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A Method for Generating Lap Joints via Friction Stir Spot Welding on DP780 Steel

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TITLE:
Generating Lap Joints via Friction Stir Spot Welding on DP780 Steel

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SUMMARY:
Here, we present a friction stir spot welding (FSSW) protocol on dual phase 780 steel. A tool pin with high-speed rotation generates heat from friction to soften the material, and then, the pin plunges into 2 sheet joints to create the lap joint.

ABSTRACT:
Friction stir spot welding (FSSW), a derivative of friction stir welding (FSW), is a solid-state welding technique that was developed in 1991. An industry application was found in the automotive industry in 2003 for the aluminum alloy that was used in the rear doors of automobiles. Friction stir spot welding is mostly used in Al alloys to create lap joints. The benefits of friction stir spot welding include a nearly 80% melting temperature that lowers the thermal deformation welds without splashing compared to resistance spot welding. Friction stir spot welding includes 3 steps: plunging, stirring, and retraction. In the present study, other materials including high strength steel are also used in the friction stir welding method to create joints. DP780, whose traditional welding process involves the use of resistance spot welding, is one of several high strength steel materials used in the automotive industry. In this paper, DP780 was used for friction stir spot welding, and its microstructure and microhardness were measured. The microstructure data showed that there was a fusion zone with fine grain and a heat effect zone with island martensite. The microhardness results indicated that the center zone exhibited a greater degree of hardness compared with the base metal. All data indicated that the friction stir spot welding used in dual phase steel 780 can create a good lap joint. In the future, friction stir spot welding can be used in high-strength steel welding applied in industrial manufacturing processes.

INTRODUCTION:

Friction stir welding (FSW) was first reported in 1991 at TWI, Abington, UK[1]. In 2003, Piccini and Svoboda determined a superior method of enhancing the advantages of FSW called friction stir spot welding (FSSW) for use in commercial automobile manufacturing processes[2]. The FSSW method involves creating a spot lap joint with no bulk area melting. The most important development for the use of FSSW has been in aluminum alloys as Al alloys deform in the welding process under high temperature conditions. The first successful example was in the automotive industry, where FSSW was used in manufacturing the entire rear door of the Mazda's RX-8[1,3,4].

Meanwhile, high strength steel is the dominant material of the car body, specifically dual phase steel. The literature indicates that DP600 produced with FSSW can have the same properties as the base metal, where all welding regions have similar microstructures and degrees of hardness[5]. FSSW methods for the use of DP steel on their microstructure of the stir zone (SZ), the thermos-mechanically affected zone (TMAZ), and the failure model of DP590 and DP600 steel have been studied by a few researchers. They observed differences in the consistency of the microstructure (ferrite, bainite, and martensite) of DP590 and DP600 steel at various rotation speeds[6-10]. Some researchers conducted comparative studies of FSSW and RSW for DP780 steel[8,9]. They reported that longer joining times and higher tool rotation speeds resulted in an increased bonding area for all plunges, which led to a higher shear force and shifted the mode from interfacial to pull out. They also concluded that FSSW had a higher strength than RSW. The FSSW process includes 3 steps: plunging, stirring, and retraction. The first step is plunging with a rotation tool pin close to the sheet of the lap joint and plugged into the sheet. The rotating tool shoulder in the FSSW process can generate frictional heat. In the second step, the heat can soften the sheet and facilitate plugging of the tool pin into the sheet, as well as dwell in the materials to stir two workpieces together and mix around the pin area. Finally, the pressure from the tool shoulder press on the workpieces can enhance the bonding. After the welding process, the pin can be retracted from the keyhole. The benefits of FSSW compared with RSW are a lower welding temperature, no splashing, and more stability in the manufacturing process.

Even though studies on the FSSW of advanced high-strength steels (AHSS) have been reported by various researchers, studies on the FSSW of DP590, DP600, and DP780 have focused on the microstructure and on the mechanical and failure models using various process parameters. In the present study, the FSSW of DP780 steel was considered. The protocol of the FSSW process was reported in detail, and the individual hardness in the stir zone, the thermos-mechanically affected zone, and the heat-affected zone, as well as the base metal were evaluated based on the measured microhardness.

