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Improving Friction Drilling and Joining through Controlled Material Flow

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Abstract

Friction drilling is a novel hole-making process that can be performed on thin-walled sheet metals. The friction between a rapid-rotating conical tool and a sheet metal workpiece generates heat to soften and displace the material to form a hole. The bushing is formed in-situ from the workpiece. This experimental study investigated the effects of feed rate and spindle speed on the thrust load curve of friction drilling. Generating a good quality bushing has been a challenge in friction drilling. A counter-bore die was proposed and implemented to eliminate cracks and petal formation. Threads were tapped to demonstrate the improvement of the bushing quality. The present work also evaluated the feasibility of joining sheet metals with friction drilling. It was found that under an appropriate process condition, it is possible to perform friction drilling through two metal sheets to create a weld joint.

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Keywords: Friction drilling; friction joining; material flow

1. Introduction

Friction drilling is a chipless hole making process. During drilling, the friction between a rotating tool and the sheet metal workpiece generates significant heat and plastic deformation to create a hole [1, 2]. Instead of removing material, the process reshapes the workpiece material upwards to form a boss and downwards to form a bushing. The length of boss and bushing provides more material than the original sheet thickness for tapping thread. The hole and thread make

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it simple to attach devices to the thin-walled sheet metal part [3-5].

Early publications on friction drilling are mostly patents issued in 1970s and 1980s [2-8]. A study of the thrust force and feed velocity in friction drilling was published by Streppel and Kals [1]. To reduce radial fracture of the bushing, experiments were conducted with pre-heating of the workpiece and higher spindle speed [9]. The thrust force and torque under various process conditions were investigated to demonstrate the benefits. It was shown that as the workpiece temperate increased, the thrust force decreased, and the shape of the bushing improved. The recorded torque, however, varied. This could be attributed to the high affinity of the workpiece and tool materials [10].

The quality of the friction-drilled hole has been extensively investigated [9, 11]. Crack and petal formation are both undesirable for threads to be tapped inside the drilled holes. Efforts were made to improve the bushing quality with changes in feed rate and spindle speed. It was found that the feed rate had limited effect on bushing quality, while spindle speed can result in either positive or negative effectives on crack formation, depending on the workpiece material. It was observed that for steel, petal formation was reduced with high spindle speed. It was also concluded that brittle cast metal was less suitable than ductile sheet metal for friction drilling applications.

To improve the bushing quality in friction drilling of brittle cast A7075-T651 aluminum alloy, pre-drilling was investigated as a novel approach [12]. Due to less contact area between the tool and the workpiece, pre-drilling technique resulted in less temperature increase. To compensate the temperature deficiency, higher spindle speed and lower feed rate were used to generate more frictional heat. With the preferred spindle speed and feed rate, the pre-drilling approach was shown to eliminate cracks and petal formation.

While the previous publications investigated the effects of various process parameters on the thrust force and bushing quality, a more thorough study on the characteristics of the force cure is needed to better understand the details of the hole making process. The present work also aims at evaluating the application of a counter-bore die to control material flow and improve bushing quality. Finally, this paper presents a feasibility study of applying friction drilling process to drill through two metal sheets as a novel joining technique.

2. Experimental Setup and Force Measurement

This section describes the components of the experimental setup. The selected three-axis computer numerical control (CNC) milling machine, friction drill bits, designed fixture, and the data acquisition system are presented. In addition, the basic friction drilling process conducted and the force data measured are reported.

2.1. Experimental Setup

The essential components to perform friction drilling are shown in Figure 1. A Bridgeport three-axis CNC milling machine, with the maximum spindle speed of 4000 rpm, was used for the experiment. A U-channel fixture to hold the workpiece was designed and fabricated. The slot was 12.7 mm in width and 25.4 mm in depth, such that there was sufficient clearance between the drill bit and the fixture when the hole was penetrated. The fixture was mounted on a dynamometer on the slide table of the Bridgeport CNC.

