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An assisted heating tool design for FSW of thermoplastics

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Abstract

An assisted heating tool design was used to obtain better weld surface finish, and lower chip formation and material loss during friction stir welding (FSW) of thermoplastics. The welded coupons of polypropylene with various tool rotational speeds were tested under tensile loading to test the efficiency of the tool design. The proposed tool improved the tensile strength of friction stir welded coupons of polypropylene and also produced the welds with more ductility than the conventional FSW tool without additional heating. Lack of heat, the reason for improper fusion and void formation during FSW of thermoplastics, was avoided by the proposed tool design.

Keywords: Friction stir welding, thermoplastics, joining, tool design, polymer processing

Introduction

Friction stir welding (FSW) is a solid state joining process invented by Thomas et al. which is successfully being used for joining of low temperature metallic materials (Thomas et al., 1991). FSW uses frictional and deformational heating to plasticize the workpiece material, and joins the material using plastic deformation (Oliveira et al., 2010). Figure 1 shows a simple schematic diagram of conventional friction stir welding process (Nandan et al., 2008).

Nelson et al. showed that heat generated due to friction and plastic deformation during FSW softens the workpiece material leading to successful joint formation (Nelson et al., 2004). FSW of thermoplastic polymers is difficult as the heat generated due to friction and plastic deformation is insufficient to form good joint. The limited heat generated during conventional FSW of thermoplastic materials, partially plasticises the workpiece material. On rotation of tool this partially plasticized material comes out of the weld zone due to centrifugal force as shown by Hilgert. Upon cooling it forms a fibrous structure instead of a contiguous welded joint (Hilgert, 2012). Insufficient heat generation causes chip formation, and improper plasticizing resulting in material loss and poor joining. Thermoplastics have lower thermal conductivity (ABS 0.17 W m-1 K-1, PP 0.22 W m-1 K-1) than metals. Strand showed that during the FSW process outer layer of material cools much faster than the inner layer. This leads to the formation of hard shell and voids (Strand, 2004).

Heat generation during FSW can be improved by increasing the tool rotation speed, tool shoulder diameter and pin diameter. However, Squeo and Bruno showed that these parameters also affect the material flow and lead to outward flow of material (Squeo and Bruno, 2009). Arici et al. (Arici and Sinmazçelýk, 2005) and Bozkurt (Bozkurt, 2012) reported formation of root defect, unwelded bottom part of the weld, during FSW of polymers. Low thermal conductivity of the polymer was suggested as the reason behind lack of heating at workpiece bottom. Bilici and Yükler (Bilici and Yükler, 2012) reported that weld formed with straight cylinderical pin profile tool were of poor strength while tapered cylindrical and threaded cylindrical pin profile tool gave much better weld strength. A study of effect of tool pin thread pitch by Boz and Kurt (Boz and Kurt, 2004) showed that smaller thread pitch produces good welds, whereas increasing thread pitch converts the process into drilling. Panneerselvam and Lenin (Panneerselvam and Lenin, 2014) used a tool with left-hand threaded cylindrical pin to join 10 mm thick nylon-6 sheets. When the tool was rotated in clock wise direction it pushed the material upwards. Such material flow resulted in loss of material and void formation. When the tool was rotated in counter clockwise direction it pushed the material downwards and kept material inside the weld pool. Figure 2 shows the mechanism of material flow due to the threaded pin as explained in their work. Jaiganesh et al. (Jaiganesh et al., 2014) attempted optimization of the process parameters for FSW of high density polypropylene plate. They observed that 10 mm/min travel speed resulted in less chip formation and improved joint strength. Essential condition for efficient joining of polymers require proper heating at the tool workpiece interface and proper mixing of the base material to avoid chip formation and produce better surface finish (Payganeh and Arab, 2011).

Recently some tool designs were proposed to provide additional heating during FSW of thermoplastic materials to avoid under-heating during joining (Nelson et al., 2004; Pirizadeh et al., 2014). Pirizadeh et al. (Pirizadeh et al., 2014) used a self-reacting tool as shown in Figure 3 that has non-rotating shoulder to avoid chip formation. Non-rotating shoulder was made of PTFE (Teflon) which has very low friction coefficient. The shoulder kept the material within the weld pool which resulted in welds with good surface finish. The self-reacting mechanism resolved the root defect in the welds. However, the joint strength is not sufficient due to less frictional heat. Kiss and Czigány (Kiss and Czigány, 2008) explored the feasibility of FSW of polypropylene using milling tool having grove slope of 15° and 45°, where the direction of the tool rotation used was reversed from the regular cutting direction during milling operation. They were able to weld the polypropylene sheets but with poor weld strength.

Various researchers have suggested tool designs to provide additional heading during FSW of polymers to reduce chip formation and improve material flow around the tool. Nelson et al. (Nelson et al., 2004) used an FSW tool with hot shoe to join polymers. Figure 4 shows the schematic diagram of the tool. The hot shoe in this tool design is a stationary metal plate which acts as non-rotating shoulder and keeps the material in the weld nugget. The hot shoe has a resistance heating element inside to provide extra heat during the process. This hot shoe design results in better solidification of the weld material. A. Bagheri et al. (Bagheri et al., 2013) studied mechanical properties of friction stir welded ABS sheets using tool with hot shoe design. Figure 5 shows schematic diagram of the tool. The main purpose of the tool shoulder is to trap the material displaced by the pin and to apply forging pressure to the joint as the weld cools (Strand, 2004). The heater in the hot shoe supplies additional thermal energy as frictional heating is not sufficient. The additional heating from hot shoe results in uniform cooling throughout the weld. However, the hot shoe tools provide the additional heat at the surface of the weld seam. The low thermal conductivity of workpiece leads to local melting due to this additional heat instead of heating at the bottom.

