Stir Welding Aluminum Plates Using a Low-Cost Milling Machine

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Abstract

In friction stir welding (FSW), no filler metal or melting is used for joining the metal, and welding is done by moving the work piece against a rotating tool. Heat is generated by friction between the tool and work piece and causes the work pieces to weld together. Friction stir welding can be expensive for small shop owners who cannot afford to have separate friction welding machines or need to send the parts out for welding. Therefore, there was a need to find a low-cost alternative of achieving FSW. This resulted in using vertical milling machines to stir weld. This article describes a project that replicates this method using an old vertical milling machine for stir welding of aluminum plates. These aluminum alloys were different from the ones used in the past studies and are commercially commonly used. Also, this study used thicker plates than those in past studies. The weld quality was determined by measuring the hardness of the weld. The results showed that some of the alloys could be welded but not others and that machine and tool holder rigidity is of utmost importance to reduce vibrations and consequently avoid defects such as cracks, chip formation, and avoid tool deflection. Hopefully, observations made in this project may aid small job shops to adopt their existing milling machines for welding at little cost. The project can also be useful for demonstrating friction welding in an educational setting by using existing machine shop resources.

Introduction

It is this idea of using a machine tool for a different purpose that gave rise to this project. Here, we want to use the vertical milling machine as a multi-purpose machine to be used for milling operations and as well as a welding of parts.

The welding process can be broadly divided into two categories: forge or pressure welding under pressure without additional filler metal, and fusion or non-pressure welding with additional filler metal. Friction stir welding (FSW) falls into the first category. FSW is one of the solid-state welding methods that are used for welding metals that cannot be welded or are difficult to weld using conventional welding techniques. In this welding process, no filler metal or fusion is used for joining the metal, and it is done by moving the work piece against the rotating tool (Neto & Neto, 2013). Heat is generated by friction between the tool and work piece and causes the metal to soften. By using this welding technique, we can produce a weld of high quality with improved properties (Rambabu, Naik, Rao, Rao, & Reddy, 2015). Friction stir welding has the ability to manipulate the properties of the material and adapt them for different applications, and it is possible to enhance mechanical application (Rao, 2000). The process also has the potential of reducing problems associated with fusion welding, such as shrinkage and porosity.

In recent years, FSW has been gaining popularity in manufacturing industries such as shipbuilding, aerospace, railway, and automobile (Siddiqui, Jafri, & Alam, 2015). However, since FSW machines are often quite costly, there was a need to find a low-cost alternative. This resulted in using vertical milling machines to stir weld. This study replicated the use of a vertical milling machine for stir welding of aluminum plates. These aluminum alloys are different from those used in past studies. Also, thicker plates than those in the past are used. This project can be especially useful for small shops that do not have regular welding facilities and cannot afford to have separate friction welding machines, hence need to send the parts out for welding. This can also be useful for teaching about pressure welding without having a separate friction welding machine. In the case of a production line, a milling machine could be used for friction welding to eliminate the need to take parts out of the production line to the welding area or having to outsource welding.

Friction Stir Welding

In FSW, the weld is made by plunging a wear resistant rotating tool into the square butt joint and moved along the joint line. The work pieces are securely clamped to form the butt joint. The tool typically consists of shoulder and a probe as shown in Figure 1. The weld made by friction stir welding generally contains a thermos-mechanically-affected region, heat affected zone, unaffected base material, and wide-ranging deformed zone (Mrudula, Srinivasulu, & Krishnaiah, 2012).

