metal and leads to forming a hole by extrusion of sheet metal. It is clean, easy and unconventional sheet metal hole drilling method. The process is also named as friction drilling, flow drilling, thermo-mechanical drilling, friction stir drilling, flow drilling, thermal friction drilling and form drilling. The purpose of this unconventional hole production method is; increased screwing length in thin-walled sheet metals through the formation of the bush, to assembling of thin sheet metals.

Initially, during the year of 1923, Jan Claude de Valliere was developed the new innovative idea to replace the traditional sheet metal drilling process. Then in 1976–1980, Geffen had awarded four patents on friction drilling process [6], [7], [8], [9]. Later in 1984, one patent was achieved by Head and another one was achieved by Hoogenboom [10], [11].

However, after sixty years only the practical applications of thermal drilling process originated into existent by the development of tungsten carbide thermal drill tool [12], [13], [14]. This development of thermal drill tool has been used to satisfy the needs of new industry trends, to enhance the productivity and tool life, to establish the process without wastage and to enhance the surface quality of holes [15], [16], [17], [18].

This method has to be applied in various sheet metals, thin-walled structure, and different cross-sectioned metals. The most important advantage of thermal drilling is drilling of round cross-section tubes, which is quite complex. Specific applications of thermal drilling are, bolted fastening, thin-square walled cross-section fittings, sealing of fire extinguisher and gas connections, sliding bearings with high strength, automobile door hinges, door locking device, a hole for protection of leakage in pressure valve, computer tables roller fittings [19], [20]. Fig.2 shows some of the diverse applications of thermal drilling technique. Table2 shows the additional applications of the thermal drilling process.

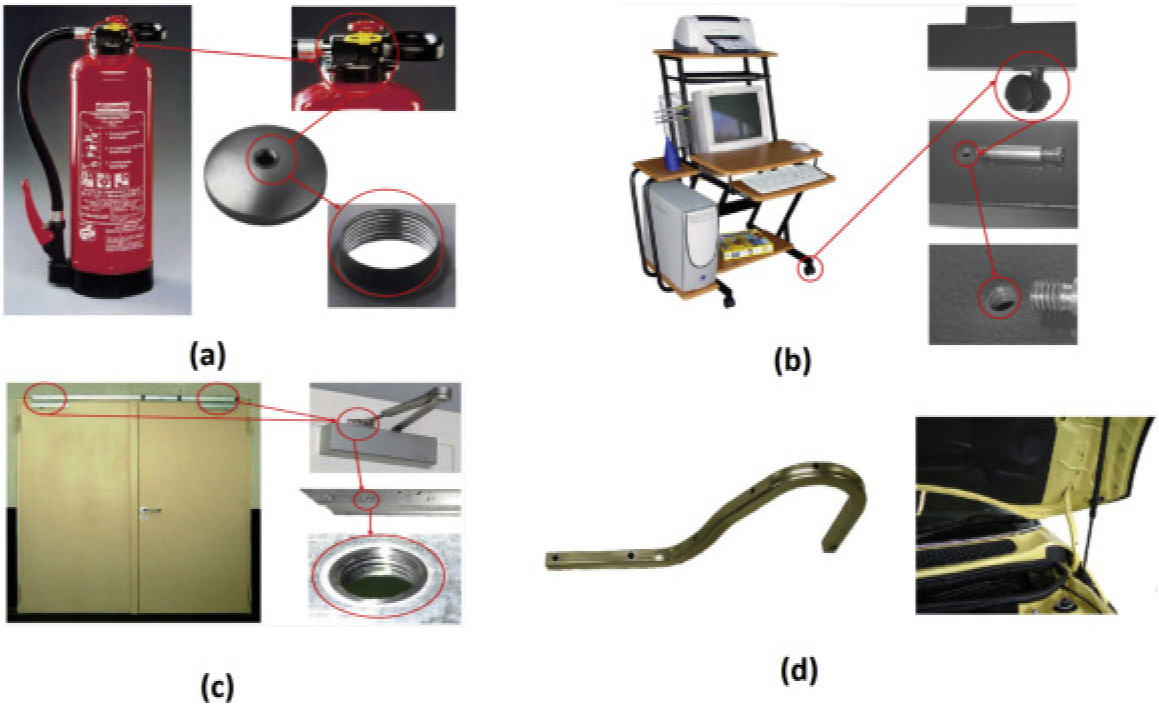

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Fig. 2. Practical industrial applications of thermal drilling process (a) sealing of fire extinguisher (b) computer rollers fitting (c) door locking device (d) automobile door hinges [20].

Table 2. List of thermal drilling applications.

Automobile	Steering mechanisms, Bull bars, Control pedals, Light fittings, Chassis frame, Fixing of hinges, Dash Frame, Fitting of seats, Exhaust pipes
Furniture	Shelving, Desk Frames and Display units
Heating, Ventilation	Boilers, Radiators, Pipe manifolds, Water tanks, Gas fittings, Air conditioning systems
Construction	Shelters, Building frames, Bridge parapet, Lift shaft, Window frames
Agriculture	Crop sprayers, Toppers, Harrows, Ploughs, Tractor Cabs

In the thermal drilling process, the possibility of producing reliable strong bolted fastenings by bush shape formation which is about 3-times thicker than the original sheet metal, because the metal at drilling zone is deformed without any metal loss. As per the working principle of process, the volume of material displaced is the same as the volume of material deformed by bushing can be calculated as follows

$$B_H = \frac{D_i^2}{[D_o^2 - D_i^2]} \times W_t \quad (1)$$

where D_i & D_o represent inner diameter and outer diameter of bush, W_t is the workpiece thickness and B_H denotes bushing height in mm.

Fig.3 demonstrates the bushing formed by this process on the round hole tube. Besides, the necessity of specially developed machines are not needed for this process, with conventional drilling machines or ordinary CNC machines, this process has to be made successfully in a just single step. With the low cost of investment, the desired surface quality of drilled holes is achieved without additional components. The surface quality of thermal drilled holes is not scratched since there is no chip formation during the processing of thermal drilling operation. Therefore it is also described as chipless drilling operation and offers an unpolluted environment in working space. Hence the life of thermal drill tool has been prolonged and manufacturing or processing costs are declined [22], [23].

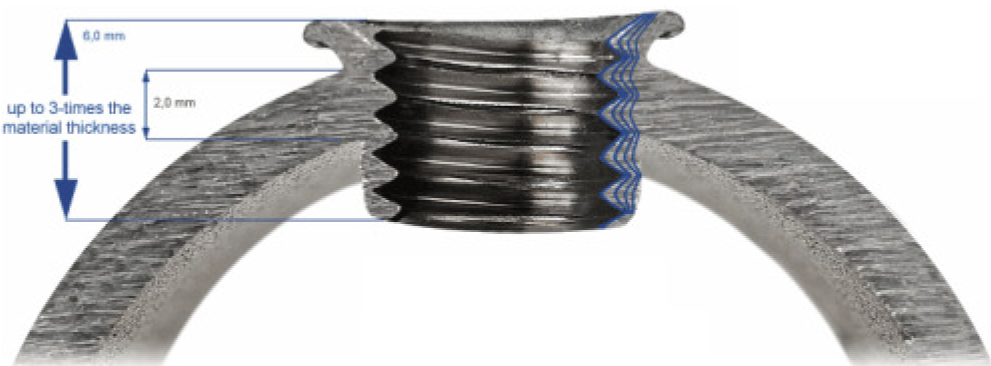

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Fig.3. Cross-sectioned thermal drilled bush with threads [21].

2. Thermal drilling process

2.1. Thermal drilling tool

Thermal drill tool creates the frictional heat by the combined action of rotational speed and downward fee rate. It allows the sheet metal at the drilling zone to be transformed into “super-plastic state” due to that the metal displacement occurs in both downward and upward direction. The bushing is formed due to the downward displacement of material flow along with a boss due to the upward material displacement. In the thermal drilling process, the temperature at the frictional contact of thermal drill and sheet metal workpiece is the most significant parameter. While processing, the temperature of the thermal drill could the damaging of metal structure leads to affect the bushing shape and also the microstructure of the bush wall surface is altered by hot thermal drill [24], [25], [26], [27]. Normally, the temperature of sheet metal workpiece increases to 600°C and the thermal drill tool temperature varies from 650 to 750°C. These values of temperature have been reported to vary according to the drilling tool shape and thermal properties of sheet metal to be drilled [28].

The different regions of the thermal drill are shown in Fig.4 have a direct influence on the formation of bushing and boss. Central region: This region is represented by the center angle (α) and height (h_c). This region has been specially designed as in a helical drill, which gives radial support as well as centering for the thermal drilling process. Conical region: This region has a high sharper conical angle than the previous center region. This region rubs against the sheet metal to generate the heat and then displaces the softened material. Conical angle and height are represented by the symbol of β and h_n. Cylindrical region: This region is used to shape the bush by its cylindrical shape. The symbols of h_l and d are used to denotes the cylindrical length and diameter of this region respectively. Shoulder region: It has a cylindrical shape which is used to compress the upward flow material and it forms a ring like boss on the top side of the hole. Besides, the shoulder region is constructed with a pointed cutting edge, which is used to trim or cut the boss on the topper side of the hole. Frequently, the diameter of this region must be greater than the diameter of the cylindrical region, and this diameter should be designated to the extent that the melt can be repressed under the entirety of the melt material. Shank region: This region is defined as the area which is covered by the tool holder [31].

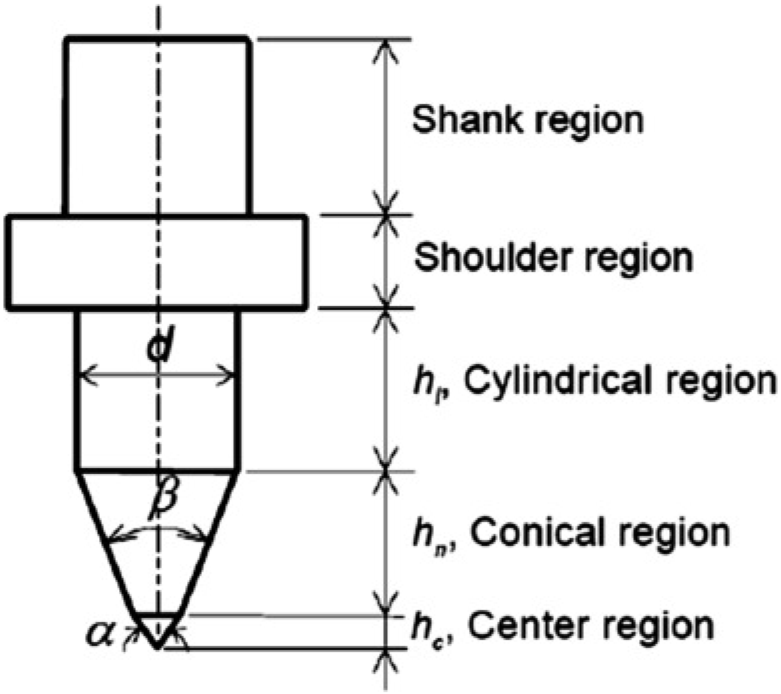

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Fig.4. Schematic representation of thermal drill [72].