The tool designs as suggested by previous researchers improve the joint strength of polymer welds. However, these designs usually require additional apparatus apart from the tool, take up extra space near the weld surface, provide heat to a larger area outside the weld seam and might be inconvenient in space constricted situations. In this work we propose an assisted heating tool design to resolve the lack of available heat during FSW of polymers without taking up extra space. The proposed design uses a resistance heat source placed inside the tool itself to provide additional heating during joining. Supplementary electrical resistance heat for joining of thermoplastics is provided with no change in outer shape of the FSW tool. The design enables addition of extra heat at the tool-workpiece interface instead of away from the interface. The proposed tool can be used in any FSW machine with electrical connections and slightly modified connecting shaft. The welds formed using this tool design show significantly better weld finish and mechanical testing of welded samples show improved strength, and elongation under tensile loading conditions.

Tool Design

Conventional friction stir welding tools do not provide sufficient heat and the newer tool designs for FSW of polymers are cumbersome in use. We here show an assisted heating tool design that introduces electrical resistance heating along with frictional and deformational heating during FSW. Unlike some previously proposed tool designs, the current tool design does not change the tool geometry while adding to the available heat during the process. In the proposed tool design, a cylindrical blind hole of 5.5 mm diameter is drilled at the core of a conventional FSW tool. The blind hole ends just before the tool pin root. A standard resistance heating element in the form of a 5mm diameter rod is inserted in this hole to provide additional heat. The tool is connected to the pulley on the induction motor through a hollow shaft. The heating element is powered with A/C source which is connected with wired running through the hollow shaft. The wires in the hollow shaft are connected with the external power supply with a slip ring attached at the end of the shaft. The tool design is shown in Figure 6, with figure 6(a) showing the schematic of the tool and figure 6(b) showing a picture of the actual tool used.

The minor changes in the machine required to use the tool are shown in Figure 7. The resistance heating element inserted in the hollow tool needs electrical connection from the open end of the tool which is inserted in the collet. Figure 7(a) and Figure 7(b) show the machine arrangement schematic for use of the tool. A slip ring arrangement is provided for A/C connection. As shown in Figure 7 the slip ring assembly is attached to the machine with an external attachment.

A resistance heating element of 50 Watt power was used in the proposed tool for testing the effectiveness during FSW of the Polypropylene (PP) sheets. The heating element of higher power can also be used in the same design for further enhancement. The heating element of 50 watt was used in the joining of PP sheets as the heat from such element was sufficient for successfully joining PP sheets. The tool used in this study had flat bottom threaded cylindrical pin with thread pitch of 0.7 mm. The threaded pin pushes the softened material downwards and creates vertical material flow for better mixing. It also prevents the outward material flow from the weld nugget during the process. Since PP is a soft material, the thermo-mechanical environment around tool during the joining is not expected to be very severe. A tool made of mild steel is selected for the joining of PP sheets considering the expected low value of temperature and stresses.

Table 1 shows the composition of the tool material used for this study. The tool design can also be used for soft alloys with a higher power resistance heating element and tool steel as the tool material.

Materials and Method

Polypropylene (PP) sheets of dimension 150 mm × 50 mm × 3 mm were joined to test the efficiency of the assisted heating tool design. Polypropylene is a light weight engineering material that finds application due to its low cost, low thermal conductivity, and chemical inertness. The PP sheets were clamped using a stainless steel fixture to keep them in place during joining. A 4-axis FSW machine with programmable control was used for joining the plates. The machine was fitted with the hollow shaft, slip ring and the tool to test the design. The welding of the PP sheets was performed with two FSW tools with shoulder diameter 18 mm & 20 mm, respectively. The tool with 18 mm shoulder diameter was used for the preliminary trial experiments. Based on the observations from preliminary experiments a tool with 20 mm shoulder diameter was used for the FSW of PP. The tools used had a threaded cylindrical pin with pin diameter of 3.5 mm and pin length of 2.75 mm. To understand the effect of additional resistance heating the same tool is used with heating is on and heating off. All other welding parameters are kept same for the comparison in order to understand the effect of additional heating from the tool.

For the preliminary experiment the tool with shoulder diameter of 18 mm was chosen. The welding was conducted with 840 RPM tool rotation speed and 20 mm/min welding speed. One trial weld was formed without any additional heating and another one with additional heat form the electrical resistance heating element. The tensile testing of the samples from preliminary experiments revealed the improvement in tensile strength & elongation upon addition of heating during FSW. It was also observed that high rotational speed and current 18 mm shoulder diameter results in the material flow out of the weld nugget. Based on these observation, a larger shoulder diameter (20 mm) was used and the welding were performed at various tool rotational speeds (360, 540, and 720 RPM) for further testing of the tool. The larger shoulder diameter facilitated confining the material in the nugget and also distributes the heat in a larger area.

An electrical resistance heating element of 50W power is used to heat the tool during FSW. The tool is preheated to 110°C before starting the joining process with resistance heating. Tilt angle of 2° was used during both without heating and with heating processes. The nomenclature used for the welds is as follows: H_RPM or N_RPM, where H/N are for heating or Non-heating and RPM is the tool rotational speed used during welding. For example, experiment using tool heating with 720 RPM tool rotational speed is named as H_720 whereas experiment without tool heating for 720RPM tool rotational speed is named H_720.

Results and Discussion

The effectiveness of additional heating during FSW using the assisted heating tool design was tested using same tool for joining with and without the resistance heating. Since the dimensions, or any outside feature on the tool does not change by turning the resistance heating on, this should show the effect of additional heat when all other parameters are kept constant. The welded coupons for all the four welding conditions in table 2 with and without additional heating are presented in Figure 8 for visual inspection. The sample coupons shown here are without any additional surface cleaning applied on the weld surface. The welds with additional resistance heating, shown on the right, have much better finish compared to the welds without additional heat, shown on the left. The surface is much smoother, and chip formation is lesser in the welds where additional heating was provided. The joints formed using FSW without additional heat show significant material loss, chip formation, lack of fusion, and rough weld surface due to lack of heat and faster solidification. The additional heat provided by the resistance heating element in the tool is able to support proper heating of the workpiece material and leads to welds with better surface finish.