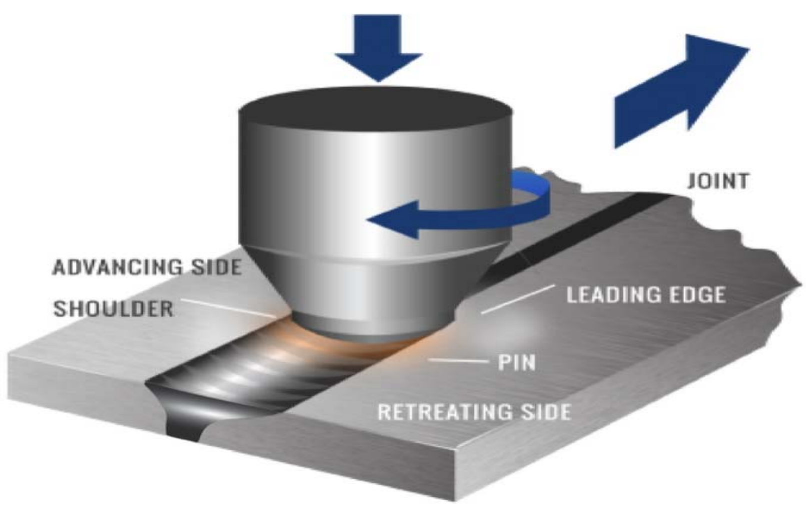

Figure 1. Friction stir welding schematic diagram (Megastir, 2018). Reprinted with permission.

As stated above, during FSW, the material is heated due to friction and it becomes softened without melting. Additional heat is also generated due to mechanical mixing of the plasticized metals. During the process, the tool's profile forces the material backwards, and the high clamping pressure on the workpieces assists in causing a forged weld.

The weld mechanical properties vary due to change in micro structures, which is caused by the heat of friction and material flow in plastic form due to tool rotation (Jata, 2000). The important parameters in FSW are tool speed and feed rate. The tool speed is the speed at which the tool rotates while welding, and feed rate is the rate at which the tool transverses along the weld seam or joint. Typical maintenance shops have the milling machine with 60-4500RPM speeds and 20-210mm/min feeds (personal communication).

Tool geometry plays a significant role in process development and material flow in FSW (Singarapu, Adepu, & Arumalle, 2015). The tool material must have high wear resistance, hot-hardness, and toughness (Schneider, 2009). These properties are often found in cutting tool materials. The principal materials used in cutting tools are high carbon steel, high-speed steel, carbides, and ceramics. High-speed steel containing 18% tungsten, 4% chromium, and 1% vanadium is considered one of the best all-purpose tool steels. They hold their hardness up to a temperature of 900º C (Khurmi & Gupta, 2006).

Previous studies such as Titilayo et al. (2012) and Sharma, Dwivedi, and Kumar (2012) investigated welding parameters of tool turning speed, tool feed rate, and microstructures and tested the properties of the welds using tensile tests of welded aluminum parts. Others investigated effects of welding speeds and tool geometry (Arora, Pandey, Schaper, & Kumar, 2010; Dwivedi, 2014). Still others reviewed the effects of tool geometry and redesign of clamping system (Siddiqui, Jafri, & Alam, 2015). Some of these are shown in Figure 2.

Figure 2. Different shapes of the tools used in friction stir welding (Megastir, 2018). Reprinted with permission.

In general, past studies have shown that tensile strength increases with increasing tool speed and feed rate, and other properties like percentage elongation, weld joint efficiency, and energy absorption are decreased.

Experimental

We used the previous studies as a guide to develop the experimental procedures. To make it realistic, we only used the equipment readily available in the college. Therefore, it involved creating simple tools and using the existing "old" milling machine and a Rockwell hardness tester.

Tool

The tool was fabricated from stainless steel rods on a lathe. Figure 3 shows the details of the tool. The lathe is shown in Figure 4.

Figure 3. Friction stir welding tool.

Figure 4. 9" south bend precision lathe model A.

Work Piece Preparation

Work pieces consisted of small aluminum plates as shown in Figure 5. Twenty pieces were made, and the edges were milled to make the butt joints. Four different aluminum alloys were selected because these are well known commonly used in wide range of applications, such as transportation components, machinery, equipment, etc., and aluminum was also used mostly in previous studies. These are described in Table 1.