With the continuous growth and heavy demand for weight reduction in the automotive and aerospace industries, the automotive industry has shown an increasing interest in AHSS and lap joints. For example, the conventional steel body of a car, on average, has more than 2,000 spot weld lap joints[11]. There are 3 common welding processes for lap joints used in the industry, including resistance spot welding, laser spot welding, and friction spot welding[12]. One way to decrease the weight is by using advanced high-strength steels (AHSS). The most popular materials are dual-phase and transformation-induced plasticity (TRIP) steels, which are being increasingly used in the automotive industry[13-16]. Because the automotive industry has increased the strength standards due to improved fuel consumption and crash energy absorption under a decreased vehicle weight, the use of different materials and welding processes is becoming an important issue.

PROTOCOL:

1. Material preparation

NOTE: Machine the 1.6 mm thick DP780 sheets into 40 mm x 125 mm coupons. The FSSW joints are designed as lap shear specimens for the mechanical tests. Join two 125 mm by 40 mm sheets with a 35 mm by 40 mm overlap following RSW standard NF ISO 18278-2; 2005. A geometry design polycrystalline diamond tool with a truncated cone shoulder. The geometry design is shown in **Figure 1a**. The diameter of the pin is 5 mm; the length is 2.5 mm, and the shoulder width is 10 mm. The real tool pin is shown in **Figure 1b**.

1.1. Safety guidelines

1.1.1. Use devices such as a hood or baffle, goggles, and gloves for protection.

1.1.2. Stand behind the hood or the baffle. Wear goggles and gloves to prevent splash contact or heat damage.

1.2. FSSW machine setting

1.2.1. Manufacture all joints using an MIRDC-made friction stir welder machine.

1.2.2. Record the Z axial force and penetration depth during each joining operation using the embedded data acquisition (DAQ) system.

1.3. Parameter settings

1.3.1. In this study, use the following parameters: a tool pin rotation speed of 2,500 rpm, 4 s of tool pin dwell time, and a rate pf 0.5 mm/s of tool pin plunge into the sheet.

1.3.2. Optimize the parameters for the operator. The range of the rotation speed is 1,000-2,500 rpm. The range of the dwell time can be from 2-10 s, and the plunge rate can be 0.1-0.5 mm/s.

2. Procedure

NOTE: The work space is shown in **Figure 2**. All the manufacturing procedures are completed in the work space. Before the procedure, the welding process sequences are comprised of a combination of tool rotations and penetration depths, as well as a series of sequences including preheating, plunging, dwelling, retracting, and post heating. All steps are shown in **Figure 3** in the form of a work flowchart.

2.1. DP780 workpiece preparation

2.1.1. Before the welding process, ensure that there are no impurity substrates contaminating the workpieces. Use knitted micro-fiber fabrics to wipe the surface of the workpiece to eliminate any small particles.

2.2. Place the DP780 workpiece, and clamp 2 DP780 sheets (size: 125 mm x 40 mm) with an overlap of 35 mm. Fix the clean workpieces on an anvil to prevent shifting.

2.3. Ensure that the pin is clean to prevent impure substrate contamination. Use knitted microfiber fabrics to wipe the surface of the tool pin to eliminate small particles.

2.4. Fix the pin with a clamp on the machine.

2.4.1. Screw on the tool pin tightly again for tool pin clamping.

2.4.2. Pay attention to the pin clamping step. Ensure that the pin is clamped tight in the machine to avoid danger. The rotating tool is surrounded by a nonrotating clamping ring with which the workpieces are pressed firmly against one another before and during welding by applying a clamping force. The illustration shown in **Figure 3a** notes the clamp ring used to fix the tool pin. After this step, the production is shown in the flowchart.

2.4.2 Ensure safety.

2.4.3. Confirm that the high-speed rotation pin without a clamp ring loosens. When the tool pin is placed on the machine, ensure that the tool pin does not separate from the clamp during rotation for safety reasons. The tool pin uses a low rotation rate from 10 to 100 rpm in 1 minute. The speed can accelerate from 100 to 1,000 rpm within 1 minute (**Figure 3b**).

2.5. Machine settings

2.5.1. Use the following parameters: a rotational speed of 3,000 rpm, a dwell of 4 s, and a plunge rate of 0.5 mm/s (**Figure 3c**).

2.6. Calibrate the welding location (**Figure 3d** and the real product shown in **Figure 4a**).

2.6.1. Set the pin in the stir spot welder machine. The gap between the pin and the workpiece is smaller than 5 cm to calibrate the joint location. After the location is confirmed, move onto the welding process.