The weld cross sections were analyzed using cross-polarized light to examine the weld quality and to identify presence of any weld defects. Figure 9 shows the micrographs of the weld cross sections for the eight samples, four without additional heating and four with additional heating. The welds where additional heat was provided show continuous welds with less or no defects. However, the welds with no additional heat show voids and lack of fusion for all the tool rotational speeds considered. The absence of defects in the assisted heating welds, and the better quality of welds should lead to better weld properties upon use of assisted heating during the FSW of plastics.

The welded coupons were tested for mechanical strength and percentage elongation at fracture under tensile loading. Three test specimens were prepared from each of the welds using ASTM D638 standard test method for tensile properties of plastics. CNC milling machine was used to prepare samples with smooth surface finish and dimensional accuracy. The samples prepared according to ASTM standards were subjected to tensile loading with 1mm/min strain rate. Figure 10 show the comparison of stress-strain curves for the welded samples using various tool rotational speeds with or without additional heat during joining. The weld notification is used as explained earlier. All the stress-strain curves show that addition of heating using the tool design leads to welds which can withstand much higher stress and show much more elongation.

Figure 11 shows the comparison of ultimate tensile strength of the welded samples for various tool rotational speeds. The error bar used are calculated using standard error considering values from all the three samples used for tensile testing (Zwillinger and Kokoska, 1999). The UTS of the welds formed using additional resistance heat from tool is almost double of the UTS values for the welds without heating. The addition of resistance heat using the proposed tool design results in better weld surface finish, and significantly more weld strength. Average tensile strength obtained in the preliminary welds (840RPM) were 5.41 MPa (20.6% of base material) for without additional heating and 12.59 MPa (47.95% of base material) for weld with additional heating. The highest tensile strength obtained was 14.57 MPa (55.51 % of base material) for FSW with tool using tool rotational speed of 720 RPM with additional resistance heat.

The elongation of the samples under tensile loading before failure is shown in Figure 12 for various tool rotational speeds. The measured values of % elongation for the welds with and without additional heat during FSW are compared. The addition of heat during the process results in increase in elongation before failure for the wide range of tool rotational speeds even when the weld strength is increasing for these cases.

The comparison of the tensile strength and elongation of the welded coupon samples shows that addition of resistance heat using the tool design results in almost double strength and elongation. The increase in both weld strength and elongation can be attributed to homogenous heating, improves material mixing, and less material loss in chip formation. The tool design is capable of delivering the extra heat required to fulfil the deficit without changing the overall tool design significantly. The tool is efficiently able to deliver the additional heat required to form good weld and does not require extra space like the previously proposed designs. The proposed tool design can also be used to join other thermoplastics, or other soft materials (may be with higher heater capacity).

Conclusions

In this work, we proposed and tested an assisted heating tool design for FSW of thermoplastics. We have shown with experiments that

- The assisted heating tool design provides additional heat during FSW to result in better weld surface finish, and lowers chip formation and material loss.

- The assisted heating tool improves the tensile strength of friction stir welded polypropylene coupons by more than double for four different tool rotational speeds.
- The elongation of the friction stir welded polypropylene coupons is also improved to nearly double with this tool design.
- The design is capable of overcoming the insufficient heat which used to result in improper fusion and lack of weld formation.

Acknowledgement

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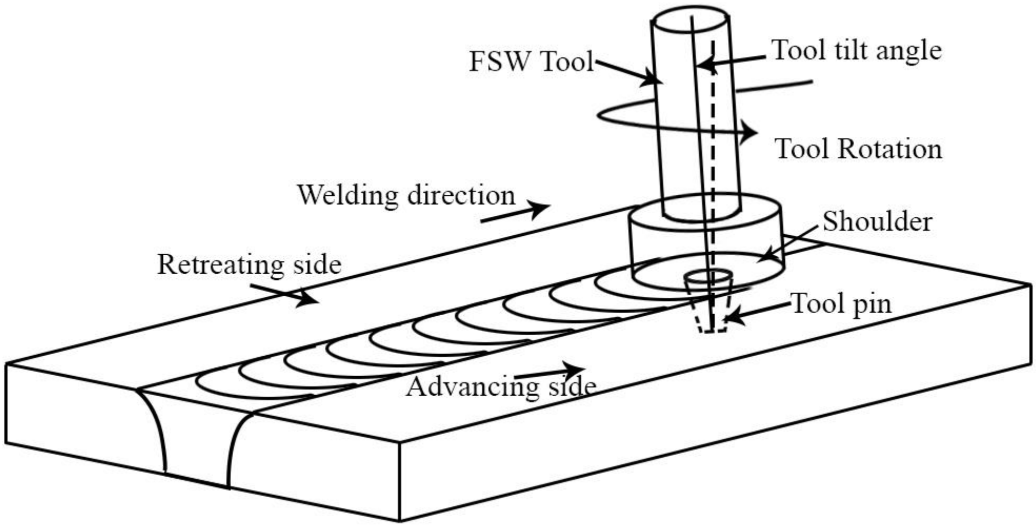

Figure 1 Schematic illustration of the friction-stir welding process (adapted from Nandan et al., 2008)

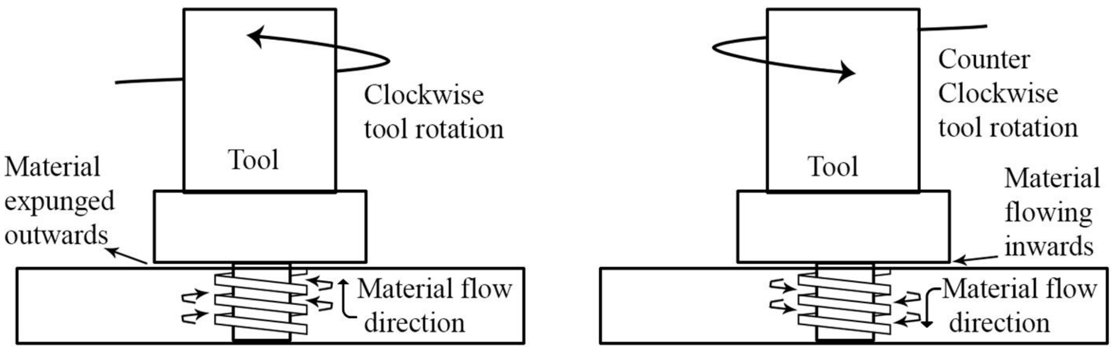

Figure 2 The effect of the tool rotation in clockwise and counter-clockwise direction on the material flow (adapted from Panneerselvam and Lenin, 2014)