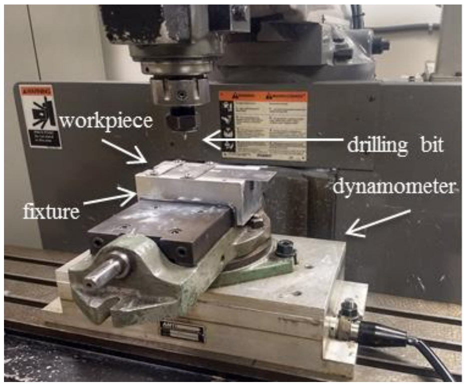


Figure 1 Flow experimental drilling setup

The AMTI (Advanced Mechanical Technology Inc.) MC818 series dynamometer used in the experiment is the platform-type and multi-component equipment. The dynamometer is capable of measuring up to 8900 N load, and providing four output channels to measure the forces in X, Y, Z directions and the moment about X axis. The measurements of force and torque are from strain gages. During the experiment, the obtained analog voltage signals were transferred to the amplifier. The Missile Command Amplifier (Model MCA amplifier) was compatible with the AMTI dynamometer. The voltage gain used in the experiment was 4000. A signal converter was needed to convert the analog signal from the amplifier into the digital signal captured by data acquisition software. The converter used in the experiment was an NI USB-6008 from National Instruments.

After the analog signal from the amplifier was converted into digital signal, it was delivered via the Universal Serial Bus to the data acquisition software. The software used in the experiment was LabVIEW SignalExpress LE. During the friction drilling process, the voltage signal was collected and recorded with the selected sampling rate of 1000 Hz. The collected digital voltage signals were then exported to Microsoft Excel. The forces were obtained from the recorded voltage signals.

The friction drilling tool purchased from Flowdrill© is made of tungsten carbide in cobalt matrix. Two sizes of the friction drilling tool, for drilling of 5.3 mm (shown in Figure 2) and 7.3 mm holes were used in the experiment. Aluminum alloy 6061-T651 was selected as the workpiece material. The material thicknesses were of 1.25 mm and 2.29 mm.

Figure 2 Flowdrill drill bit (5.3 mm diameter)

2.2. Force measurement

Using the experimental setup, various friction drilling experiments were conducted. The axial forces were measured and the geometries of the bushing were characterized. The spindle speeds were set at 2000, 3000, and 4000 rpm. The axial feed rates were at 38.1, 65.3, and 88.9 mm/min. To establish a baseline, the spindle speed of 3000 rpm and feed rate of 63.5 mm/min were used to drill 5.3 mm diameter holes in 1.25 mm thick aluminum alloy workpiece. The repeatability of the force measurement is shown in Figure 3. It can be observed that the measured force curves are fairly consistent. The first peak is the thrust force just prior to the penetration of the sheet meal. Some difference is observed between the first and the second peak. The amount of lubricant applied and the adhesion of the aluminum to the drill bit may cause the difference in the results. The final peak occurs when the back-extruded material (boss) contacts the tool shoulder.

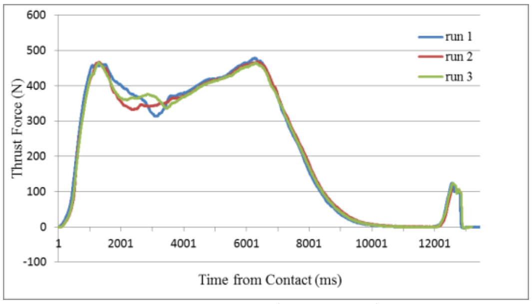


Figure 3. The repeatability of the thrust force measurement

3. Friction Drilling Experiments

3.1. Force curves for drilling thick and thin sheets

Two significantly different thrust force curves were observed in friction drilling of sheets with different thickness. A series of friction drilling tests were executed to study the cause of the difference. For each test, while the drilling tool travels to a selected position, locations A to F, and then retracts to the initial position, the thrust force data are recorded. The force curve of friction drilling of 2.29 mm thickness workpiece is shown in Figure 4. The experiments were conducted at 3000 rpm spindle speed with 63.5 mm/min constant feed rate using the Long Flat 5.3 Flowdrill© tungsten carbide drill bit. The curve has two peaks (at A and F) with the maximum force at about 1300 N (location A). It occurred just before the tool penetrates the workpiece material. The forces were very close for all experiments, indicating good repeatability. This result is consistent with the results published in the literature and thus is not further discussed.