Some of the thermal drills used in the previous research works are given in Table3. As thermal drilling is typically a pre-tapping process, drill manufacturers do not use drill diameters for generating their products. Mainly, the dimension of drill tool bit is determined by determining the size of the thread to be used. Most of the researchers used the material for the thermal drill tool is tungsten carbide [46], [51], [53], [72], [73] and high-speed steel material is used by the research [68]. Generally, the center angle used in the design of tool as 90° and conical angle has varied from 33° to 36°. Different value of center and conical angle are connected with the change of the peripheral speed to decrease friction force after workpiece piercing and not implement thermal changes into workpiece while forming. The height of the cylindrical region has varied based on the thickness of the workpiece material. It may be varied from 5mm to 10mm.

Table3. Dimensions of thermal drills used in previous research work.

Dimensions	**Krasauskas etal. [46]**	**Pantawane etal. [51]**	**Miller etal. [53]**	**Somasundaram etal. [68]**	**Miller etal. [72]**	**Biermann etal. [73]**
Diameter (d)	5.2mm	9.2mm	7.3mm	5.3mm	5.3mm	5.4mm
Center angle (α)	86°	90°	90°	90°	90°	90°

Dimensions	Krasauskas etal. [46]	Pantawane etal. [51]	Miller etal. [53]	Somasundaram etal. [68]	Miller etal. [72]	Biermann etal. [73]
Conical angle (β)	33°	33°	36°	36°	36°	34°
center height (h_c)	0.6mm	1.7mm	0.970mm	1mm	0.940mm	0.75mm
conical height (h_n)	4.4mm	11.5mm	8.490mm	10mm	5.518mm	7mm
cylindrical height	5mm	9.3mm	8.896mm	15mm	7.043mm	9mm

2.2. Types of thermal drill tools

Different designs of thermal drills are commercially available in the industrial market is given in Fig.5. These drills are divided into four groups. They are: short (Fig.5a), short flat (Fig.5b), long (Fig.5c) and long flat (Fig.5d) [33]. The short and long drills are produced a short tapered bush and long cylindrical bush respectively. Also, in both drills usages produces a boss or sealing ring on the top of sheet metal. Besides, the short flat and long flat design of drills, different mills cutter like features are incorporated in the shoulder regions. This milling cutter involves producing a flat surface on the top of the sheet metal. Thus, a clean and smooth surface can be obtained [34], [35]. The conical angles of the conical regions of the drills used in all types of tool are the same, but changes in both lengths according to the needs and thickness of the material to be drilled.

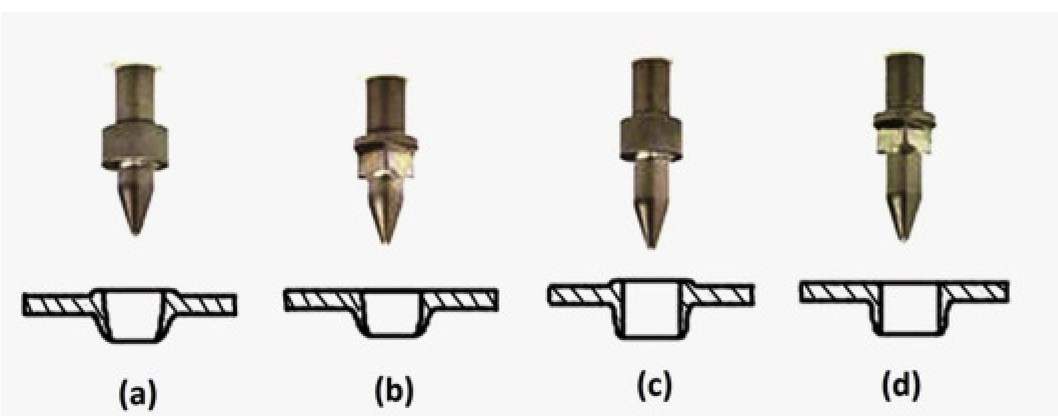

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Fig.5. Different types of thermal drills and corresponding bushing shapes [32].

3. Processing of thermal drilling operation

Processing of thermal drilling is divided into five different stages [36]. These stages of the process are given in Fig.6. In the first stage, the center region of tool approaches the sheet metal to be drill and creates a maximum pushing force on it. In the second stage, the heat generation rate is starting to increase continuously and high torques required to pierce the sheet metal while the penetration of conical region of the tool. In the third stage, the softened metal at the drilling zone is pushing down by the cylindrical region of the tool while piercing. At this stage, the formation of sleeve or bush is started. As well as the upward flow of metal is compressed by shoulder region of the tool, leads to ring shape boss is formed at the top portion of the hole. In the fourth stage, the thermal drilling process is finished and thermal drill tool is withdrawn from the drilling zone. In the fifth stage, from the bush is accomplished by rubbing guide tool. This is a cold forming process which is done by the inverted vane of rubbing tool. During this process, the material in bush gets displaced without damages & chip formation to produce a screw thread inside the bush wall. It has resulted that the quality of the surface of the drilled hole is better in screws opening and also friction forces extracted at a very low rate. Then the bolt is screwed through threads to produce the joints.

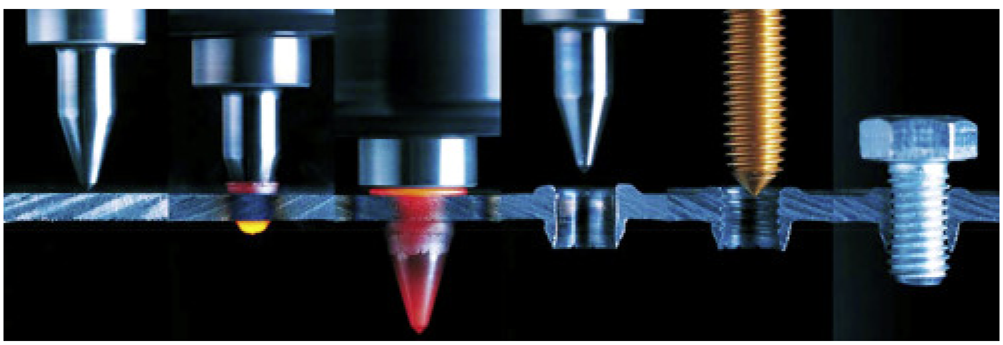

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Fig.6. Different stages of thermal drilling process [36].

4. Thermal drilling applications in various sheet metals

Many researchers used the thermal drilling process on various metals and studied the different quality characteristics of this drilling process [27], [28], [29], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47]. Literature studies have shown that some of the significant previous research works of the thermal drilling process. This process applied to produce precision drilled holes in most ferrous and non-ferrous metals of sheet metals including steel, dual phase steels, stainless steel, aluminium alloy, magnesium alloy, titanium, superalloy, copper, and brass with metal thickness up to 12 mm. In this section, the review of thermal drilling is studied according to sheet metal types and is given in the following sections.

4.1. Thermal drilling on different steels

ST12 and ST 37 steel are cold rolled steels which are used in the following applications such as aerospace and automobile manufacturing, electrical products and precision instruments. This cold rolled steel is a suitable material for the thermal drilling process.

Özek et al. [48] conducted the thermal drilling process on the ST 37 sheet metal using tungsten carbide thermal drill tool. They have studied the following response characteristics such as surface roughness, bushing length, bushing shape and bushing wall thickness. When the ratio of material thickness to hole diameter increases, the amount of material providing the bush formation increases, and this ratio is the most significant factor which affects the bushing length and shape. It has resulted that increasing of feed rate and rotational speed, increases the deformation in the bush formation as well as the bushing wall thickness increases as the bushing length decreases by reason of distribution of the flowing softened metal around the drilled hole in the radial direction.

Kaya et al. [49] studied the thermal drilling process on ST 12 sheet metal and used the input process parameters such as spindle speed, feed rate, friction angle and friction contact area ratio. Fig. 7 shows the different shapes of thermal drills were used in this research work. They investigated the output parameters as the surface temperature of the workpiece, thrust force, and torque. As a result of the study, the thrust force and torque values were increased with increasing of friction angle, feed rate and friction contact area ratio values. However, when increasing drilling speed, both thrust force and torque were decreased. It has also been determined that the increase of drilling speed leads to increases surface temperature of the workpiece. Moreover, it has been noticed that there is no significant effect of increasing or decreasing the friction angle and friction contact area ratio on the surface temperature of the workpiece.

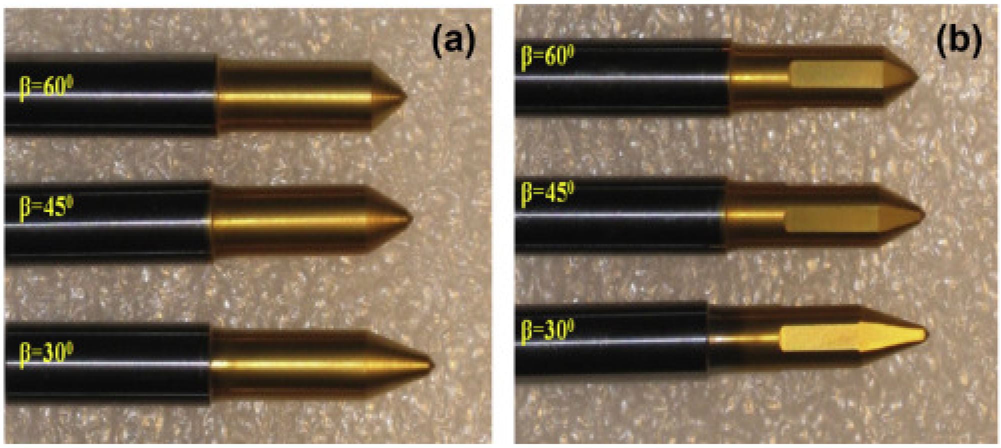

Fig. 7. Different views of the thermal drills with different friction contact area ratio (a) 100% and (b) 50% [49].