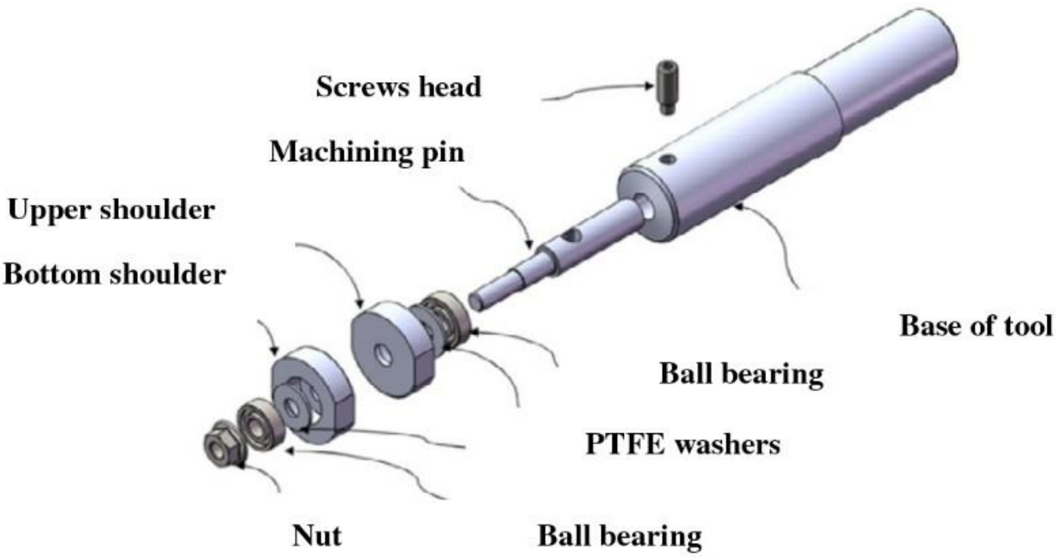

Figure 3 A self-reacting tool with non-rotating shoulder (Pirizadeh et al., 2014)

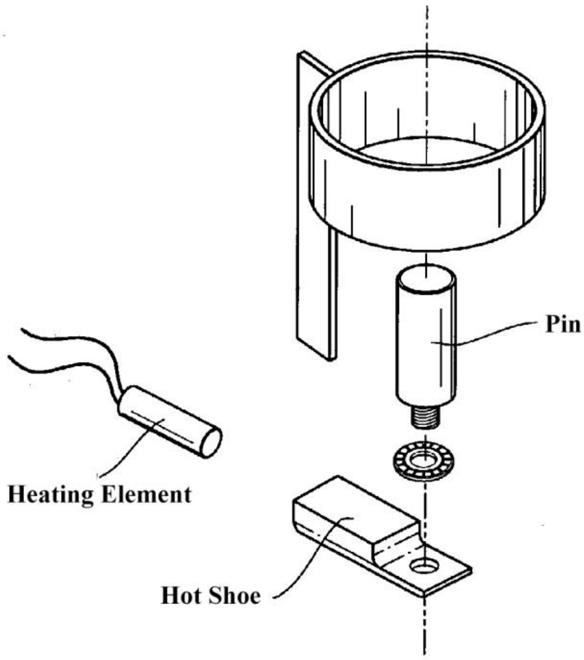

Figure 4 Patented drawing of hot shoe tool design (Nelson et al., 2004)

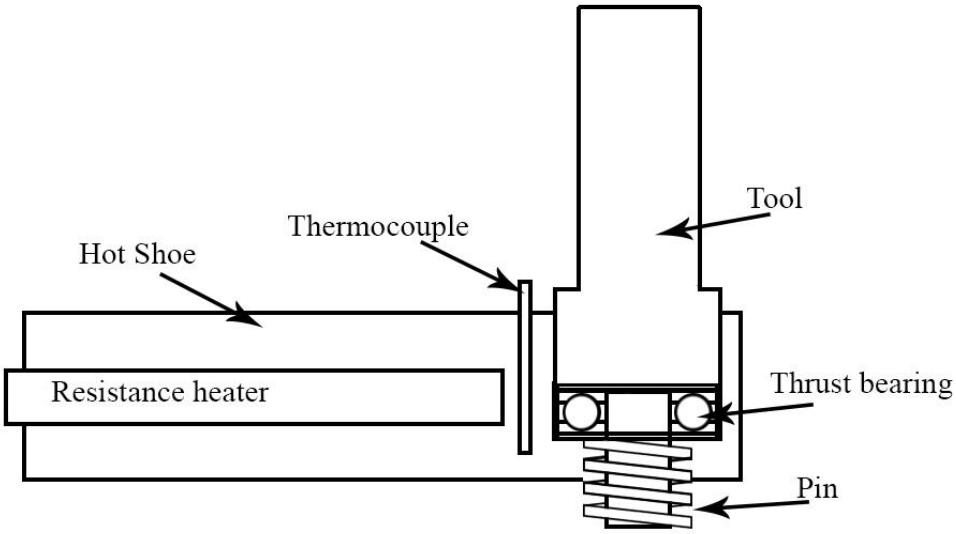

Figure 5 The schematic figure of the hot shoe tool design.(adapted from Bagheri et al., 2013)