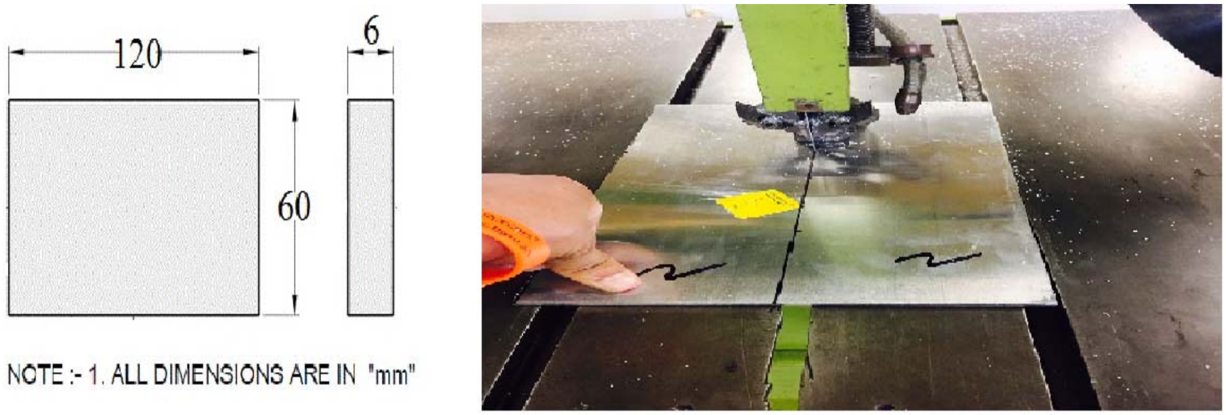

Figure 5. Aluminum plate with dimensions.

Research Design

The vertical milling machine with automatic transverse speed was used for welding as shown in Figure 6. The aluminum plates were butted tightly in a milling vise. The fabricated tool was fixed in the spindle using a drill chuck. The fixed work pieces were moved from one end to another against the rotating tool as shown in Figure 7. The welding parameters used are shown in Table 2. Feed rate, tool speed and depth of penetration were the welding parameters selected because, as shown by previous studies such as by Syed, they directly affect the weld quality (Ahmed & Syed, 2010).

Figure 6. 1½ HP J head Bridgeport-vertical milling machine.

Table 1. The work pieces alloys.

Materials	**Composition Wt %**	**Hardness Number**	**Ultimate Tensile Strength**	**Increasing Melting Point**
Al-2024	Aluminum- copper alloy can be age hardened	High about Brinell-120	High about 500 Mpa	Low about 500 centigrade
Al-5086	Aluminum- Magnesium Alloy Typically Strain hardened	↑	↑	↓
Al-5052	Aluminum- Low Alloy Typically Used for corrosion resistance	↑	↑	↓
Al-3003	Almost pure Aluminum	Low about Brinell-40	Low about 150 Mpa	High More than 600 centigrade

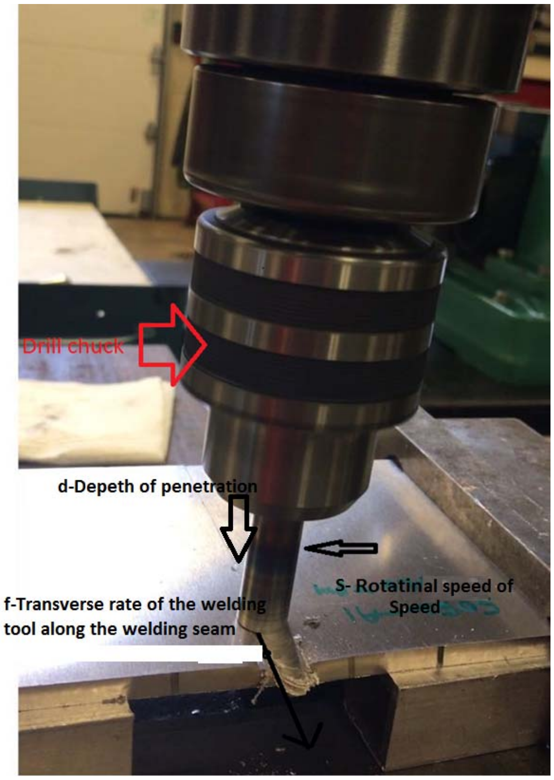

Figure 7. Work piece movement against the rotating tool.