The merit of the thermal drilling process is applicable in the thin-walled profiles and pipes which have a significant role in the applications of lightweight structure and steel manufacturing. Miller et al. [50] have investigated that the thermal drill tool wears in the thermal drilling process on AISI 1015 carbon steel workpiece with 1.5 mm thickness. Fig. 8 shows the isometric and cross-sectioned view of thermal drilling AISI 1015 carbon steel. It has resulted that the tungsten carbide is durable and shows low tool wear even after 11,000 holes drill on the workpiece. Also, they have noticed that the severe circular abrasive grooves were formed on the tip of the tool which is shown in Fig. 9.

Fig. 8. Thermal drilled AISI 1015 steel profile (a) isometric view (b) cross sectioned view [50].

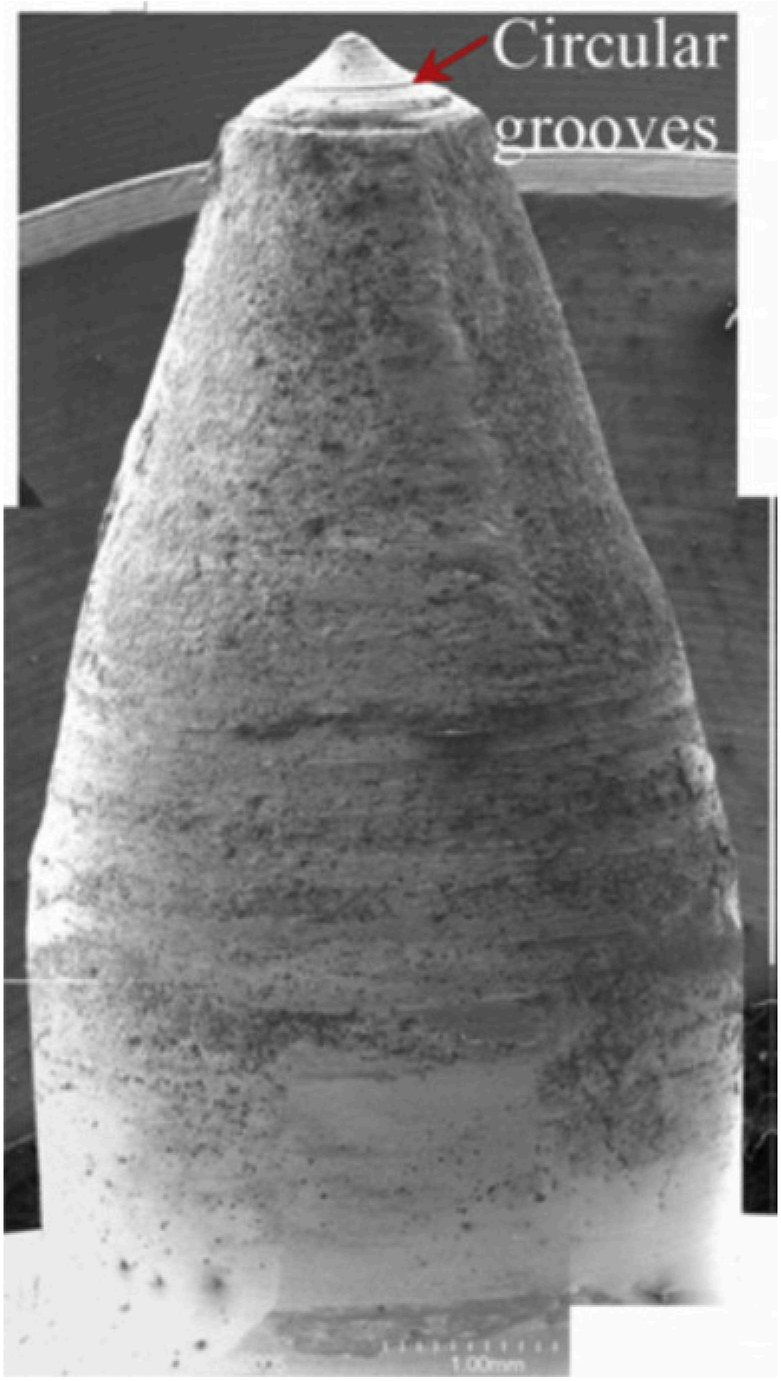

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Fig.9. SEM image of thermal drill after the production of 11,000 holes [50].

Pantawane etal. [51] have reported that the thermal drilled AISI 1015 steel and studied the effect of process parameters such as spindle speed, feed rate and workpiece thickness to tool diameter ratio on the responses such as thrust force, torque and surface roughness of thermal drilled holes. Analysis of variance and Taguchi methods were applied to analyze the response parameters and developed the relationship in between the input and output process parameters.

In another study, Özler et al. [52] reported that the AISI 1010 carbon steel square profile workpiece with 2 mm thickness was drilled with tungsten carbide tool. They developed the thermal drill tool with different friction angles and diameters and studied the influences of processing parameters on bushing strength and temperature. From this study, they concluded that the workpiece temperature of the drilled region increases with increasing of drilling speed and decreasing of feed rate.

Miller et al. [53] have reported that the thermal and mechanical aspects of the thermal drilling of AISI 1020 carbon steel metal. They developed a new finite element modeling of thermal drilling process in order to understand the flow of material, strain rate, stress and temperature distributions which are very difficult to determine by the experimental way. Also, another semi-empirical analytical model is also developed based on the contact pressure to compute the thrust force and torque. Similarly, Bilgin et al. [54] studied the thermal drilling of AISI 1020 carbon steel using the tungsten carbide tool. In this study, they have developed that the finite element model by deform-3D software to determine the torque, thrust force, and heat transfer coefficient. They have concluded that the torque and thrust forces values reduced with enhancing of spindle speed, but the temperature values were increased with increasing of spindle speed.

4.2. Thermal drilling on dual phase steel

The thermal drilling process has been examined for dual-phase steels which are extensively used in the automotive industry. Nardi et al. [55], [56] evaluated the optimum thermal drilling conditions for dual phase steels with different thicknesses. They have determined the required torque and thrust force for drilling of the workpiece and also studied the hole size tolerances.

In addition to that, they have focused to develop a bush without cracks or flaws by the thermal drilling process. As a result of this study, they have presented that an innovative method of introduction of pure argon gas into the thermal drilling process. Fig. 10 shows the result of this study in which thermal drilled holes are produced on galvanized steel with and without shielding gas. Hynes et al. [57] also investigated the thermal drilling experiment on galvanized steel with various thicknesses by tungsten carbide tools with different tool angles. They developed an artificial neural network model for bushing length and optimized the process parameters by using the simulated annealing technique. They have noticed a luder bands mark in the thermal drilled galvanized steel due to the generation of thermal stresses.

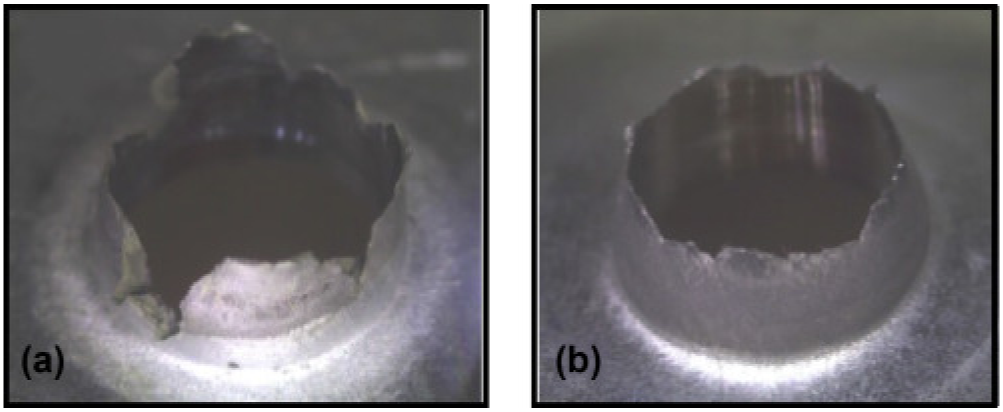

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Fig. 10. Thermal drilled holes on Galvanized Dual Phase steel. (a) Without shielding gas, (b) with shielding gas [56].

The thermal drilling process was conducted on galvanized steel using M2 tool steel material [79], [80], [81]. Three thermal drilling tools were developed with three different tool angles such as 30^o, 37.5^o and 45^o. The three different thickness of galvanized steel such as 1 mm, 1.5 mm and 2 mm are selected for performing the thermal drilling process. The experimentation of thermal drilling process was conducted based on the Taguchi L_{27} design of experiments with the varied level of input process parameters. The results were collected and analyzed by using the analysis of variance method. All the experiments were carried out with a constant feed rate of 120 mm/min and dry machining conditions. The response quality characteristics of thermal drilling such as bushing length, surface roughness, roundness error, run-out, peak workpiece temperature, peak axial force and torque, microhardness and microstructure are experimentally determined for investigation. After the completion of all experiments, the thermal drilled holes showed different regions. They are identified as tail end region, luder band region, lower critical region, upper critical region and bending region.

Kumar et al. [83] developed a finite simulation model for thermal drilling process using DEFORM-3D software to study the material flow via point tracking technique and the results of the simulation are compared with the experimental results. The bushing length of 5.92 mm is obtained from the experimental work against the simulated result of 6.01 mm. This result shows a high degree of closeness between the simulation and experimental value with a minimum deviation of ±1.497%. The numerical model could also be used to predict the thermal behavior of the thermal drilling of workpiece material [82], [84], [85].

4.3. Thermal drilling on stainless steel

Stainless steel sheet metal is commonly used in the automobile manufacturing industry to offer high strength and durability. It is also used in the structural sections of military vehicles, ships, and trucks. Some studies are revealing the thermal drilling on stainless steel sheet metal as follows.