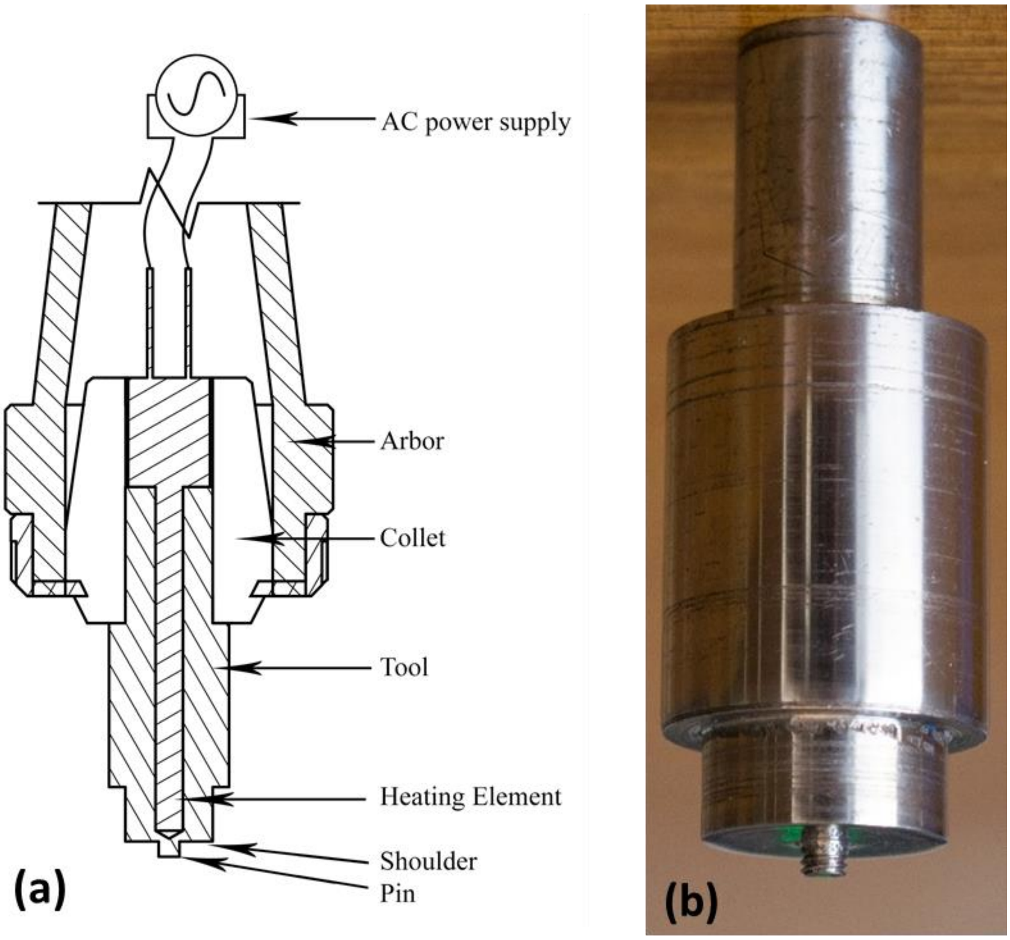

Figure 6 Schematic diagram of tool design (a) and tool with shoulder diameter 20 mm (b) photo of the tool used in the study