Table 2. Welding parameters.

Trial	Material	Tool Speed(S) RPM	Feed Rate(f) mm/min	Depth of Penetration(d) mm
1	Al-2024	2720	12.8	5.8
2	Al-2024	1750	15.4	5.8
3	Al-5052	1750	67	5.8
4	Al-5052	2720	10.51	5.8
5	Al-5052	2720	6.68	5.8
6	Al-5052	1750	25	5.8
7	Al-5052	1750	25	6
8	Al-5086	2720	23	5.8
9	Al-5086	1750	25	5.8
10	Al-5052	2720	9.7	5.8

Hardness Testing

We used Rockwell hardness as a measure of mechanical properties of the welded plates. Reasons for using Rockwell hardness is the availability of equipment and relatively low specimen preparation requirement. Hardness is also generally related to tensile strength (Alavudeen, Venkateshwaran, & Jappes, 2006) and hence is a good means for overall evaluation. The test samples of size 100mm X 25mm were made by cutting the welded work pieces to be accommodated in the hardness testing machine as shown in Figure 8. Figure 9 and Table 3 show the hardness indentation positions. Taking into considering the statistical significance and due to limitations of being able to accommodate the work pieces in the hardness machine 8 to 10 indentations were used. The 'B' scale was used with a 100 kgf load and 1/16'' ball indenter with a dwell time of 10-15 sec. as recommended in the manual for aluminum.

Table 3. Number of indentations and their position on the sample.

Sl.no	Hardness type	Total number of indentations	Position of the indentation
1	Weld material	10	On the weld
2	Edge of weld	8	1mm from the weld
3	Little away from the weld	10	1cm from the weld
4	Base material	8	Randomly away from the weld

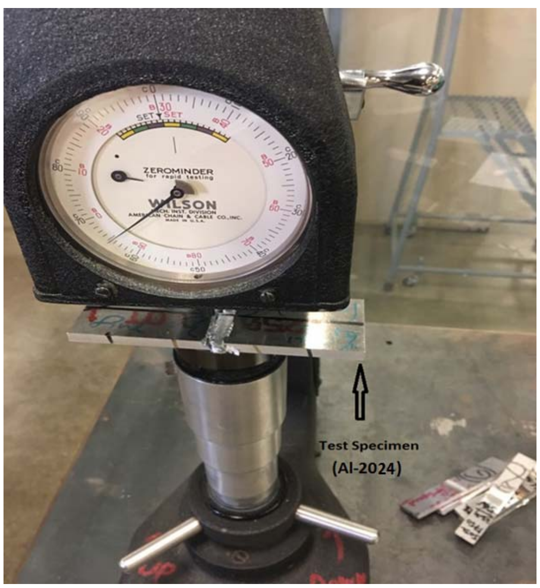

Figure 8. Rockwell hardness tester.

Results

The parent metal hardness of the different alloys is shown in Table 4. The parent metal hardness refers to the hardness values of the raw materials provided by the manufacturer. The average hardness values for each trial are plotted in graph shown in Figure 10.

Table 4. Brinel hardness of the alloys used.

Materials	Parent metal Hardness
Al-2024	120
Al-5086	78
Al-5052	60
Al-3003	40

All readings are HRB and positions of indentation correlate with Figure 9. Base metal refers to area well away from the weld. Depth of penetration of the tool was 5.8mm and the length of the tool projecting from the chuck holder was 70mm. These were selected by trial and error to reduce vibrations. Consequently, the contact between the work piece and the tool shoulder was reduced. In general, welding was not successful. Cracks were formed on downside of the weld nugget when we welded from right to left and vice versa in most cases. An example is shown in Figure 11. The severity of the cracks varied in different trials but in general was less in the Alloy 5020.