Chow et al. [58] developed a new design of thermal drill tool which was made by tungsten carbide material and utilized this tool for thermal drilling on AISI 304 stainless steel plates. The surface roughness of 0.96 μm resulted in the optimal conditions of thermal drilling as 100 mm/min feed rate, 90 m/min drilling speed. They noticed the poor surface roughness was produced at the higher feed rates. Because at the high axial feed rate produces complete melting of the material. These melting materials have adhered to the thermal drill leads to produce poor surface roughness. Moreover, at the same time very low feed rate of thermal drill also produced poor surface quality. Since at the low feed rate, the rate of cooling of meting material in the upper layer is faster than the lower layer. Due to this different rate of cooling, those materials were interlocked during the rotary movement of the thermal drill; finally, a poor surface quality resulted. In addition to inspecting the bushing length of stainless steel with the process of thermal drilling, Lee et al. [59] thermal drilled an AISI 304 sheet metal with 2 mm thickness by using TiAlN and AlCrN coated thermal drill tools. Fig. 11 shows the thermal drilled AISI 304 sheet specimen. In this investigation, they observed the high surface temperature in the AlCrN coated thermal drill during thermal drilling process because the temperature of drill increased with the rotation of the tool and also the low surface temperature in the uncoated thermal drill was observed. Likewise, it has been noticed that the thermal drills surface temperature were enhanced with an increasing number of thermal drilled holes. This was resulted because of interlocking of molten workpiece material during thermal drilling to enhance the surface roughness of the surface of the thermal drill and then the friction coefficient was increased at the next operation of drilling. Also, they observed that the coated thermal drill had a lesser amount of wear than the uncoated thermal drill and reduced tool wear was observed in AlCrN coated thermal drill than the coated TiAlN thermal drill. Besides, at high rotational speeds, the coating of the thermal drill has affected and extensive wear of coating was noticed.

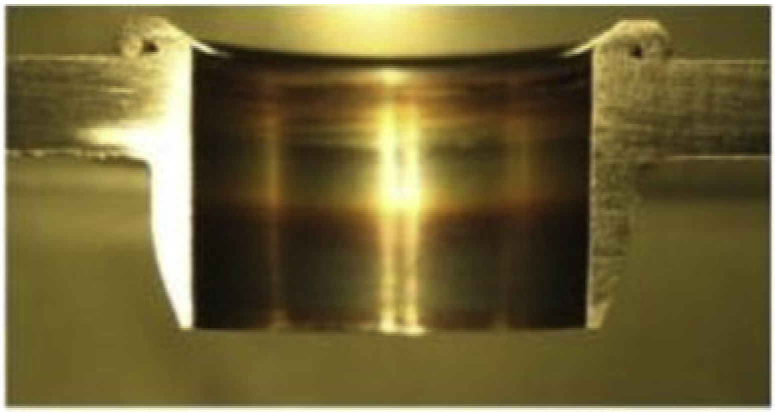


Fig. 11. Cross-sectional view of thermal Drilled hole in AISI304 sheet material [59].

Similarly, Ku et al. [60] also conducted the thermal drilling experiments on SUS 304 stainless steel plate with 2 mm thickness. They have developed a novel type of thermal drill which is made by the material of sintered tungsten carbide. In this work, they have investigated the influences of spindle speed, feed rate, friction contact area ratio, and friction angles on the response characteristics such as surface roughness and bushing length. They also observed that the tool wear during drilling of SUS 304 stainless steel as shown in Fig. 12. From this study, tool wear after 30 runs almost without wear of thermal drill was observed. Besides, it only produced a little amount of wear drilling process after 60 runs. Fig. 13, Fig. 14 demonstrate the microstructure of thermal drilled holes at various friction angles and spindle speeds. It was observed that 30° friction angle thermal drill shows smaller surface roughness since it generates uniform melting temperature at the contact zone. However, when the increase of friction angle, increased surface roughness was obtained. Also, they have observed that when increasing spindle speed, the high amount of heat energy was produced due to the friction at the contact leads to giving better surface quality. Fig. 14 shows the better surface quality at the spindle speed of 3600 rpm.

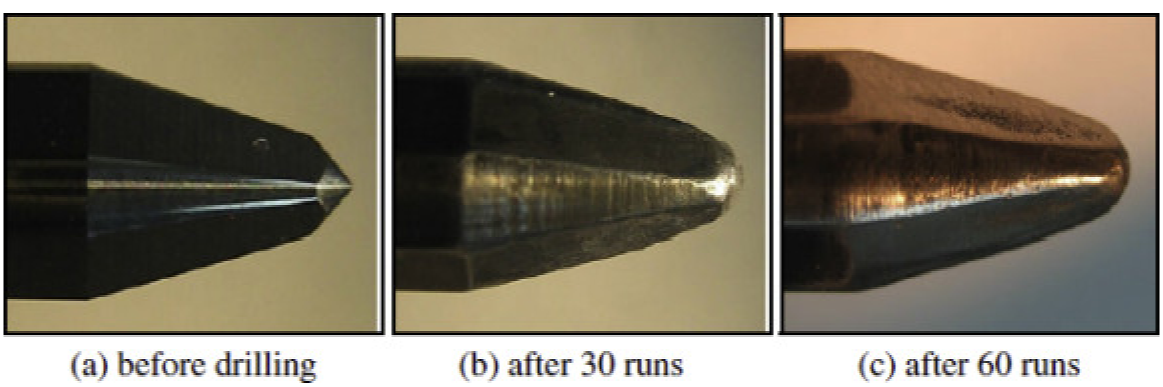
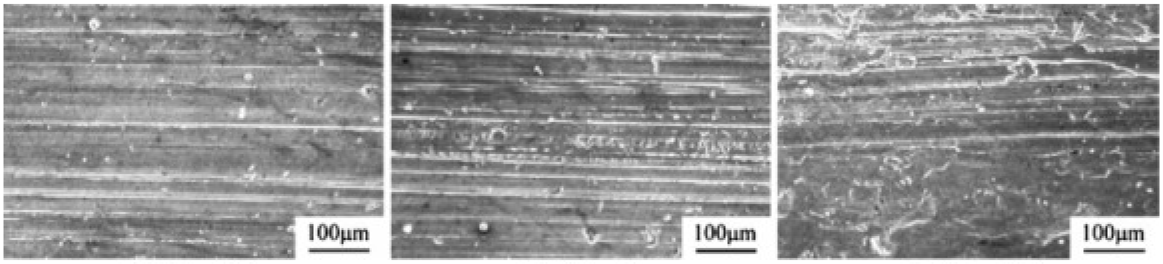


Fig. 12. Thermal drills before and after drilling of the SUS 304 stainless steel [60].



(a) FA=30°   (b) FA=45°   (c) FA=60°

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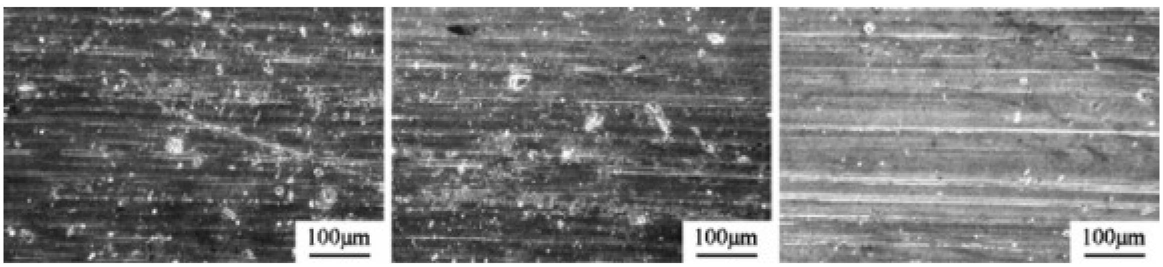
Fig. 13. SEM images of drilled holes in SUS stainless steel with various friction angles [60].



(a)1200 RPM   (b) 2400 RPM   (c) 3600 RPM

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Fig. 14. SEM images of drilled holes in SUS stainless steel with various spindle speed [60].

4.4. Thermal drilling on aluminium alloys

Aluminium alloys are used in all manufacturing sectors to produce various products and are also applicable in the aviation and aerospace industries. Miller et al. [61] investigated the thermal drilling process on AA 6061-T6 alloy. They developed a three-dimensional finite element model to model the deformation of workpiece and temperature in thermal drilling. They have reported that the finite element technique was effectively used to obtain converged result and effective solution in the thermal drilling process. Similarly, Dehghan et al. [62] developed a finite element model by using ABAQUS finite element software and studied the plastic strain, stress and temperature distribution in the thermal drilling of AA 6061 alloy. They have justified that the developed finite element model was used to predict the thermal histories in the thermal drilling of aluminium alloys.

Hynes et al. [63] examined the thermal behavior in the thermal drilling of AA 6061-T6 alloy by the way of numerical analysis. The numerical results showed that the friction contact point in between the tool and workpiece attains the highest temperature 332.85 °C within the few seconds. They also reported that the sheet metal at the drilling zone becomes viscoplastic and then allow to flow out leads to form a sleeve-like shape.

Özek et al. [64] studied the thermal drilling of aluminium alloys such as AA 1050, AA 6061, AA 5083 and AA 7075-T651 having different thermal conductivity. They have varied the spindle speeds from 1200 rpm to 4200 rpm, the feed rates from 25 mm/min to 100 mm/min. They reported that at high spindle speeds and feed rates, the high frictional heat was created in the thermal drilling of aluminium alloys which have low thermal conductivity. The high temperature was measured as 241.8 °C in thermal drilled AA 5083 alloy which has low thermal conductivity. The outcomes of this research work on aluminium alloy are shown in Fig. 15. From this study, it has been identified that the higher bushing heights are produced at low spindle speed and high feed rates. The optimum surface roughness was observed at 2400 rpm of spindle speed and all of the feed rates which were selected.

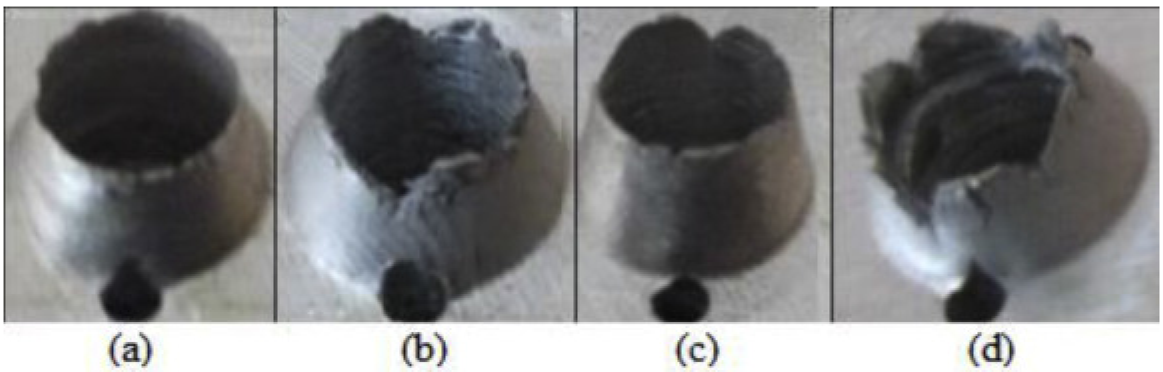

Fig. 15. Thermal drilling on different aluminium alloys (a) AA1050, (b) AA6061, (c) AA5083 and (d) AA7075-T651 [64].