The second type of the thrust force curves was found to have three peaks. The experiment was conducted to drill thinner 1.25 mm workpiece at 4000 rpm spindle speed with 38.1 mm/min constant feed rate using the Long Flat 5.3 Flowdrill© tungsten carbide drill bit. The top and cross-section views of the specimens at various drill depths are shown in Figure 5 and the corresponding force curve is shown in Figure 6. Figure 5 shows the progressive states of the specimen during the drilling process The photos A to E correspond to letters A to E marked in Figure 6. Note that the top views are shown in A, B, C. After the penetration of the workpiece, the section views C, D, E are shown. Two photos of C are provided to show the top and section views.

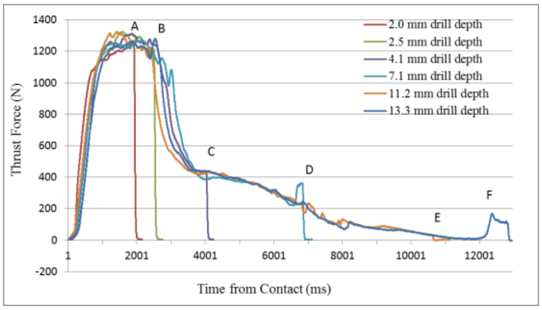


Figure 4: Thrust force curve in 2.29 mm thick aluminum alloy workpiece friction drilling

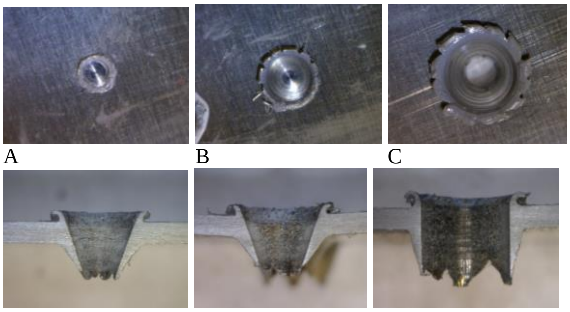


Figure 5 Top and cross-section view of the specimen (1.25 mm thickness and 5.3 mm diameter drill bit).

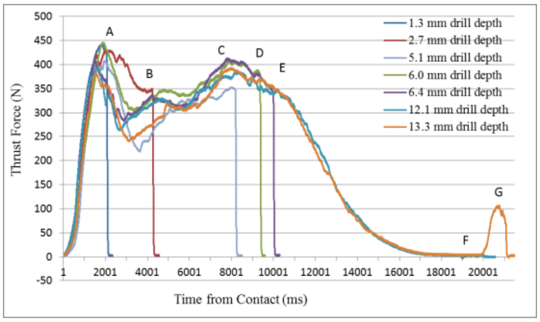


Figure 6 Thrust force curve in 1.25 mm thick aluminum alloy workpiece friction drilling

The maximum force was at 450 N, occurred just before the tool penetrated the workpiece at location A. As the tool keeps rotating, the temperature in the work region rises due to the frictional heat. The flow stress of the work material reduces as the temperature increases, and the force is reduced as seen at location B. With increasing drill depth, the amount of the material build-up increases. The force again increases, as shown at location C, due to the increased contact area. As the drill bit advances, the thrust force then progressively declines at positions D and E. After the hole is completely penetrated, the shoulder part contacts the boss and results in the third peak at position G. The thrust force then decreases rapidly to zero as the drill bit retrieves. From the experimental data, it can be observed that the thrust force is affected by the flow stress of the material and the tool-workpiece contact friction.