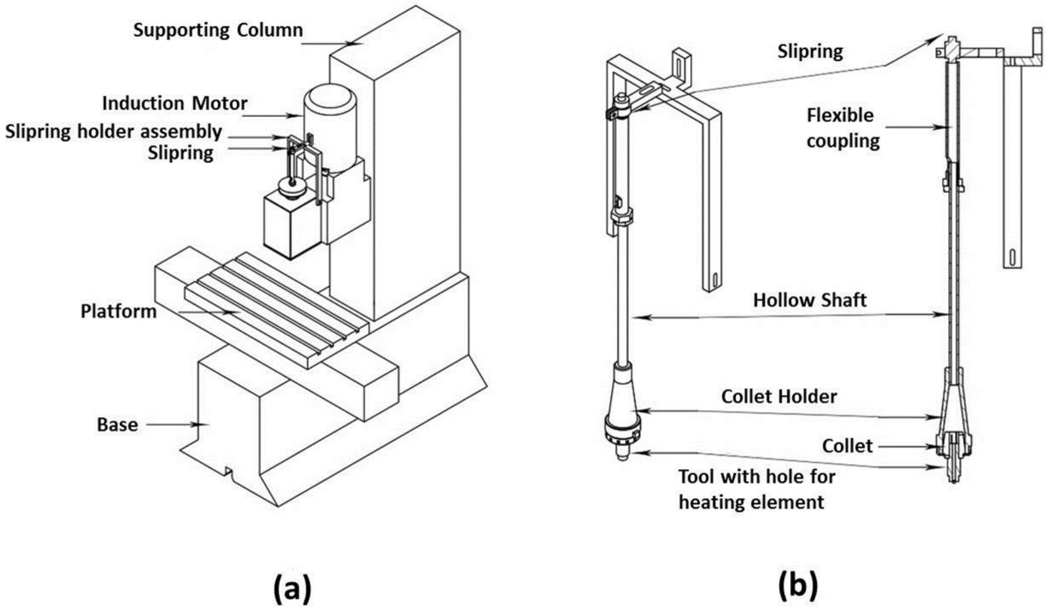

Figure 7 Schematic diagram of the (a) FSW machine and (b) tool holding assembly

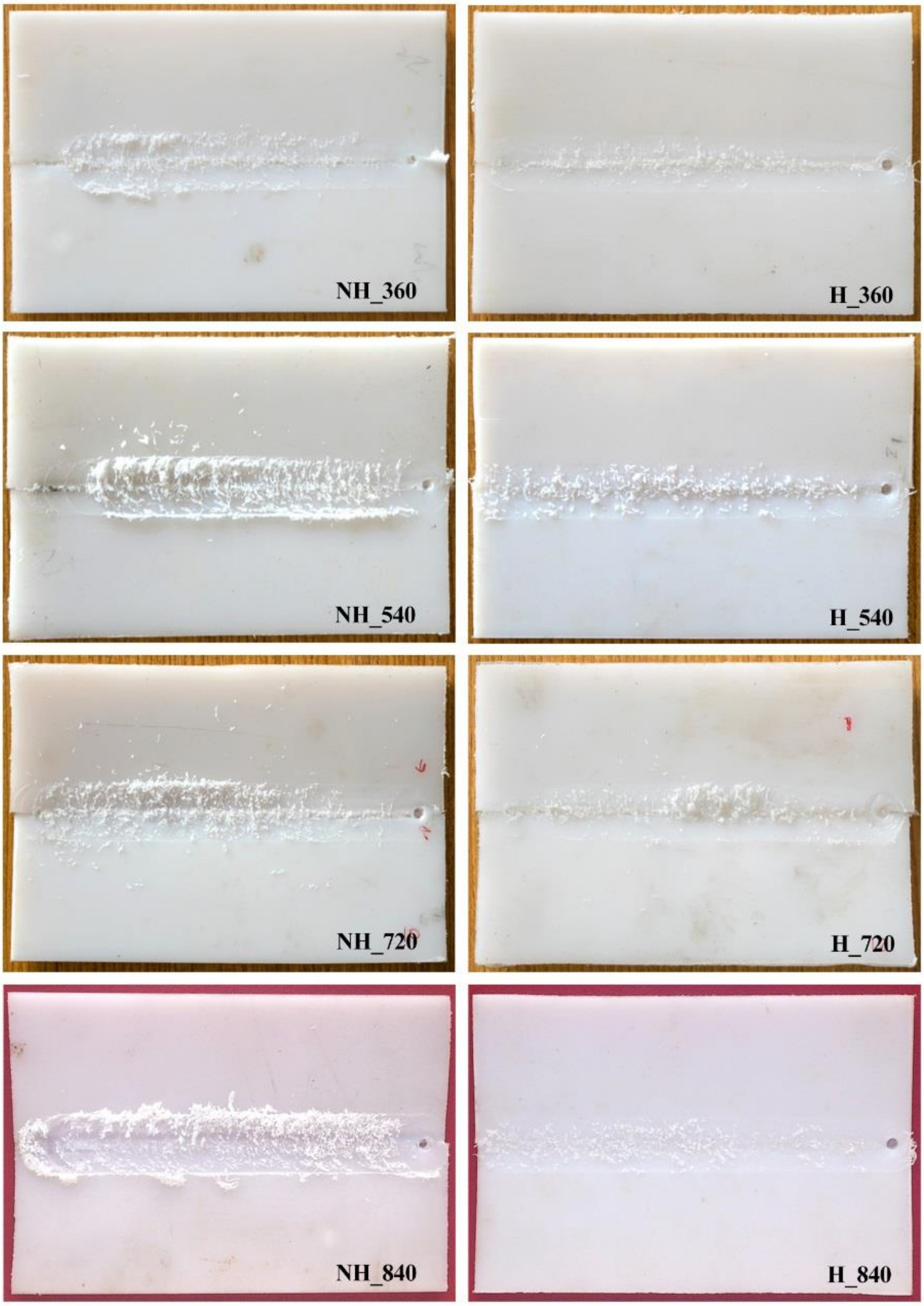

Figure 8 Welded samples joined using the tool without additional heating (NH) and with additional heating (H)

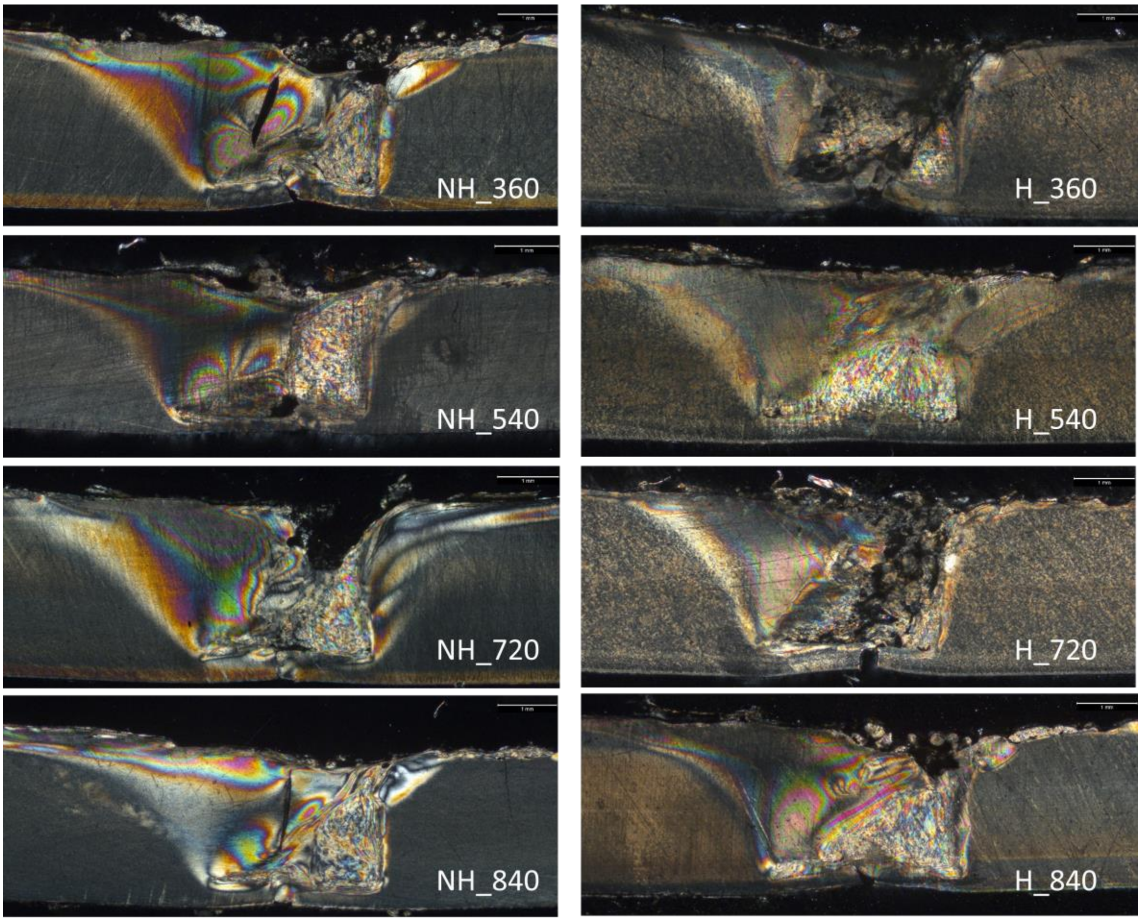

Figure 9 Weld cross sectional micrographs under cross-polarized light for samples welded with assisted heating (H) or without assisted heating (NH)