Demir et al. [65] investigated that the influences of the spindle speed, feed rate, workpiece thickness and pre-drilling diameters on process characteristics such as workpiece temperature and bushing shapes of thermal drilled AA 7075-T651 alloy. The workpiece temperatures were calculated by means of installed two thermocouples near the hole to be drilled which is shown in Fig. 16. They have observed that the workpiece temperature was varied in between the range from 0.5 to 0.67 of AA 7075-T651 alloy melting point temperature. The workpiece temperatures were increased with reduced feed rate and increased spindle speed. Also, the bushing shapes were enhanced with decreasing of spindle speed, pre-drilling diameter, and feed rates.

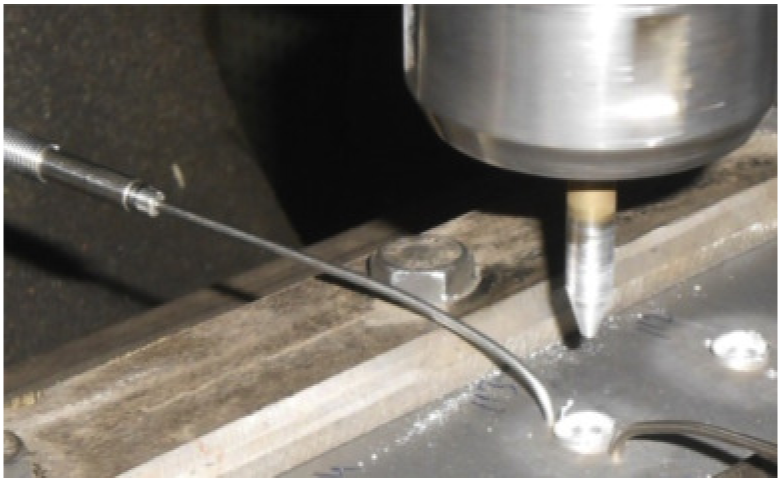

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Fig. 16. Thermocouples installation to measure workpiece temperature [65].

Krishna et al. [66] studied the mechanical aspects in thermal drilling on AA 6351 alloy with 1 mm thickness using high-speed steel thermal drill tool. They have designed the Taguchi based experimental layout to determine the performance of thermal drilling process. They have concluded that the following conclusion when increasing of friction angle from 30° to 60°, the thrust force values were increased from 299N to 549N and the torque values were decreased from 1.76 Nm to 0.796 Nm. Also, when increasing of spindle speed from 2000rpm to 3000rpm, both the values of torque and thrust forces were decreased from 1.295 Nm to 1.248 Nm and from 454N to 394N respectively. They have concluded that at low and medium spindle speed, a high polished surface was obtained in thermal drilled AA 6351 alloy and at high spindle speed, discolorations were observed.

Diwakar et al. [67] applied the Taguchi method to determine the high-speed steel thermal drill performance on AA1100 alloy metal with 6mm thickness. They developed the relationship between torque and thrust forces with rotational speed, feed rate, and frictional contact area ratio. From the experimental measurements, the following conclusions arrived. When the frictional contact area ratio was increased from 0.11 mm to 0.4mm, thrust force and torque values were increased from 192N to 250N and 2 Nm to 2.6 Nm respectively. When the spindle speed was increased from 700rpm to 760rpm, the thrust force reduced from 237N to 205N, therefore for thermal drill tool requires less amount of torque. From this result, it was concluded that the frictional contact area ratio is the most significant factor and was affecting both thrust force and torque value.

Somasundaram et al. [30], [68], [69], [70] utilized a stir casting technique to the fabrication of Al-SiC metal matrix composites plates and then the fabricated plates were thermal drilled by the newly developed high-speed steel. They have analyzed through response surface methodology the effects of following parameters such as spindle speed, feed rate, workpiece temperature, thickness and composition on the roundness error of thermal drilled holes. Fig. 17 shows the influences of process parameters on the response parameter of roundness error. They have concluded that the roundness error increased with increased spindle speed, feed rate, and workpiece thickness. Also, it was decreased by the increased percentage of workpiece composition in Al-SiC composites.

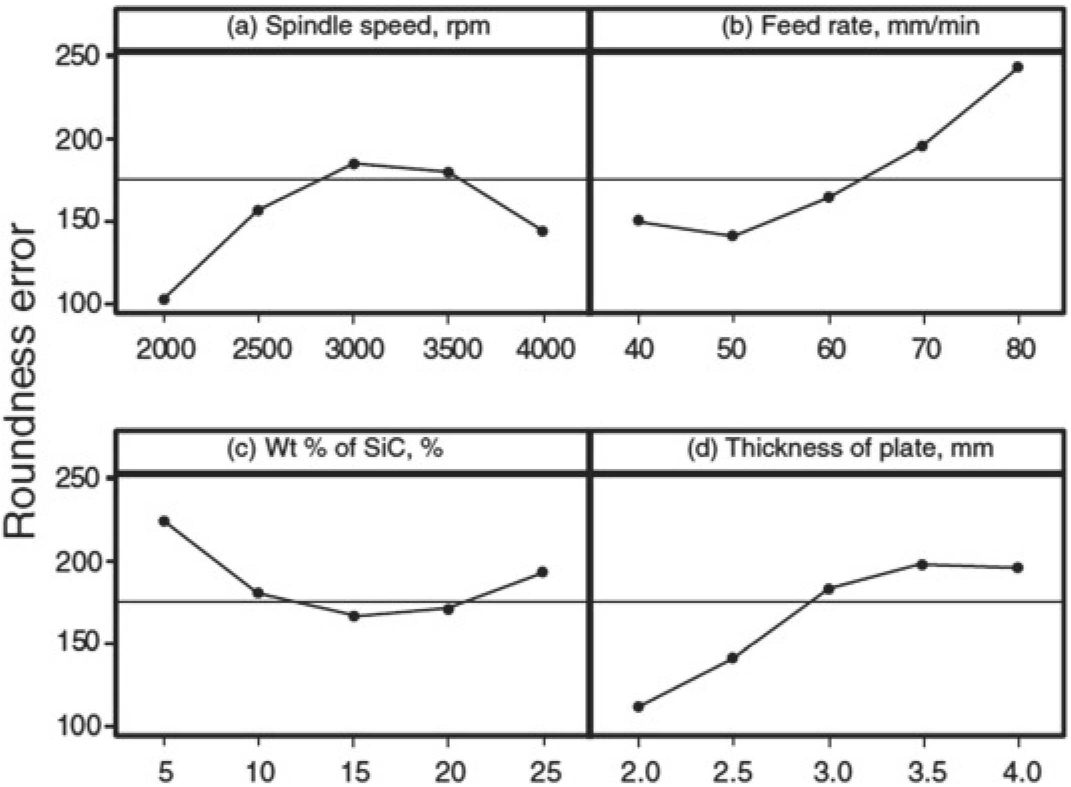

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Fig. 17. Effect of process parameters on roundness errors [68].

Eliseev et al. [71] investigated that the microstructure of thermal drilled AA 2024 alloy and identified the different zones of the material was formed around the hole. They have been found that the generation of high temperature in this process, leads to recrystallization of grain structure was occurred. Fig. 18 shows the different zones in thermal drilled AA 2024 alloy. The zones were noted in this figure, stir zone (SZ), thermo-mechanically affected zone (TMAZ), and heat affected zone (HAZ). The SZ represent the metal which direct contact with the thermal drill and experiences high deformation. The TMAZ was formed by the function of high temperature; however, it is not direct contact with the thermal drill. The HAZ was formed by heat which is emitted from the contact zone.

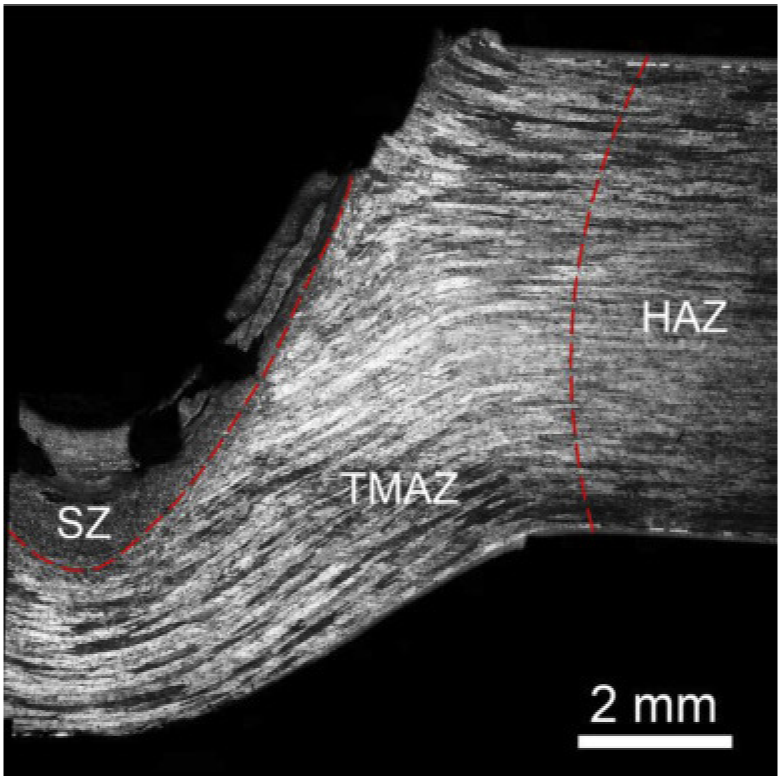

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Fig. 18. Different zones in thermal drilled AA 2024 alloy [71].

4.5. Thermal drilling on magnesium alloy

Magnesium alloy is used in lightweight components which are designed to enhance the vehicle efficiency because of its low-density property. Miller et al. [72] investigated that the thermal drilled MgAZ91D magnesium alloy which is brittle cast metals. They faced the thermal drilling technical challenge of radial fracture or petal formation in thermal drilled brittle metal. For this issue, they have proposed two ideas of pre-heating the workpiece material and high rate of spindle speed drilling.