3.2. Effects of process parameters

Since the load cures of drilling thin sheets are different from the previous results of drilling thicker workpiece, it is of interest to observe the effects of process parameters (spindle speed and feed rate) and workpiece thickness on the thrust force.

Figure 7 shows the force curves of drilling 1.25 mm thickness specimen with 63.5 mm/min feed rate at the spindle speed of 2000, 3000, and 4000 rpm. It can be observed that as the spindle speed increases and the workpiece temperature increases due to friction, the material softens and the thrust force decreases. Similar trend can be observed when investigating the effect of feed rate on drill force, as shown in Figure 8. At the spindle speed of 3000 rpm, the thrust force decreases as the feed rate decrease. With a lower feed rate, it takes a longer time to complete the process, and thus allows more heat to be generated to reduce the flow stress of the workpiece material. Figure 9 compares the force curves obtained from drilling of 1.25 mm and 2.29 mm specimen thicknesses. It is clear that the thicker sheet has a higher recorded reaction force during the hole make process.

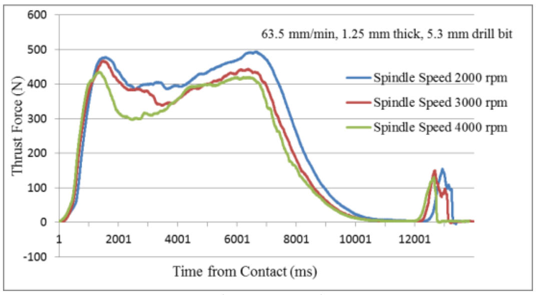


Figure 7 Comparison of the thrust forces with 63.5 mm/min feed rate

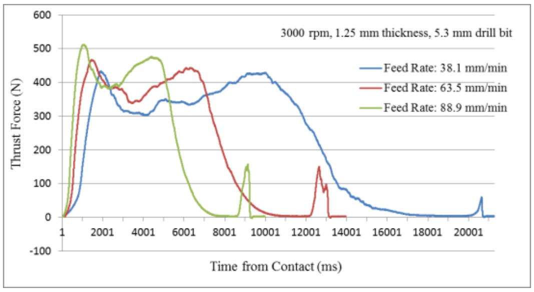


Figure 8. Comparison of the thrust forces with 3,000 rpm

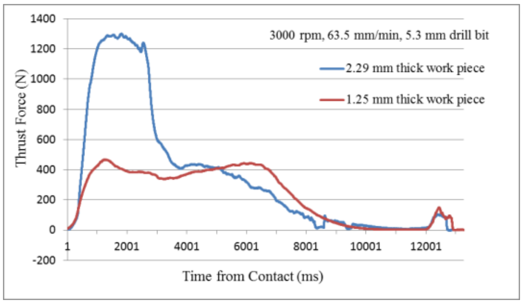


Figure 9 Comparison of the thrust forces for different workpiece thicknesses using 5.3 mm friction drill bit

The effects of process parameters on the peak thrust force can be summarized in Table 1. It can be observed that the thrust force can be reduced with low feed rate with high spindle speed.

Table 1 Effects of process parameters on the peak trust load

Feed rate/Spindle speed	2000 rpm	3000 rpm	4000 rpm
38.1 mm/min	483 N	431 N	404 N
63.5 mm/min	490 N	463 N	446 N
88.9 mm/min	530 N	508 N	470 N

3.3. Bushing quality

To evaluate the quality of holes made from friction drilling, the shape of bushing is an important criterion. The quality of bushing shape is commonly evaluated based on its cylindricality, effective length, cracks, and petal formation [11]. In this study, the specimens with the drilled hole were sheared by the cutting blade at the center of the hole. The cross-sectioned surface of the workpiece was manually polished using finer sand papers progressively. The preparation facilitated the optical microscopy examination. A digital microscope was used to capture the cross-sectioned images of the drilled specimens. Low magnification optical images of the cross-sectioned specimens were inspected to assess the hole quality. The cross-sectioned view is capable of revealing different features of the drilled hole clearly. The cracking and petal formation are undesirable bushing features. For further application, these undesirable characteristics influence the effective length and strength for threading. In other words, the cracking and petal formation destroy the useful surface area and limit the load carrying capability of the threaded holes.