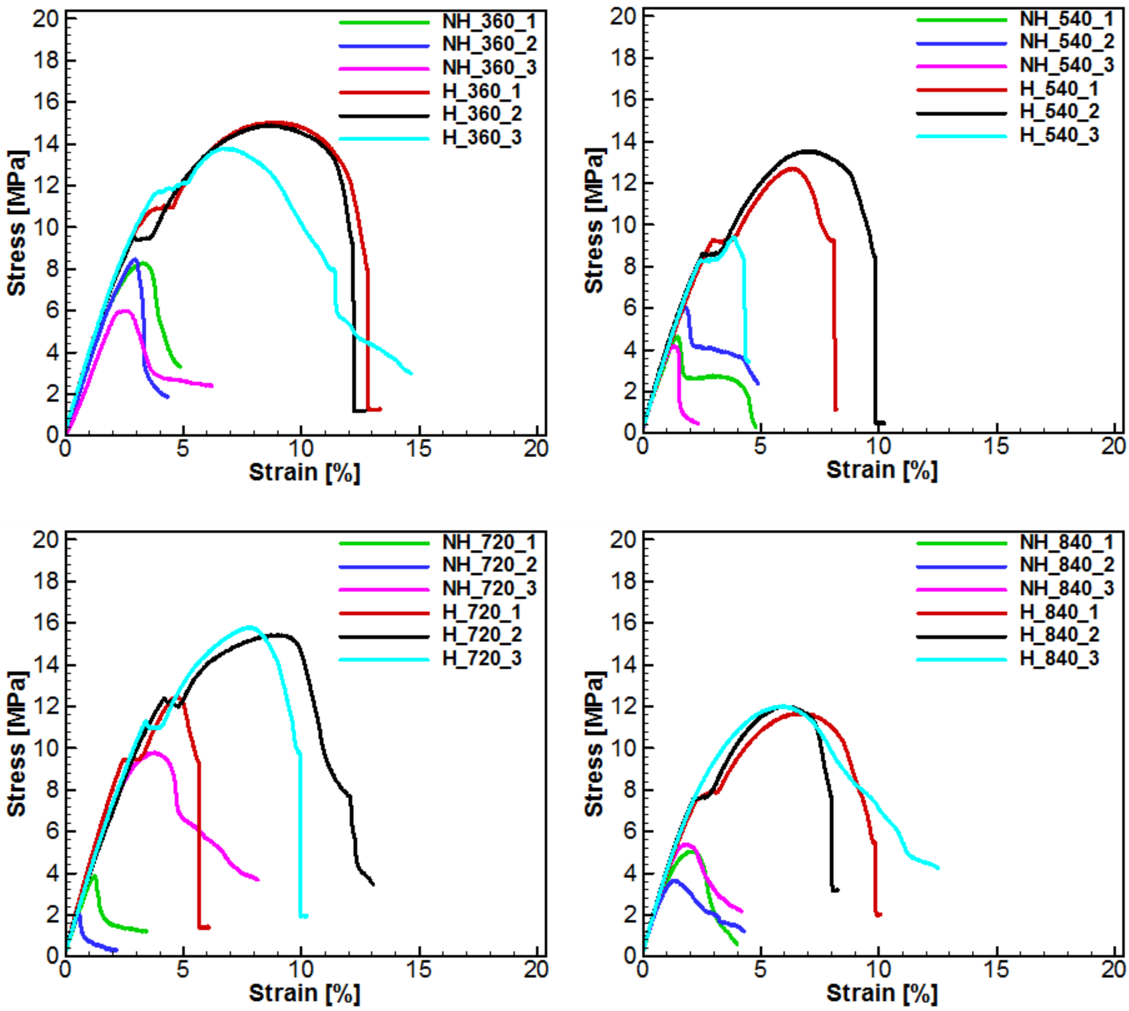

Figure 10 Comparison of stress-strain curves for both heating and non-heating welds at various tool rotational speeds