Fig. 19 it was noticed that the alternations in spindle speed have an undesirable effect on the formation of the bushing in Magnesium alloy metal. As shown in Fig. 19, the petal creations turn out to be more apparent when the spindle speed increases from 3000 rpm to 15,000 rpm. At 3000 rpm and 7000 rpm, no significant petal formation occurs but at 15,000 rpm, a very extensive petal has occurred. After that, Biermann et al. [73] have proposed to examine the output characteristics such as torque, thrust force and workpiece temperatures on thermal drilling of AZ31 magnesium alloy metal with 4 mm and 5 mm workpiece thicknesses. It has been noticed that the values of thrust force and torque were increased with increasing feed rate. They also reported that the alteration in tool diameter leads to giving alternation in the amount of heat generation during the thermal drilling process. The maximum temperatures of 420°C and 437°C were obtained at the thermal drilling with 5mm and 5.4mm tool diameter respectively.

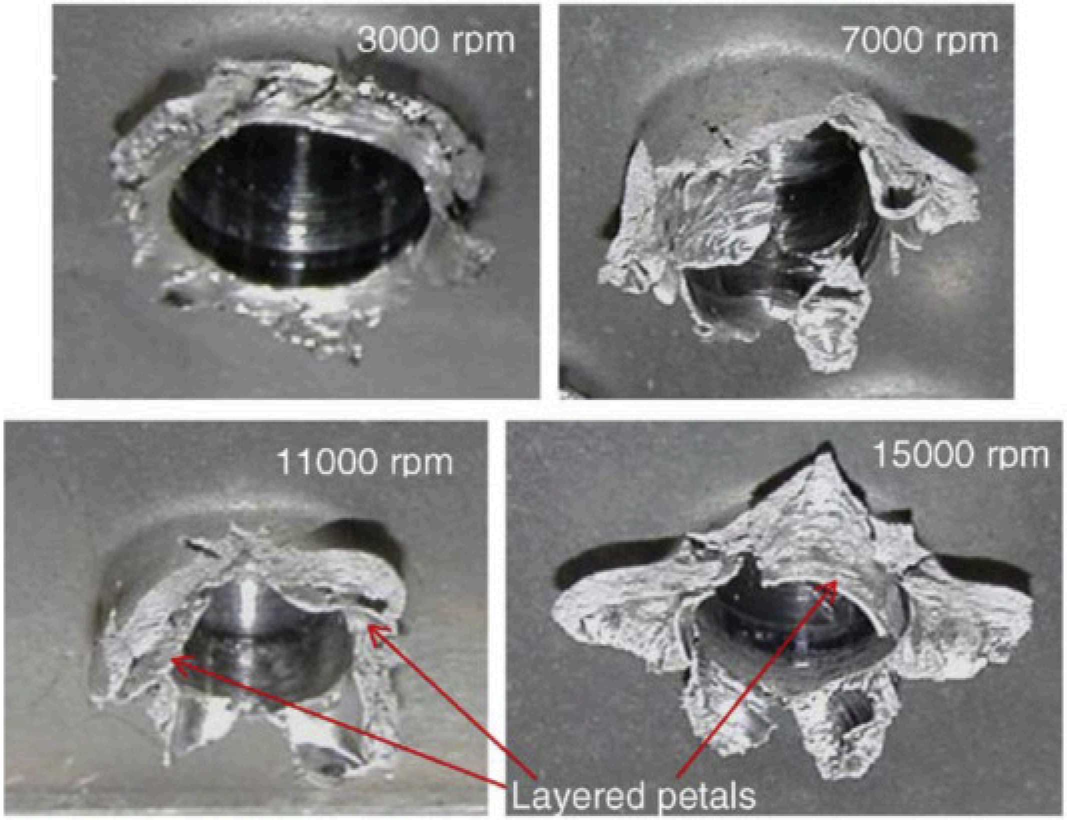

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Fig. 19. Formation of Bush in magnesium alloy at various spindle speed [72].

4.6. Thermal drilling on titanium

Nowadays, titanium sheet metal is a progressively more demanded material in all the engineering and medical applications which have been considered as the workpiece in following thermal drilling research work. Miller et al. [74] investigated the thermal drilled pure titanium sheet metal with 1.59mm thickness and analyzed the alternations in hardness, microstructure after the thermal drilling process. It was very challenging to drilling the titanium sheet by the thermal drilling process. They also noticed that the micro-crack in the drilled hole as shown in Fig. 20, due to the creation of thermal stresses by the high surface temperature of titanium during thermal drilling.

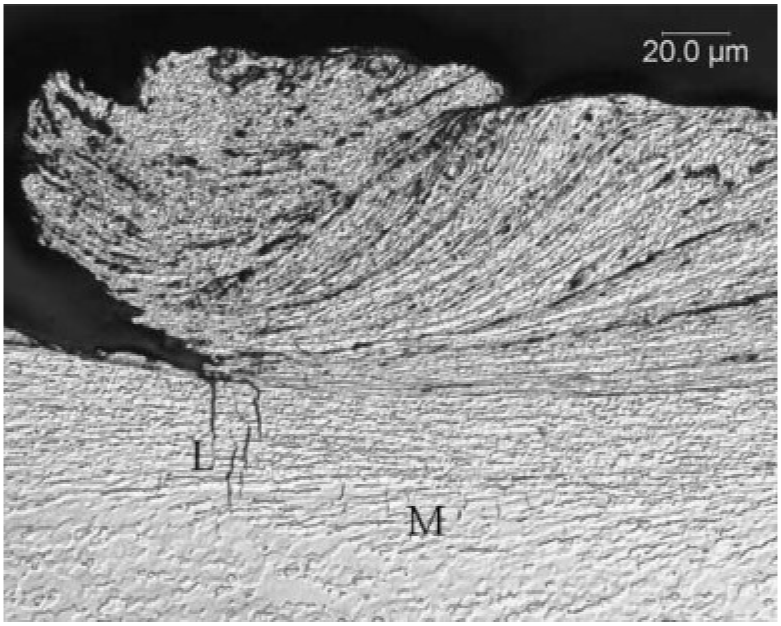

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Fig. 20. Cracks produced in thermal drilled titanium sheet metal [74].

4.7. Thermal drilling on superalloys

Currently, superalloy has been extensively used in the fabrication of aircraft engines and nuclear industry components. Nickel-based superalloy IN-713C is considered as the workpiece for thermal drilling process by Lee et al. [75]. In that study, they have been thermal drilled under various spindle speeds (2400 rpm, 3600 rpm, 4800 rpm, and 6000 rpm) and feed rates (100 mm/min, 125 mm/min, 150 mm/min). The output characteristics such as hardness, roundness, and surface roughness were studied during the process. The experimental results delivered that the hardness property is higher in the hole wall but it was decreased with increased distance from the edge of the hole. They also revealed that at higher spindle speed and feed rate could offer good roundness and smooth surface in thermal drilled superalloy.

Yang et al. [76] investigated used three nickel-based superalloys (Mar-M247, Haynes-230, and Inconel-718) for conducting the thermal drilling process. They also used spindle speed and feed rate as input process parameters in order to explore the surface roughness and bushing length of thermal drilled superalloys.

Fig. 21 shows the result of thermal drilling of superalloys under the conditions of three feed rate (100 mm/min, 125 mm/min and 150 mm/min) and spindle speed 4800 rpm. They have concluded that thermal drilled Haynes-230 superalloy shows longest bush length and better surface roughness than others. Moreover, the worst bush length and poor surface roughness were identified in thermal drilled Inconel-718 superalloy.

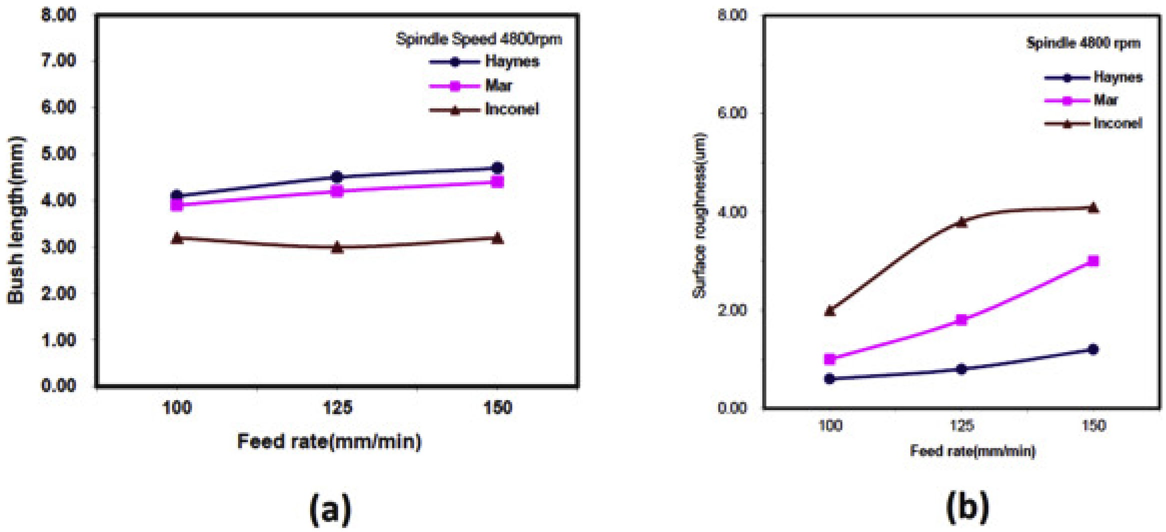

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Fig.21. Comparison of bushing length and surface roughness in thermal drilled superalloys [76].

4.8. Thermal drilling on brass and copper

Brass and copper sheet metals are widely used in many industrial applications. Vergara etal. [77] studied the bush quality in copper and α-brass alloy thin sheet metals by varying the process parameters such as spindle speed, feed rate, and tool diameter. They have reported that the best quality of bushing in copper sheet was obtained at optimum conditions of 4000rpm spindle speed, 50mm/min feed rates and 2.5mm tool diameter. Also, the sufficient quality of bushing in the α-brass sheet was achieved at the conditions of process parameters of spindle speeds varied from 500rpm to 1000rpm, feed rates varied from 100mm/min to 300mm/min. Afterward, Boopathi etal. [78] examined the thermal drilled brass sheet metal and measured thrust forces involved in thermal drilling process for different spindle speeds and feed rates. Also, changes in hardness and temperature distribution occurred for different spindle speeds were measured.

5. Future scope

Even though some investigates about thermal drilling have previously been done, there are still plenty of issues needed to be addressed. The main objective of the research is to provide a deeper knowledge of the non-traditional hole-making process. It consists of fundamental parameters study in the improvement of the bushing shape, investigation of joining sheet metals by thermal drilling. Also, tool wear of the thermal drills used can be studied for determining the tool life. Variation in the hardness of the work material before and after hole making by friction drilling can be studied. Better tool geometry can also help to reduce the thrust force and deflection. Thermal effect of the process on the tool material as well as the work material can be studied with the support of microstructures.