The bushing geometry is slightly improved by the decrease of the feed rate. As the feed rate decreases, the length of bushing extends. The raised feed rate promotes more rapid deformation of the work material in lower work zone temperature. The rapid deformation reduces the temperature increase, and the improvement of the plasticity of the work material becomes less significant. The bushing extrusion length is therefore shortened at high feed rate and low temperature condition. However, compared to the effect of spindle speed, the effect of feed rate on the bushing quality is relatively small.

Figure 10 shows the quality of the holes drilled at 2000, 3000, and 4000 rpm. It can be observed that, as the spindle speed increases, the length of the bushing extends. At constant feed rate, higher spindle speed results in more frictional heat. As the temperature rises, the workpiece material becomes more ductile and formable and results in better hole quality.


(a) 2000 rpm (b) 3000 rpm (c) 4000 rpm

Figure 10 Effect of spindle speed on the quality of the bushing

The effects of the workpiece thickness and tool diameter on the bushing quality can be best evaluated based on the thickness to diameter (*t/d*) ratio. As previous reported, with a lower t/d ratio, less material is available to be distributed to generate the bushing and hence it is more likely to observe cracking and petal formation as shown in Figure 11.


t/d = 0.43 *t/d = 0.24* *t/d = 0.17*

Figure 11 The effect of t/d ratio on the bushing quality

4. Friction Drilling with Controlled Material Flow

The objective of forming a bushing on the thin workpiece is to facilitate joining. The bushing provides additional material to thread the hole. As shown in the previous section, poor quality such as cracks and petals can significantly reduce the useable length for thread making. In this research, a novel but simple approach is introduced to improve the shape of the bushing. The approach is to carry out the friction drilling with a well-designed lower die as shown in Figure 12. The die adopts the geometry of a counter-bore where the material flow is controlled within the confined area. The counter-bore diameter, d_2, and depth, h, are calculated based on the assumption of volume consistency such that

$$h\left(d_2^2 - d_1^2\right) = td_1^2 \qquad (1)$$

where d_1 is the hole diameter and t is the sheet metal thickness. The design assures that there is adequate space to accommodate the displaced material such that damage of the drill bit or the CNC machine can be prevented. Experiments were conducted to evaluate the thrust force and bushing quality resulting from friction drilling with counter-bore die.

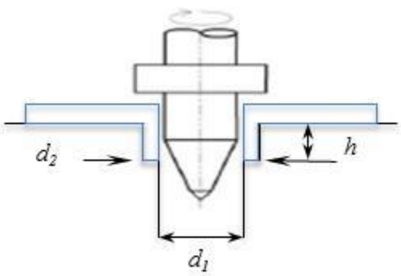


Figure 12 Counter-bore die used for material flow control

4.1. Friction drilling with counter-bore die

Two counter-bore dies were designed and fabricated for friction drilling experiments. The first die has the hole diameter (d_1), counter-bore diameter (d_2), and counter-bore depth (h) of 5.3 mm, 6.33 mm, and 2.60 mm, respectively. The second die has the hole diameter (d_1), counter-bore diameter (d_2), and counter-bore depth (h) of 5.3 mm, 6.37 mm, and 2.00 mm, respectively. The thickness (t) of the workpeice was 1.25 mm. The experiments were conducted at 4000 rpm spindle speed and 38.1 mm/min feed rate. To obtain high quality bushing, it is critical to position the tip of drill bit at the center of the counter-bore.