2.7. During welding, wear goggles and gloves to avoid injury.

2.7.1. Begin the welding process with the tool under high-speed rotation to plunge the tool pin into the workpiece. The tool shoulder contacts the workpieces and stops the rotation and retracts the pin.

2.8. Plunging

2.8.1. Turn the stir button on. When the machine warms up, confirm that the tool pin is consistently operating at a 2,500 rpm rotation speed. Ensure that the tool pin is clamped well under the high-speed rotation at 2,500 rpm. The pin plunges into the workpieces under a high-speed rotation and the shoulder contacts the workpieces at a high angular speed (**Figure 3e**). The real product is shown in **Figure 4b**.

2.9. Stirring

2.9.1. As the plunged tool pin continues stirring in the workpiece, soften the interface of the pin and the material from the friction heat to create the grain. When the shoulder of the tool pin comes into contact with the top of the workpiece, stop the process because the high rotation of the tool pin can generate high temperatures. It is important to wear protective gear that ensures operational safety (see **Figure 3f**.) The real product is shown in **Figure 4c**.

2.10. Retracting

2.10.1. Draw out the tool pin in the vertical direction. After the procedure, the pin creates the key-hole welding spot in the lap joint. Note that the friction stir spot weld stops in this step (**Figure 3g**). The real product is shown in **Figure 4e**.

2.11. Remove the workpieces.

2.11.1. Turn off the machine power.

2.11.2. After the welding is finished, remove the workpieces from the anvil. Observe the samples for cracks and lack of fusion.

2.11.3. Remove the tool pin.

2.11.4. After the procedure, remove the tool pin from the clamp ring. The appearance of the tool pin is observed and checked (**Figure 5**).

3. Mechanical property evaluation

3.1. Microscopy examination of the FSSW welds (**Figure 3h**)

3.1.1. Microscopic sample preparation

3.1.2. Measure the cross-sectional area of the bonded region using an optical microscope image and a secondary electron image analysis. Prepare the microscopic samples using grounded silicon carbide paper with a grit size ranging from 200 to 2,000 starting with a grit size of 200 and increasing in sequence. Polish the samples with 0.03% alumina and etch with a 4% nital solution for 7–10 s at room temperature.

3.1.3. Microscopy observation

3.1.4. Observe and characterize the microstructures using optical microscopy and scanning electron microscopy. Use a voltage of 20 kV, and a working distance of 10 µm. From the optical microscopy, any tiny crack line or lack of a fusion zone can be determined. Use scanning electron microscopy to analyze the martensite and austenite distribution and the grain size.

3.2. Microhardness

3.2.1. Verify the microhardness experiments more than 3 times. The values were too small to clearly denote the standard deviation.

3.2.2. Press the Vickers diamond indenter with a 300 g test load sample and 0.5 mm per test.

3.2.3. Conduct the microhardness testing of the DP780 steel sheet using a microhardness testing machine with a 300 g load and a holding time of 15 s. The microhardness testing revealed the hardness distribution and the individual hardness values in the stir zone, the thermomechanical affect zone, the heat affected zone, and in the base metal of the welds.

REPRESENTATIVE RESULTS:

There is a diagram in **Figure 3** that demonstrates that the friction stir spot welding process is comprised of 3 parts: plunging (**Figure 3e**), stirring (**Figure 3f**), and retracting (**Figure 3g**). In our research, the welding spot could be generated. The penetration depth is one factor that was evaluated. In **Figure 6a**, the FSSW creates the keyhole in the center to create the joint for 2 sheets. The measurement depth of the keyhole is from the sheet top to the keyhole bottom surface (**Figure 6b**). The measurement values are shown in **Figure 6c**, for which the setting values are 2 cm and the real values are 1.92 to 1.98 cm. In **Figure 7**, the image shows the key-hole overall view of the welding spot in the DP780 sheet. The analysis of the base metal microstructure showed martensite islands in a ferrite matrix (**Figure 8a**). The microstructures of the TMAZ near the keyhole show a mixture of needle-like martensite and fine acicular ferrite (**Figure 8b**,**c**). The stir region around the keyhole revealed a fine grain martensite and porosity (**Figure 8d**).