6. Conclusions

The thermal drilling process is extensively used in all engineering industries due to the benefits of screw connections of different types of thin sheet metals. In this review study, the basic philosophy about thermal drilling process, the tools used and the materials applied are studied in depth and the work is done in this area is compiled. The main results found from the application of the thermal drilling process are discussed. During this process, the sheet metal is reshaped or deformed without any loss. Therefore, the bushing length is about three times greater than the original thickness of the sheet metal can be formed. Thermal drilling process does not need any special machines, however, can be carried out in one step by using the conical thermal drill. It is also a more cost-effective process since it does not require additional processes such as welding of nuts and inserting of rivets. Also, it does not pollute the surroundings for the period of operation since it is a chipless hole manufacturing method. It has been perceived that the value of hardness at drilled zones increases with the influence of frictional heat, and this circumstance increases the strength. By preheating of the workpiece and high spindle speed, the requirement of thrust force and torque could be reduced.

Conflicts of interest

The authors declared that there is no conflict of Interest regarding the publication of this article.

Appendix A. Supplementary data

The following is the supplementary data to this article:

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Multimedia component 1.

Data not available / The data that has been used is confidential

Further information on research data ↗

References

[1] L.M. Alves, E.J. Dias, P.A.F. Martins
Joining sheet panels to thin-walled tubular profiles by tube end forming
J. Clean. Prod., 19 (2011), pp. 712-719
View PDF View article View in Scopus ↗ Google Scholar ↗

[2] O. Waldmann
The Thermdrill® Method Solves an Old Problem
http://thermdrill.com/threaded-bushing-flowing-drill-instead-of-rivet-nut/ ↗, Accessed 8th Oct 2017
Google Scholar ↗

[3] E. Solmaz, K. Çavdar
Experimental Determination of Screw Efficiency, TMMOB Chamber of Mechanical Engineers Konya Branch II. Machine Design and Manufacturing Technologies Congress, Konya, Turkey
(2003)
Google Scholar ↗

[4] P.V. Shalamova, I.A. Kulyginaa, E.N. Yaroslavovab
ANSYS software-based study of thermal drilling process
Proc. Eng., 150 (2016), pp. 746-752
Google Scholar ↗

[5] B.P. Raju, M.K. Swamy
Finite element simulation of a friction drilling process using deform-3D
Int. J. Eng. Res. Appl., 2 (6) (2012), pp. 716-721
Google Scholar ↗

[6] J.A. Geffen
Piercing Tools
(1976)
U.S. Patent No. 3939683

Google Scholar ↗

[7] J.A. Geffen
Method and Apparatuses for Forming by Frictional Heat and Pressure Holes Surrounded Each by a Boss in a Metal Plate or the Wall of a Metal Tube
(1979)
U.S. Patent No. 4175413
Google Scholar ↗

[8] J.A. Geffen
Rotatable Piercing Tools for Forming Holes Surrounded Each by a Boss in Metal Plates or the Wall of Metal Tubes
(1979)
U.S. Patent No. 4177659
Google Scholar ↗

[9] J.A. Geffen
Rotatable Piercing Tools for Forming Bossed Holes
(1980)
U.S. Patent No. 4185486
Google Scholar ↗

[10] G.D. Head, W.C. Le Master, L.P. Bredesky, *et al.*
Flow Drilling Process and Tool Therefore
(1984)
U.S. Patent No. 4428214
Google Scholar ↗

[11] A.J. Hoogenboom
Flow Drill for the Provision of Holes in Sheet Material
(1984)
U.S. Patent No. 4454741
Google Scholar ↗

[12] J.E. France, J.B. Davidson, P.A. Kirby
Strength and rotational response of moment connections to tubular columns using flowdrill connectors
J. Constr. Steel Res., 50 (1999), pp. 1-14
View PDF View article View in Scopus ↗ Google Scholar ↗

[13] J.E. France, J.B. Davidson, P.A. Kirby
Strength and rotational stiffness of simple connections to tubular columns using flowdrill connectors
J. Constr. Steel Res., 50 (1990), pp. 15-34
Google Scholar ↗

[14] J.E. France, J.B. Davidson, P.A. Kirby
Moment capacity and rotational stiffness of endplate connections to concrete-filled tubular columns with flow drilled connectors
J. Constr. Steel Res., 50 (1999), pp. 35-48
View PDF View article View in Scopus ↗ Google Scholar ↗

[15] D. Bak
Friction heat from integral bushings
Des. News, 43 (1987), p. 124
Google Scholar ↗

[16] W.L. Weingaertner, F. Tikal, J.C. Lopes
Flowdrilling: Bushes Formed in Thin Plates, Int. Manuf. Eng. Conference
ASME, Connecticut, USA (1996), pp. 227-231
Google Scholar ↗

[17] W.L. Weingaertner, F. Tikal, J.C. Lopes
Flowdrill system: high resistance threads in thin metal sheets
Int. J. Manuf. Sci. Prod., 1 (1997), pp. 41-50
Google Scholar ↗

[18] M. Kerkhofs, M. Van Stappen
The performance of (Ti, Al) N-coated flow drills
Surf. Coat. Technol., 68 (1994), pp. 741-746
View PDF View article View in Scopus ↗ Google Scholar ↗

[19] N. Doğru
Investigation of Drilling Characteristics of AISI 1010 Steel Material Drilled by Frictional Drilling
M.Sc. Thesis
Institute of Natural and Applied Sciences, Firat University (2010)
Google Scholar ↗

[20] M.A. El-Dakrory

Investigation into Friction Drilling Process
(2016)
Google Scholar ↗

[21] O. Waldmann
What Characterizes a Thermdrill® Bushing
http://thermdrill.com/threaded-bushing-flowing-drill-instead-of-rivet-nut/ ↗, Accessed 8th Oct 2017
Google Scholar ↗

[22] T. Prabhu, A. Arulmurugu
Experimental and analysis of friction drilling on aluminium and copper
Int. J. Mech. Eng. Tech., 5 (2014), pp. 130-139
Google Scholar ↗

[23] S.A. El-Bahloul, H.E. El-Shourbagy, T.T. El-Midany
Optimization of thermal friction drilling process based on taguchi method and fuzzy logic technique
Int. J. Sci. Eng. Appl., 4 (2015), pp. 55-59
Google Scholar ↗

[24] L. Sobotová, E. Spišák
The Contribution of Evaluation of Material Joining with New Technologies, the 11th International Scientific Conference Trends in Business Management Systems, High Tatras
(2008)
Google Scholar ↗

[25] Z. Demir
Experimental Investigation of A7075-T651 Aluminum Alloy and St37 Steel Material Punching by Frictional Drilling Method
Ph.D. Thesis
Institute of Natural and Applied Sciences, Firat University (2012)
Google Scholar ↗

[26] A. Acıyan
Inner Threading by Rubbing Method
M.Sc. Thesis
Selcuk University Institute of Science and Technology (2011)
Google Scholar ↗

[27] W. Matysıak, L. Bernat
Shaping the edges using flowdrill technology
Metalurgija, 54 (2015), pp. 235-238
View in Scopus ↗ Google Scholar ↗

[28] P. Krasauskas
Experimental and statistical investigation of thermo mechanical friction drilling process
Mechanika, 17 (2011), pp. 681-686
View in Scopus ↗ Google Scholar ↗

[29] P.D. Pantawane, B.B. Ahuja
Parametric analysis and modelling of friction drilling process on AISI 1015
Int. J. Mecha. Manuf. Sys., 7 (2014), pp. 60-79
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[30] G. Somasundaram, S.R. Boopathy
Fabrication and Friction Drilling of Aluminum Silicon Carbide Metal Matrix Composite
IEEE Explorer (2010), pp. 21-26
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[31] T. Kanagaraju, J.S.J. Peter, D.R. Samuel, *et al.*
Optimization of drilling parameters for thrust force and torque in friction drilling process, Middle-East
J. Sci. Res., 24 (2016), pp. 1577-1582
Google Scholar ↗

[32] Thermal drilling tool
Tool Selection
https://www.indiamart.com/parksons/thermal-drilling-tool.html ↗, Accessed 8th Oct 2017
Google Scholar ↗

[33] Formdrill
Catalog Formdrill
http://www.formdrill.com/english/catalog1.htm ↗, Accessed 15th Nov 2016
Google Scholar ↗

[34] Flowdrill
Products

http://www.flowdrill.com/eu_en/products#category-title ↗, Accessed 15th Nov 2016

Google Scholar ↗

[35] Centerdrill

Products

http://www.centerdrill.de/english/products/centerdrill.html ↗, Accessed 15th Nov 2016

Google Scholar ↗

[36] Aliexpress

Product Description

https://www.aliexpress.com/item/Collar-Raised-Type-Flow-Drill-M5X0-8-Fdrill-4-5mm-Tensile-drill-flowdrill-friction-drilling-flow/32382782896.html ↗

, Accessed 8th Oct 2017

Google Scholar ↗

[37] K. Overy

Flow drilling bush formation in thin metal

Chart. Mech. Eng., 25 (1978), pp. 70-71

View in Scopus ↗ Google Scholar ↗

[38] F. Tikala, R. Heiler, W. Weingaertner, J.O. Lopes, *et al.*

Flowdrill® system: high resistance threads in thin metal sheets

J. Manuf. Sci. Prod., 1 (1997), pp. 41-50

Crossref ↗ Google Scholar ↗

[39] P. Krasauskas, S. Kilikevičius, R. Česnavičius, *et al.*

Statistical research on forming of threaded holes in thin plates

Mechanika, 22 (2016), pp. 237-242

View in Scopus ↗ Google Scholar ↗

[40] A. Fernández, L.N. Lopez de Lacalle, A. Lamikiz

Friction drilling of stainless steels pipes

AIP Conf. Proc., 1315 (2011), p. 1187

Crossref ↗ Google Scholar ↗

[41] N.R.J. Hynes, M.V. Maheshwaran

Numerical analysis on thermal drilling of aluminum metal matrix composite

AIP Conf. Proc., 1728 (2016), p. 020546

Crossref ↗ Google Scholar ↗

[42] J. Qu, P.J. Blau
Anew model to calculate friction coefficients and shear stress in thermal drilling
J. Manuf. Sci. Eng. (2008), p. 130
View in Scopus ↗ Google Scholar ↗