Figure 13 shows the plot of thrust force vs. time. It is observed that comparing to the typical friction drilling process (marked as “free space”), the thrust force is higher when a counter-bore die is used. With bushing material confined in the counter-bore, it is reasonable that the force is higher. It can also be observed that the drop of the thrust force after the second peak is somewhat irregular due to a strong interaction between the bushing material and the counter-bore surface. Since the dimensions of the two dies are different, the thrust force curves also vary slightly. Finally, it is important to note that while the peak force is increased from 400 N to 580 N, significant improvement of the bushing quality can be observed.

Figure 14 shows the geometry of the bushing while drilling with and without counter-bore dies. It can be observed that with control of the material flow, the cracks and petal formation is eased. To obtain stronger fastening, it is common to cut threads inside a friction drilled hole. In this study, M6×1.0 tap size was used for thread making. Figure 14 also shows that friction drilling with counter-bore die can improve bushing quality and increase one additional pitch (from 2 to 3 pitches) when tapping a thread, representing a 50% improvement.

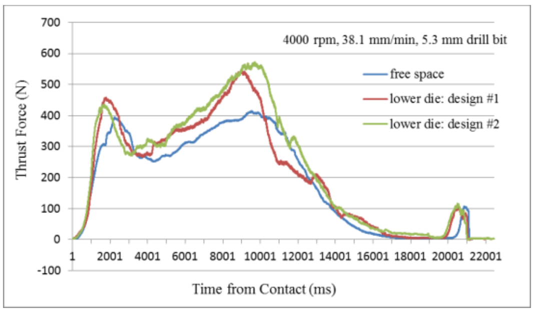
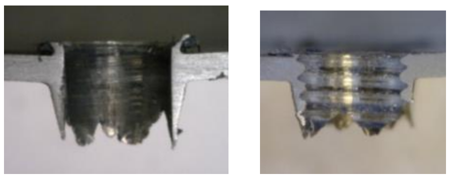
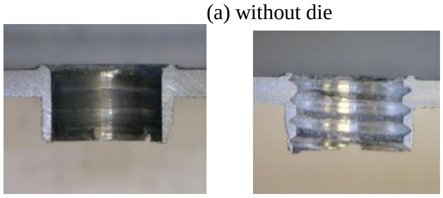


Figure 13 Thrust force with and without counter-bore die



(a) without die



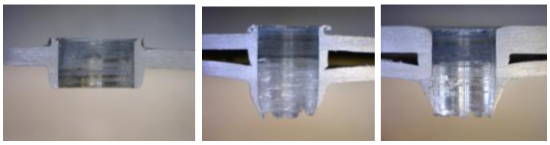
(b) with die

Figure 14 Friction drilling and thread with and without counter-bore die

4.2. Joining with and without counter-bore die

Friction welding is a common solid state joining process. It produces welds at temperatures below the melting temperatures of the workpiece materials. With frictional heat, the bonding is created through plastic deformation and diffusion. Similar to friction welding, friction drilling also involves heating and deformation of the workpiece materials. Therefore, it is of interest to investigate the feasibility of joining two metal sheets by a simple friction drilling operation.

Thin aluminum alloy 6061-T651 sheets with the thickness combinations of 1.25/1.25 mm, and 2.29/1.25 mm were used for the tests. The experiments were first conducted with 1.25/1.25 mm specimens without a supporting counter-bore die. With the feed rate of 63.5 mm/min and spindle speed of 3000 rpm, the process failed to achieve any bonding. It was, however, found that the process produce a top sheet with very high quality bushing where no crack can be observed as shown in Figure 15(a). This indicates that, during the deforming process, the bushing of the top sheet was supported by the bottom sheet, and the bottom sheet became a sacrificial layer. Figure 15(b) shows that with an increase of spindle speed to 4000 rpm, the temperature is increased and the frictional heat can promote bonding. The figure also shows that there was a significant gap between the two sheets due to the deflection of the workpieces. The formation of the bushing pushed the top sheet up and the bottom sheet down. This gap can be reduced when friction drilling of 2.29/1.25 mm specimens that the deflection of the thicker and stiffer top sheet was reduced. As shown in Figure 15(c), the fusion between the two workpiece at the joint is improved. During the experiments, the thrust force curves were recorded. Figure 16 compares the thrust force curves of friction drilling single 2.29 mm sheet and 2.29/1.25 mm sheets. It is found that the increase of thrust force in friction drilling two metal sheets is not very significant.