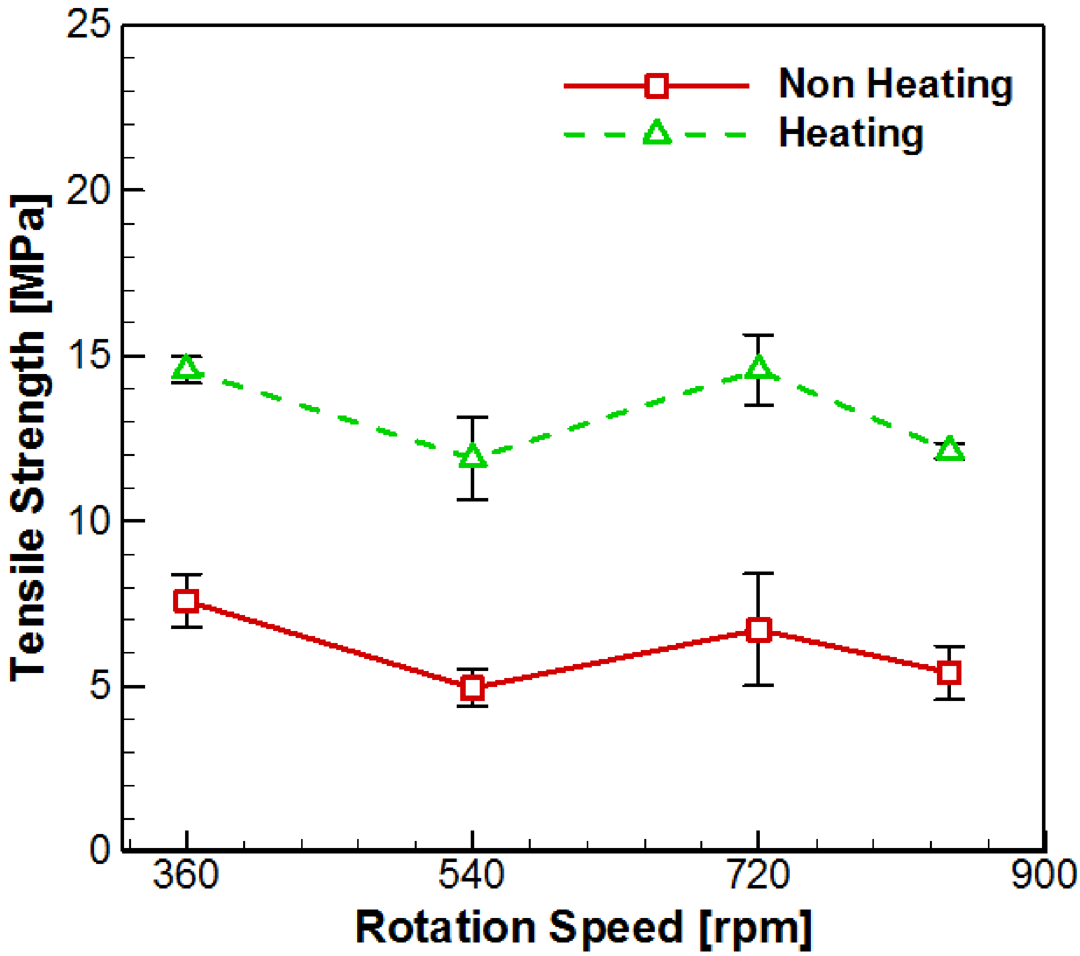

Figure 11 Comparison of Tensile Strength of welded coupons using FSW with additional heating or without for various tool rotational speeds

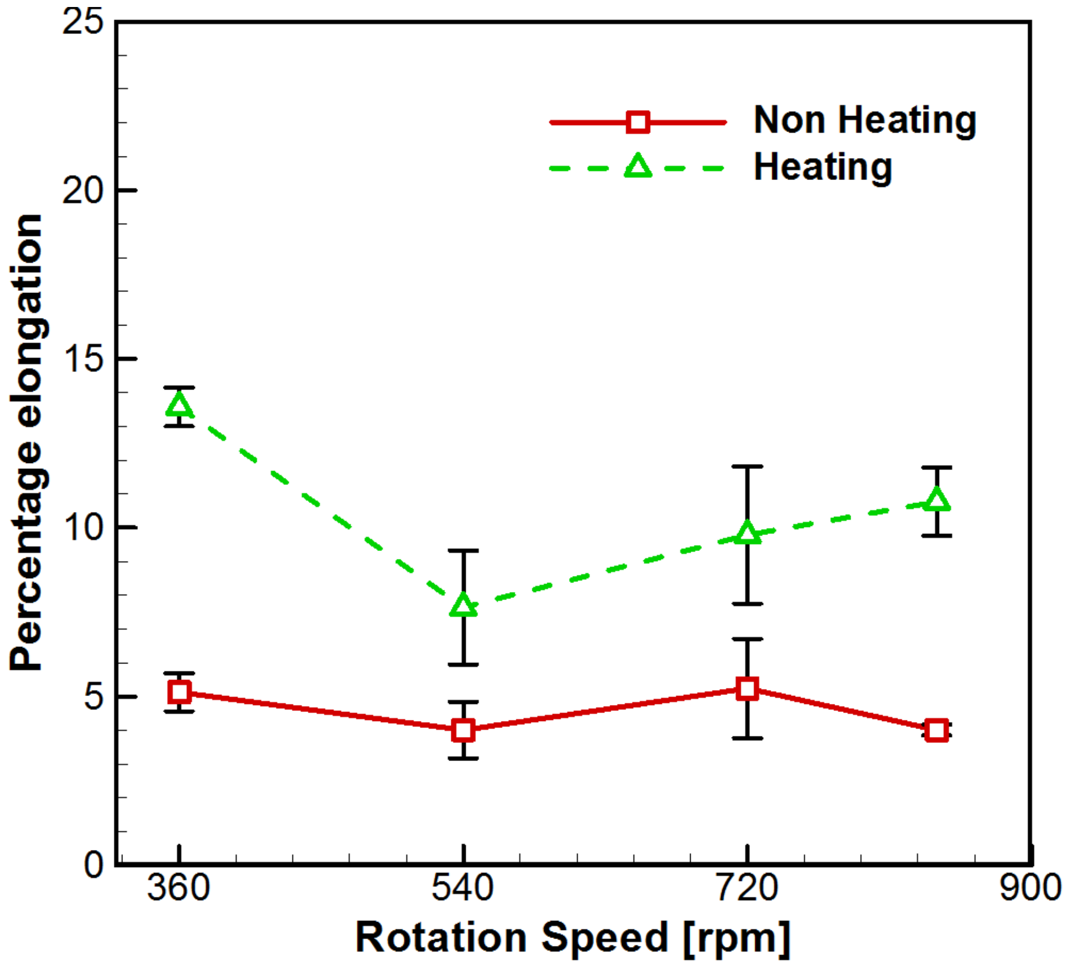

Figure 12 Comparison of percent elongation at fracture of welded coupons using FSW with additional heating or without for various tool rotational speeds

Table 1 Composition of tool material

Element	Carbon	Silicon	Manganese	Phosphorus	Sulphur
Content (%)	0.400%	0.280%	0.670%	0.037%	0.029%

Table 2 Welding Parameters

Parameter	Value
Tool rotation speed (RPM)	360, 540, 720, 840
Travel speed (mm/min)	20, 30
Shoulder diameter [mm]	18, 20
Pin diameter (mm)	3.5
Pin length (mm)	2.75
Tilt angle	2°
Thread pitch (mm)	0.7
Resistance heating element power (watt)	50