[43] A.S. Nama, N.S. Namer, T.I. Abdullah
Effect of Pre-hole Diameter on Bushing Dimensions for Friction Drilling Process of A6063-T6 Aluminum Alloy
J. Al Rafidain University College (2016), pp. 373-387
Google Scholar ↗

[44] M. Folea, D. Schlegel, E. Gete, *et al.*
Preliminary tests on flow drilling of maraging steels
Acad. J. Manuf. Eng., 10 (2012), pp. 42-47
Google Scholar ↗

[45] W.L. Ku, H.M. Chow, Y.J. Yao-Jang Lin, *et al.*
Optimization of thermal friction drilling using grey relational analysis
Adv. Mater. Res., 154 (2011), pp. 1726-1738
View in Scopus ↗ Google Scholar ↗

[46] P. Krasauskas, S. Kilikevičius, R. Česnavičius, *et al.*
Experimental analysis and numerical simulation of the stainless AISI 304 steel friction drilling process
Mechanika, 20 (2014), pp. 590-595
View in Scopus ↗ Google Scholar ↗

[47] G. Urbikain, J.M. Perez, L.N. L Lacalle, *et al.*
Combination of friction drilling and form tapping processes on dissimilar materials for making nutless joints
Proc. IMechE Part B J Eng. Manuf., 232 (2018), pp. 1-14
Google Scholar ↗

[48] C. Özek, Z. Demir
Investigation of the Optimum Rotation Speed and Progress Ratio in the Friction Drilling of St 37 Steel, 3rd National Design Manufacturing and Analysis Congress, Balıkesir, Turkey
(2012)

Google Scholar ↗

[49] M.T. Kaya, A. Aktaş, B. Beylergil, *et al.*
An experimental study on friction drilling of St12 steel
Trans. Canad. Soc. Mech. Eng., 38 (2014), pp. 319-329
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[50] S.F. Miller, P.J. Blau, A.J. Shih
Tool wear in friction drilling
Int. J. Mach. Tool Manuf., 47 (2007), pp. 1636-1645
View PDF View article View in Scopus ↗ Google Scholar ↗

[51] P.D. Pantawane, B.B. Ahuja
Experimental investigations and multi-objective optimization of friction drilling process on AISI 1015
Int. J. App. Eng. Res., 2 (2011), pp. 448-461
Google Scholar ↗

[52] L. Özler, N. Doğru
An experimental investigation of hole geometry in friction drilling
Mater. Manuf. Process., 28 (2013), pp. 470-475
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[53] S.F. Miller, R. Li, H. Wang, *et al.*
Experimental and numerical analysis of the friction drilling process
J. Manuf. Sci. Eng., 128 (2006), pp. 802-810
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[54] M.B. Bilgin, K. Gök, A. Gök
Three-dimensional finite element model of friction drilling process in hot forming processes
Proc IMechE Part E: J Proc. Mech. Eng., 231 (2017), pp. 548-554
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[55] D. Nardi, L.N. López de Lacalle, A. Lamikiz
Friction drilling in double-phase steels
Rev. de Metalurgia., 48 (2012), pp. 13-23
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[56] D. Nardi, L. N. López de Lacalle, A. Lamikiz, etal., Friction Drilling of Galvanized Dual Phase Steels, 1-9.

Google Scholar ↗

[57] N.R.J. Hynes, R. Kumar
Process optimization for maximizing bushing length in thermal drilling using integrated ANN-SA approach
J. Braz. Soc. Mech. Sci. Eng., 39 (2017), pp. 5097-5108
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[58] H.M. Chow, S.M. Lee, L.D. Yang
Machining characteristic study of friction drilling on AISI 304 stainless steel
J. Mater. Proc. Tech., 207 (2008), pp. 180-186
View PDF View article View in Scopus ↗ Google Scholar ↗

[59] S.M. Lee, H.M. Chow, F.Y. Huang, *et al.*
Friction drilling of austenitic stainless steel by uncoated and PVD AlCrN and TiAlN-coated tungsten carbide tools
Int. J. Mach. Tool Manuf., 49 (2009), pp. 81-88
View PDF View article Crossref ↗ View in Scopus ↗ Google Scholar ↗

[60] W.L. Ku, C.L. Hung, S.M. Lee, *et al.*
Optimization in thermal friction drilling for SUS 304 stainless steel
Int. J. Adv. Manuf. Tech., 53 (2011), pp. 935-944
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[61] S.F. Miller, A.J. Shih
Thermo-mechanical finite element modeling of the friction drilling process
J. Manuf. Sci. Eng., 129 (2007), pp. 531-538
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[62] S. Dehghan, M.I.S. Ismail, M.K.A. Ariffin, *et al.*
Numerical simulation on friction drilling of aluminium alloy
Mater. Sci. Eng. Tech., 48 (2017), pp. 241-248
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[63] N.R.J. Hynes, M.M. Kumaran, N. Rakesh, *et al.*
Numerical Analysis in Friction Drilling of AISI1020 Steel and AA6061-T6 Alloy, Recent Advances in Environmental and Earth Sciences and Economics
Zakynthos Island, Greece (2015)
Google Scholar ↗

[64] C. Özek, Z. Demir

Investigate the friction drilling of aluminium alloys according to the thermal conductivity
TEM J., 2 (2013), pp. 93-101
Google Scholar ↗

[65] Z. Demir
Investigation of the effect of tool geometry on friction piercing of A7075-T651 alloy
Batman Univ. J. Life Sci., 5 (2015), pp. 13-25
Crossref ↗ Google Scholar ↗

[66] P.V.G. Krishna, K. Kishore, V.V. Satyanarayana
Some investigations in friction drilling AA6351 using high speed steel tools
ARPN J. Eng. Appl. Sci., 5 (2010), pp. 11-15
Google Scholar ↗

[67] R.V. Diwakar, G. Krishnaiah, C. Gopi, *et al.*
Analysis in Form Drilling AA1100 Using HSS Tools, International Conference on Trends in Mechanical and Industrial Engineering (ICTMIE'2011)
(2011)
Bangkok, Thailand
Google Scholar ↗

[68] G. Somasundaram, S. Rajendra Boopathy, K. Palanikumar
Modeling and analysis on roundness error in friction drilling of aluminum silicon carbide metal matrix composite
J. Compos. Mater., 46 (2012), pp. 169-181
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[69] G. Somasundaram, S. Rajendra Boopathy, K. Palanikumar
Experimental investigation on roundness error in friction drilling and mechanical properties of Al/SiC-MMC composites
Mecha. Ind., 12 (2011), pp. 445-457
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[70] G. Somasundaram, S. Rajendra Boopathy, A. Krishnamoorthy
Roundness Error Prediction in Friction Drilling of Aluminum Silicon Carbide Metal Matrix Composites Using Adaptive Neuro Fuzzy Inference System,

Second International Conference on Advances in Materials Processing and Characterization
Anna University, Chennai, Tamilnadu (2013)
Google Scholar ↗

[71] A.A. Eliseev, S.V. Fortuna, E.A. Kolubaev, *et al.*
Microstructure modification of 2024 aluminum alloy produced by friction drilling
Mater. Sci. Eng. A, 691 (2017), pp. 121-125
View PDF View article View in Scopus ↗ Google Scholar ↗

[72] S.F. Miller, J. Tao, A.J. Shih
Friction drilling of cast metals
Int. J. Mach. Tool Manuf., 46 (2006), pp. 1526-1535
View PDF View article View in Scopus ↗ Google Scholar ↗

[73] D. Biermann, Y. Liu
Innovative flow drilling on magnesium wrought alloy AZ31
Proc. CIRP, 18 (2014), pp. 209-214
View PDF View article View in Scopus ↗ Google Scholar ↗

[74] S.F. Miller, P.J. Blau, A.J. Shih
Microstructural alterations associated with friction drilling of steel, aluminum, and titanium
J. Mater. Eng. Perform., 14 (2005), pp. 647-653
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[75] S.M. Lee, H.M. Chow, B.H. Yan
Friction drilling of IN-713LC cast superalloy
Mater. Manuf. Process., 22 (2007), pp. 893-897
Crossref ↗ View in Scopus ↗ Google Scholar ↗

[76] L.D. Yang, W.L. Ku, H.M. Chow, *et al.*
Mar-M247, Haynes-230 & Inconel-718 study of machining characteristics for Ni-based superalloys on friction drilling
Adv. Mater. Res., 459 (2012), pp. 632-637
View in Scopus ↗ Google Scholar ↗

[77] J. Vergara, S. Damm, J. Villanaueva, J.M. Godoy, *et al.*
Bush making by thermal flow drilling in copper and brass

Int. J. Manuf. Sci. Prod., 4 (2001), pp. 103-112

Crossref ↗ Google Scholar ↗

[78] M. Boopathi, S. Shankar, S. Manikandakumar, R. Ramesh
Experimental investigation of friction drilling on brass, aluminium and stainless steel
Process Eng., 64 (2013), pp. 1219-1226

View PDF View article View in Scopus ↗ Google Scholar ↗

[79] R. Kumar, N.R.J. Hynes
Influence of rotational speed on mechanical features of thermally drilled holes in dual-phase steel
P. I. Mech. Eng. B J Eng, 233 (2018), pp. 1614-1625

Google Scholar ↗

[80] R. Kumar, N.R.J. Hynes
Prediction and optimization of surface roughness in thermal drilling using integrated ANFIS and GA approach
Eng. Sci. Tech. Int. J. (2019), pp. 1-12

Google Scholar ↗

[81] N.R.J. Hynes, R. Kumar, J.A.J. Sujana
Optimum bushing length in thermal drilling of galvanized steel using artificial neural network coupled with genetic algorithm
Mat. In Tehn., 51 (2017), pp. 813-822

View in Scopus ↗ Google Scholar ↗

[82] R. Kumar, N.R.J. Hynes
Numerical analysis of thermal drilling technique on titanium sheet metal
AIP Conf. Proc., 1953 (2018), pp. 13001-13004

Google Scholar ↗

[83] R. Kumar, N.R.J. Hynes
Finite-element simulation and validation of material flow in thermal drilling process
J. Braz. Soc. Mech. Sci. Eng., 40 (2018), 10.1007/s40430-018-1091-y ↗

Google Scholar ↗

[84] N.R.J. Hynes, R. Kumar
Simulation of friction drilling process of Cu_2C

Mat. Today SAVE Proc., 5 (2018), pp. 27161-27165

Google Scholar ↗

[85] N.R.J. Hynes, R. Kumar
Simulation and experimental validation of Al7075-T651 flow drilling process
J Chin. Soc. Mech. Eng., 38 (2017), pp. 413-420

Google Scholar ↗

Cited by (29)

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