(a) (b) (c)

Figure 15 Friction drilling and joining

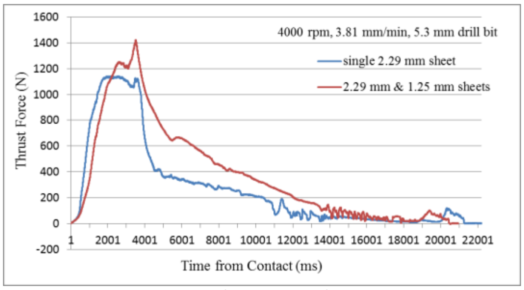


Figure 16 Thrust force curve for joining process

To accommodate additional material and control material flow in friction drilling two metal sheets, a new counter-bore die was designed and fabricated with the hole diameter (d_1), counter-bore diameter (d_2), and counter-bore depth (h) of 5.3 mm, 7.00 mm, and 3.50 mm, respectively. The specimen was of 2.29/1.25 mm sheet thickness combination. The experiments were conducted with and without the counter-bore die at the feed rate of 38.1 mm/min and spindle speed of 4000 rpm. The thrust force curves are depicted in Figure 17. It can be observed that the curves have similar trends, and the difference in peak forces is small (200 N) at about 14%. Note that without the counter-bore die, the force fluctuated near the end of the process as the material was not supported underneath the drill bit. Figure 18 shows the cross section of the hole/joint. It can be observed that the two metal sheets are successfully bonded and the bushing is formed without cracks. The experimental result also shows that despite the application of the counter-bore die, the gap between the two workpiece cannot be completed eliminated.

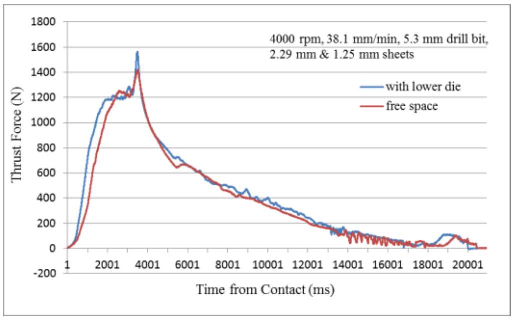


Figure 17 Thrust force for joining with and without counter-bore die

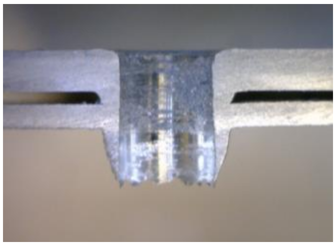


Figure 18 Joint quality with count-bore die

5. Conclusions

In this paper, friction drilling of aluminum alloy sheets was investigated. The work focuses on examining the thrust force, improving the bushing quality, and applying the process for joining of metal sheets. The experimental work in this research contributed to the following conclusions:

- Two different types of thrust force curves were observed from friction drilling experiments. It was found that the shape of the curve and the peak force are affected by the process parameters, as reported previous, as well as the material properties and the specimen thickness.
- Experimental results show that while the spindle speed and feed rate can both affect the thrust force, within the studied ranges, the spindle speed had a more dominant influence on the thrust force than the feed rate.
- To control and confine the material flow to improve the bushing quality, counter-bore dies were designed, fabricated, and used in the experiments. It was shown that the approach can eliminate cracks and petal formation. Threads were tapped to demonstrate significant improvement of the bushing for practical applications.
- Under an appropriate process condition, it is possible to perform friction drilling through two metal sheets to create a weld joint.
- The quality of the threaded bushing and the weld joint can be further evaluated through pull tests in the future.

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