Photos of the welded parts are shown in Figure 12. Following are some observations from these results:

- Al-3003 with parent hardness of 40 could not be welded due to extreme chatter and tool shifting off center. This material has one of the low alloy content, and higher melting point.
- The average hardness of Al-5052 was more than its parent's hardness for all tool speeds and feeds rates.
- It is also evident that the average hardness numbers of Al-2024 and Al-5086 shows that the average hardness values for these materials was less than its parent hardness values for all tool speeds and feeds rates.

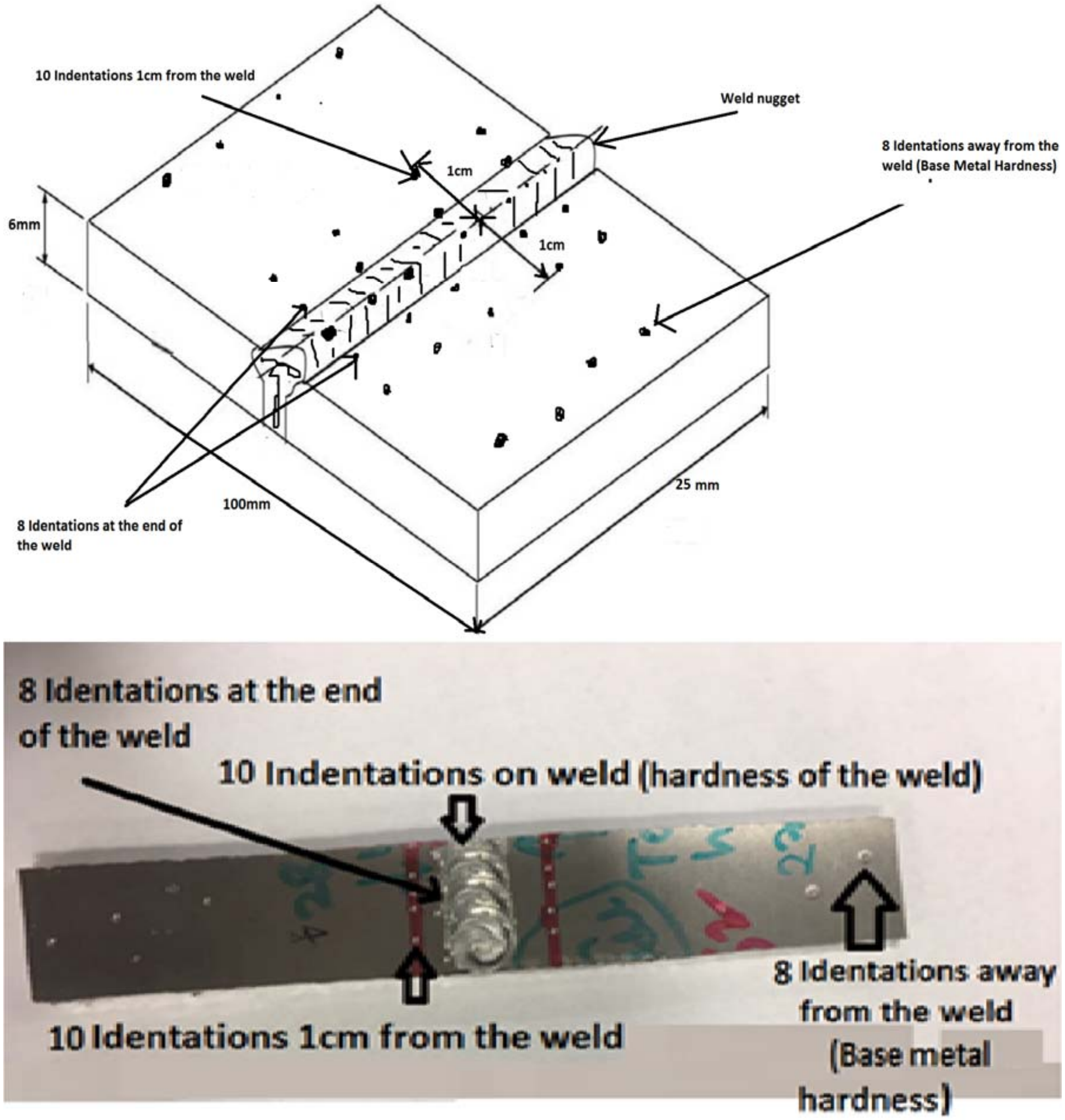

Figure 9. The test sample with hardness indentation positions.