Hsu et al.[25] studied the hardness of a base metal compared with the original material property. In the HAZ intercritical region, the hardness value was found to be in a range of approximately 310 to 330 Hv. The hardness of TMAZ was approximately 360 Hv. The hardness in the stir zone of friction stir spot welds is significantly higher than in other regions; the values were found to be 370 Hv (**Figure 9**, modified from Hsu et al.[25]). If the welding process is not successful, there will be some cracks and a lack of fusion in the weld zone.

FIGURE AND TABLE LEGENDS:

Figure 1. A diagram of the tool pin.
(a) The size and geometry of the tool pin (**b**) the actual tool pin

Figure 2. A diagram to demonstrate the work space.

Figure 3. A flowchart to illustrate the friction stir spot welding process.
(a) clamp pin (b) safety confirmed (c) machine setting confirmed (d) calibration (e) plunging (**f**) stirring (**g**) retracting (**h**) validation of the mechanical properties of the joints

Figure 4. The welding process. (**a**) calibration (**b**) plunging (**c**) stirring (**d**) retracting

Figure 5. **A diagram showing the used pin.** The pins are consumed at high temperatures.

Figure 6. Confirmation of the dwell depth using a comparison of the settings.
(**a**) The macro view of the FSSW creating the keyhole. (**b**) A diagram illustrating where the depths are measured (**c**) The dwell depths are set at 2 cm. The actual measurement values range from 1.92 to 1.98 cm.

Figure 7. An overall view of the friction stir spot welding. The analyzed area contained 4 parts: (I) base metal (II) HAZ (III) TMAZ, and (IV) the stir zone.

Figure 8. The microstructure composition of the joint created using FSSW. (**a**) base metal: the base metal of the workpieces is comprised of DP 780 sheets. The base metal shows no change in material properties (**b**) HAZ: the thermal cycle around the welding site with heat transfer. HAZ zone shows the martensite islands. (**c**) TMAZ: thermomechanically affected zone around the stir zone. The needle-like martensite and fine acicular ferrite shown in the TMAZ zone. (**d**) Stir zone: the pin hole created in the welding process with the formation of recrystallization grains. Fine grain smaller than 10 µm appeared in the stir zone.

Figure 9. The microhardness values of the workpiece examined using a Vickers test machine with a loading weight of 300 g was held for 15 s. This figure was modified from Hsu et al.[25].

DISCUSSION:

The plunging stage is the most important during the FSSW process. Without enough friction heat coming from the shoulder of the pin to soften the workpiece, the pin will fracture. Tool geometry, rotation speed, dwell time, and tool penetration depth[26] parameters of the FSSW process play a critical role in determining the joint integrity. TPD and tool geometry[27] particularly have an important effect on the weldability and joint properties was reported.

The geometry of the pins were cylindrical, Whorl, MX Triflute, Flared-Triflute, A-skew, and Re-stir designed by TWI[28]. They are suitable for butt welding but not for lap welding because the tool motion and the welding torque can be reduced by the traversing force caused by the intense stirring. Flared-Triflute, A-skew, and Re-stir tool pins are suitable for lap welding; the design is intended to increase the swept volume of the pin in order to expand the stir region to form a wider worked lap joint[29]. Meanwhile, during FSSW, friction generates heat at the interface of the rotating tool and the work piece. The tool geometry and FSSW parameters affect the strength of the FSSW welds[4]. The tool shoulder and pin are the main parts of the FSSW tool[5]. The pin generates friction heat, deforms the material around it, and stirs the heated material[6]. The size[7], angle[8], thread orientation[9], length[10] and profile[11] of the pin depends on nugget formation. Meanwhile the tool shoulder generates heat during the FSSW process, forges the heated material, prevents material expulsion, and assists material movement around the tool[12]. The size and concavity of the shoulder are also important factors in friction stir spot welding[13].

The pin materials are comprised of the following components: 12% Cr steel, low carbon steel, Mo and W alloy, W alloy, polycrystalline cubic boron nitride (PCBN), and polycrystalline cubic boron. Because tool wear occurred in the plunging period at the initial stage of welding, tool deformation and rubbing wear could be found in the tool. This problem can be resolved by choosing a suitable material for the pin that is hard and can withstand elevated temperatures compared to the workpieces for increasing the tool lifetime. In our research, we used the polycrystal diamond to weld the workpiece.

The pin length and the penetration depth are also factors that can influence the maximum loading in the welding process. It has been indicated that there will be an increased tool penetration depth and decreased pin length, resulting in a higher[2].

The rotation rate is an important factor that leads to pin friction on the workpieces to begin the welding process. A speed ranging from 300-1,000 rpm can be used to detect the peak temperature from approximately 430 to 470 °C in the welding center zone. Far from the welding zone, the heat effect zone exhibited a decrease in temperature to 350 °C for the Al alloy (6061Al-T6)[30]. From other references, the friction situation at a low rotation speed with a stick can transform to a stick/slip at high speeds. The rotation rate is the key factor leading to the generation of the heat necessary to forge the workpiece. In the past, studies have been focused on Al alloy. However, in our study, the focus is on DP steel. There is no test value by which to identify the temperature. However, based on the fact that the microstructure at the centerline exhibited fine grain martensite, it can be inferred that the substrate temperature exceeded the Ac3 standard.

The study of FSSW workpieces in the past has concentrated on aluminum alloys because low melting temperature in metal welding leads to deformities and low strength that require being fixed via FSSW. Since the FSSW was developed, different materials have been used, including lightweight steel. Different kinds of DP steel welded with Al alloys are new areas for investigation. Based on commercial applications, the FSSW can be a useful method for different component alloys used in industrial production due to savings in terms of both time and cost.

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DISCLOSURES:
The authors have nothing to disclose.

REFERENCES:
1 Mazda. Mazda Develops World's First Aluminum Joining Technology Using Friction Heat, <http://www.mazda.com./publicity/release/200302/0227e.htm.> (2003).
2 Piccini, J. M., Svoboda, H. G. Effect of pin length on Friction Stir Spot Welding (FSSW) of dissimilar Aluminum-steel joints. *Procedia Materials Science.* **9**, 504-513, doi:10.1016/j.mspro.2015.05.023 (2015).
3 Iwashita, T. Method and Apparatus for joining. USA patent US6601751B2 (2003).
4 Allen, C. D., Arbegast, W. J. Evaluation of Friction Spot Welds in Aluminium Alloys. *SAE Technical.* No 2005-2001-1252 (2005).
5 Feng, Z., et al. Friction Stir Spot Welding of Advanced HighStrength Steels - a Feasibility Study. SAE 2005 Congress, SAE-International, Detroit, MI, Technical Paper No 2005-2001-1248 (2005).
6 Miles, M. P., Nelson, T. W., Steel, R., Olsen, E., Gallagher, M. Effect of friction stir welding conditions on properties and microstructures of high strength automotive steel. *Science and Technology of Welding and Joining.* **14** (3), 228-232 (2009).
7 Feng, Z. et al. Friction stir spot welding of advanced high-Strength steels-a feasibility study. *SAE Technical Paper Series 2005-01-1248* (2005).
8 Santella, M., Hovanski, Y., Frederick, A., Grant, G., Dahl, M. Friction stir spot welding of DP780 carbon steel. *Science and Technology of Welding and Joining.* **15** (4), 271-278 (2010).
9 Saunders, N. et al. Joint strength in high speed friction stir spot welded DP 980 steel. *International Journal of Precision Engineering and Manufacturing.* **15** (5), 841-848 (2014).
10 Khan, M. I. et al. Resistance and friction stir spot welding of DP600: a comparative study. *Science and Technology of Welding and Joining.* **12** (2), 175-182 (2007).
11 Sarkar, R., Sengupta, S., Pal, T. K., Shome, M. Microstructure and Mechanical Properties of Friction Stir Spot-Welded IF/DP Dissimilar Steel Joints. *Metallurgical and Materials Transactions A.* **46** (11), 5182-5200 (2015).

12 Yang, X. W., Fu, T., Li, W. Y. Friction Stir Spot Welding: A Review on Joint Macro- and Microstructure, Property, and Process Modelling. *Advances in Materials Science and Engineering.* **2014,** 11 (2014).

13 Esther T.A., Stephen, A.A. Trends in Welding Research 2012: Proceedings of the 9th International Conference. *Materials Characterisation of Friction Stir Processed 6082 Aluminum Alloy*. Edited by Tarasankar DebRoy et al., 548-551, ASM Press. Chicago, IL (2012).

14 Ghosh, P. K. et al. Influence of Weld Thermal Cycle on Properties of Flash Butt Welded Mn-Cr-Mo Dual Phase Steel. *ISIJ International.* **33** (7), 807-815 (1993).