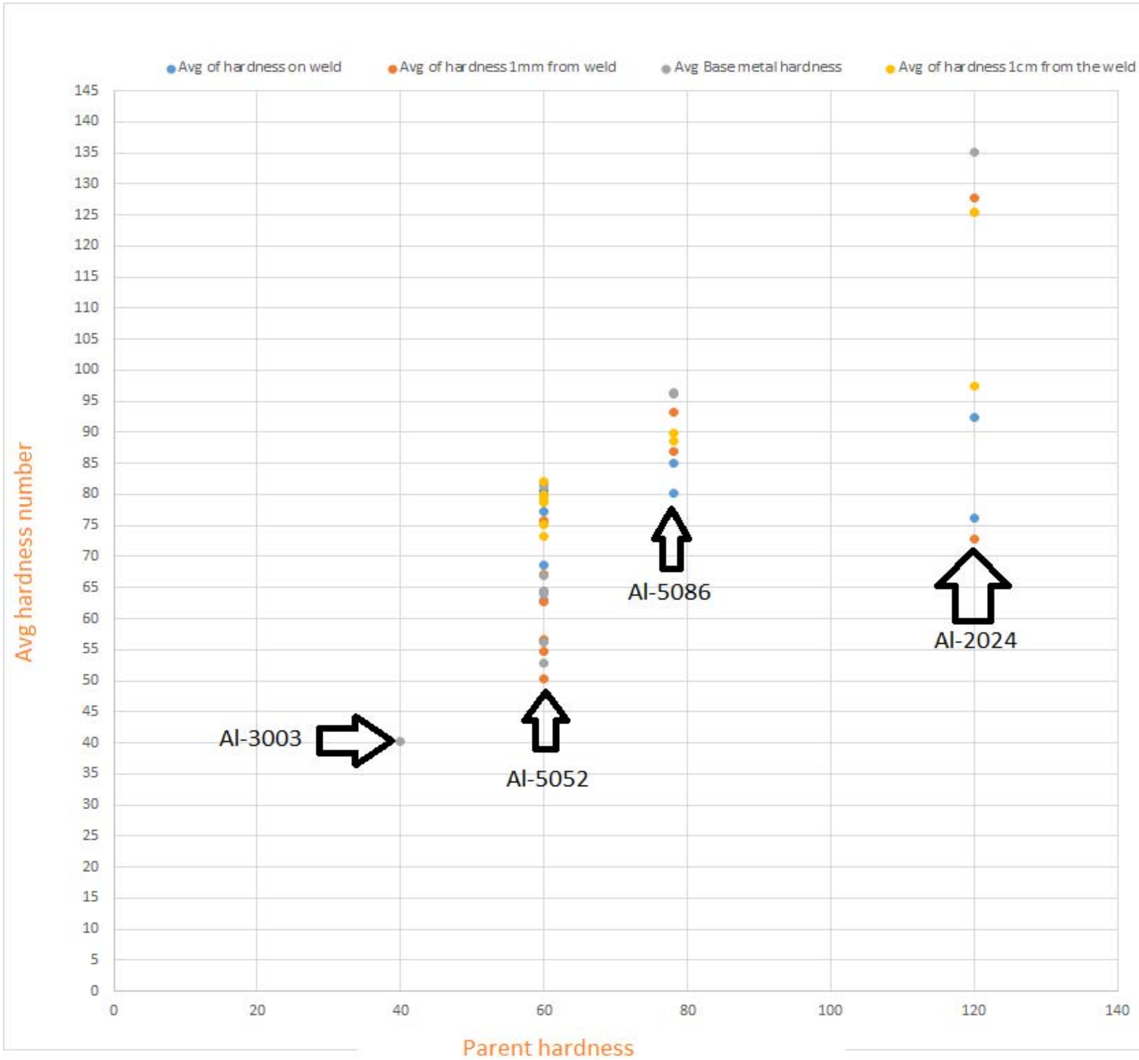

Figure 10. Graph of parent hardness vs average hardness.