15 Schultz R. A. Metallic materials trends for north American light vehicles. Power point presentation of great designs in steel *Semina, American Iron and Steel Institute*, Michigan, US (2007).

16 Horvath, C. Material challenges facing the automotive and steel industries from globalization. Power point presentation of great designs in steel *Semina, American Iron and Steel Institute*, Michigan, US (2007)

17 Pouranvari, M., Marashi, S. P. H. Critical review of automotive steels spot welding: process, structure and properties. *Science and Technology of Welding and Joining.* **18** (5), 361-403 (2013).

18 Khan, M. S. et al. Welding behaviour, microstructure and mechanical properties of dissimilar resistance spot welds between galvannealed HSLA350 and DP600 steels. *Science and Technology of Welding and Joining.* **14** (7), 616-625 (2009).

19 Ma, C. et al. Microstructure and fracture characteristics of spot-welded DP600 steel. *Materials Science and Engineering: A.* **485** (1), 334-346 (2008).

20 Hilditch, T. B., Speer, J. G., Matlock, D. K. Effect of susceptibility to interfacial fracture on fatigue properties of spot-welded high strength sheet steel. *Materials & Design.* **28** (10), 2566-2576 (2007).

21 Yan, B., Zhu, H., Lalam, S. H., Baczkowski, S., Coon, T. Spot Weld Fatigue of Dual Phase Steels. *SAE Technical Paper Series 2004-01-0511* (2004).

22 Wilson, R. B., Fine, T. E. Fatigue behavior of spot welded high strength joints. *SAE Technical Paper Series 1981-02-01* (1981).

23 Sun, X., Stephens, E. V., Khaleel, M. A. Effects of fusion zone size and failure mode on peak load and energy absorption of advanced high strength steel spot welds under lap shear loading conditions. *Engineering Failure Analysis.* **15** (4), 356-367 (2008).

24 Pouranvari, M., Mousavizadeh, S. M., Marashi, S. P. H., Goodarzi, M., Ghorbani, M. Influence of fusion zone size and failure mode on mechanical performance of dissimilar resistance spot welds of AISI 1008 low carbon steel and DP600 advanced high strength steel. *Materials & Design.* **32** (3), 1390-1398 (2011).

25 Hsu, T.-I., Wu, L.-T., Tsai, M.-H. Resistance and friction stir spot welding of dual-phase (DP 780)—a comparative study. *The International Journal of Advanced Manufacturing Technology* (2018).

26 Piccini., J. M., Svoboda, H. G. Effect of the tool penetration depth in Friction Stir Spot Welding (FSSW) of dissimilar aluminum alloys. *Procedia Materials Science.* **8**, 868-877 (2015).

27 Aissani, M., Gachi, S., Boubenider, F., Benkedda, Y. Design and Optimization of Friction Stir Welding Tool. *Materials and Manufacturing Processes.* **25** (11), 1199-1205 (2010).

28 Zhang, Y. N., Cao, X., Larose, S., Wanjara, P. Review of tools for friction stir welding and processing. *Canadian Metallurgical Quarterly.* **51** (3), 250-261 (2013).

29 Nandan, R., DebRoy, T., Bhadeshia, H. K. D. H. Recent advances in friction-stir welding – Process, weldment structure and properties. *Progress in Materials Science.* **53** (6), 980-1023 (2008).

30 Tang, W., Guo, X., McClure, J., Murr, L., Nunes, A. C. *Heat Input and Temperature Distribution in Friction Stir Welding*. **7** (1998).