Discussion of results

The weld quality is affected by the tool vibrations because friction between the tool and work piece is influenced by the vibrations. Hence, the area of contact between tool and work piece was uneven due to vibrations so this affects the friction (Sheng & Lee, 2013).

The literature shows that tool speed plays a vital role in the weld quality. The range of speeds used in our experiment was 1750-2720RPM, whereas the range of speeds used in past studies was 250-1200RPM. Hence, heat generation due to tool rotation was probably not a major factor in our study. There was insufficient heat to create good welds; i.e., the heat generated in our study due to tool rotation would be more than in the previous studies. Since a typical commercial machine shop has milling machines with speeds of 60-4500RPM, rotational speed would not be a limitation in most cases. Also, typical maintenance shops have milling machines with 60-4500RPM speeds and 20-210mm/min feeds.

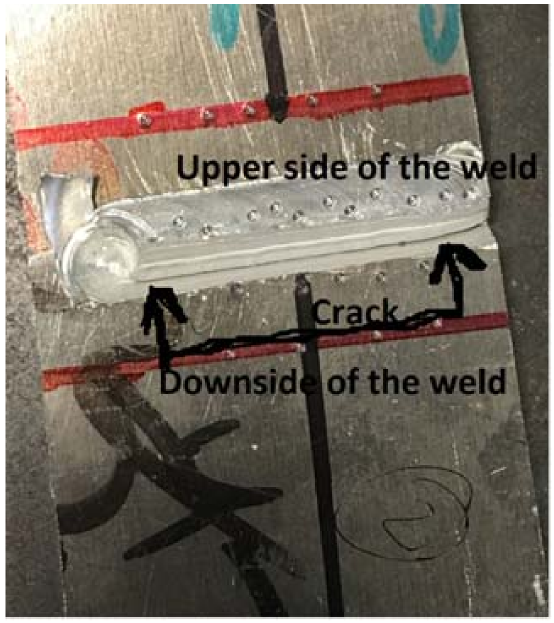

Figure 11. Example of crack formation on down side of the weld.

The shoulder of tool plays a very significant role in the weld quality. Some studies have estimated that, 86% of the heat generated is from friction between the shoulder of tool and work piece surface (Sattari, Bisadi, & Sajed, 2012). In our case, due to vibrations, we were forced to move the tool away from the workpiece hence reducing this source of heat. This in turn would not raise the temperature to cause sufficient plastization of the metal.

Our work plates were 6mm thick with a depth of cut of 5.8mm. In the past studies, the plates welded hand a range of 2.9-3mm. So, the 6-mm thickness allowed more heat to escape away from the weld, further exacerbating the lack of high temperature.

These factors combined reduced the temperature being attained leading to partial welding, cracking and higher forces on the tool causing tool deflections. In addition, Al-3003 has a high melting point and so would require higher temperature for plasticizing hence it could not be welded.

As expected, the higher alloyed materials have higher hardness and lower melting point. From the trails for each alloy, we found that the effect of tool speed is vital, i.e. lower speed seems to give higher hardness at the weld. And as we move away from the weld, hardness seems to increase. This may due to recrystallization and stress relief in the plates near the weld since the parent metals plates are cold worked. The alloys used in our work are Al-Cu and Al-Mg alloys. These are routinely hardened by participate hardening methods. Therefore, there is also the possibility of over aging near the weld thus reducing the hardness. Further microstructural work is needed to explain these effects.

Figure 12. All experimented work piece pictures with their material name, feed rate, and tool speed.

Conclusion

Although stir welding of aluminum plates using low cost milling machines is possible, the machine and tool holder rigidity is of utmost importance to reduce vibrations and consequently avoid defects such as cracks, chip formation and avoid tool deflection, which we observed. It also seems that only metals of melting point lower than about 650º C are candidates for this process, and thicker plates are difficult to weld.

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