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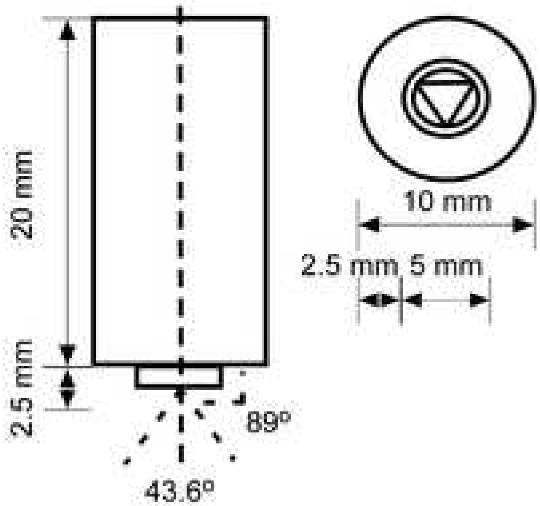
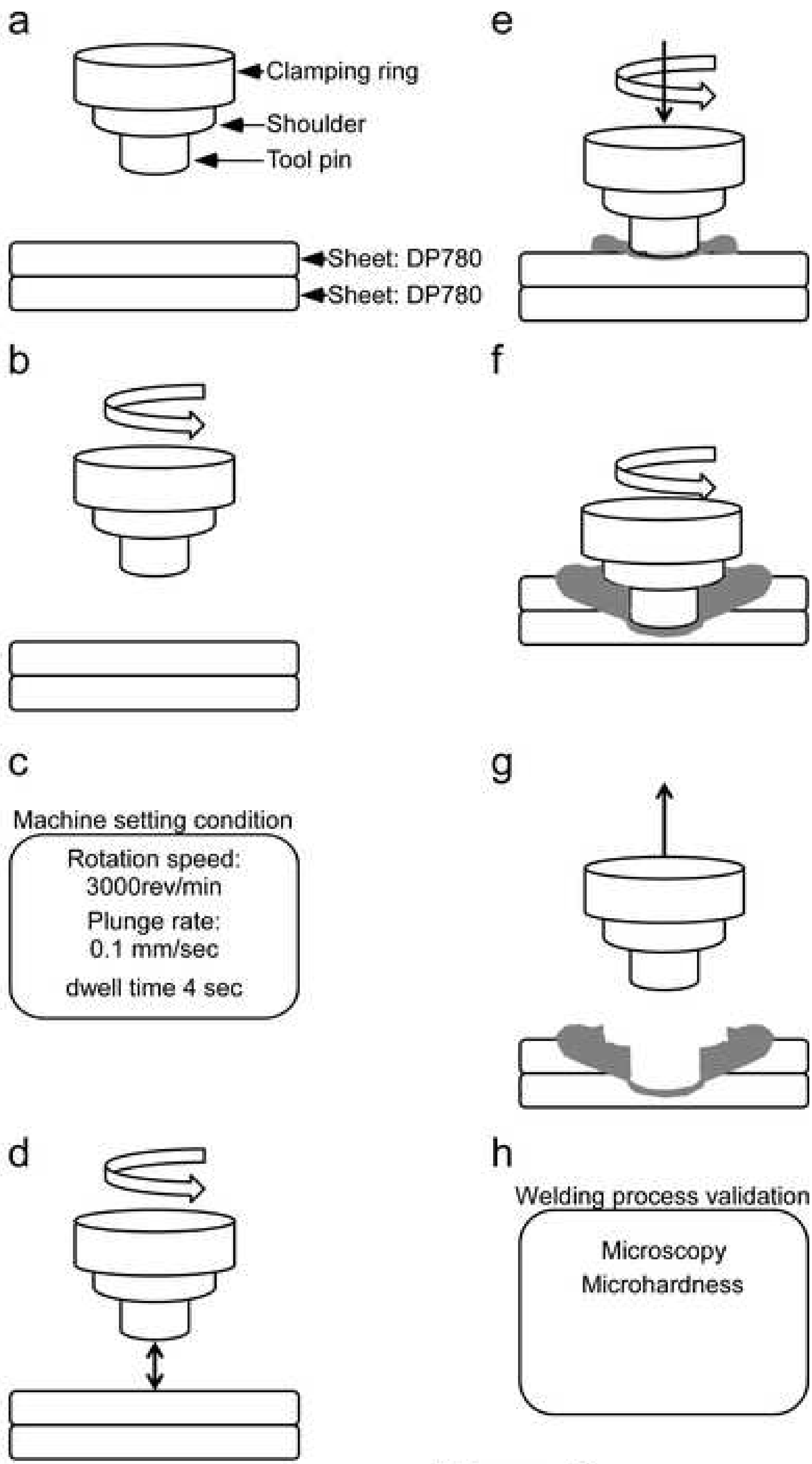


b

Figure 1

a

Figure 2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Clamping ring
Shoulder
Tool pin
Sheet: DP780
Sheet: DP780
b
c
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dwell time 4 sec
d
e
f
g
h
Welding process validation
Microscopy
Microhardness

Figure 3

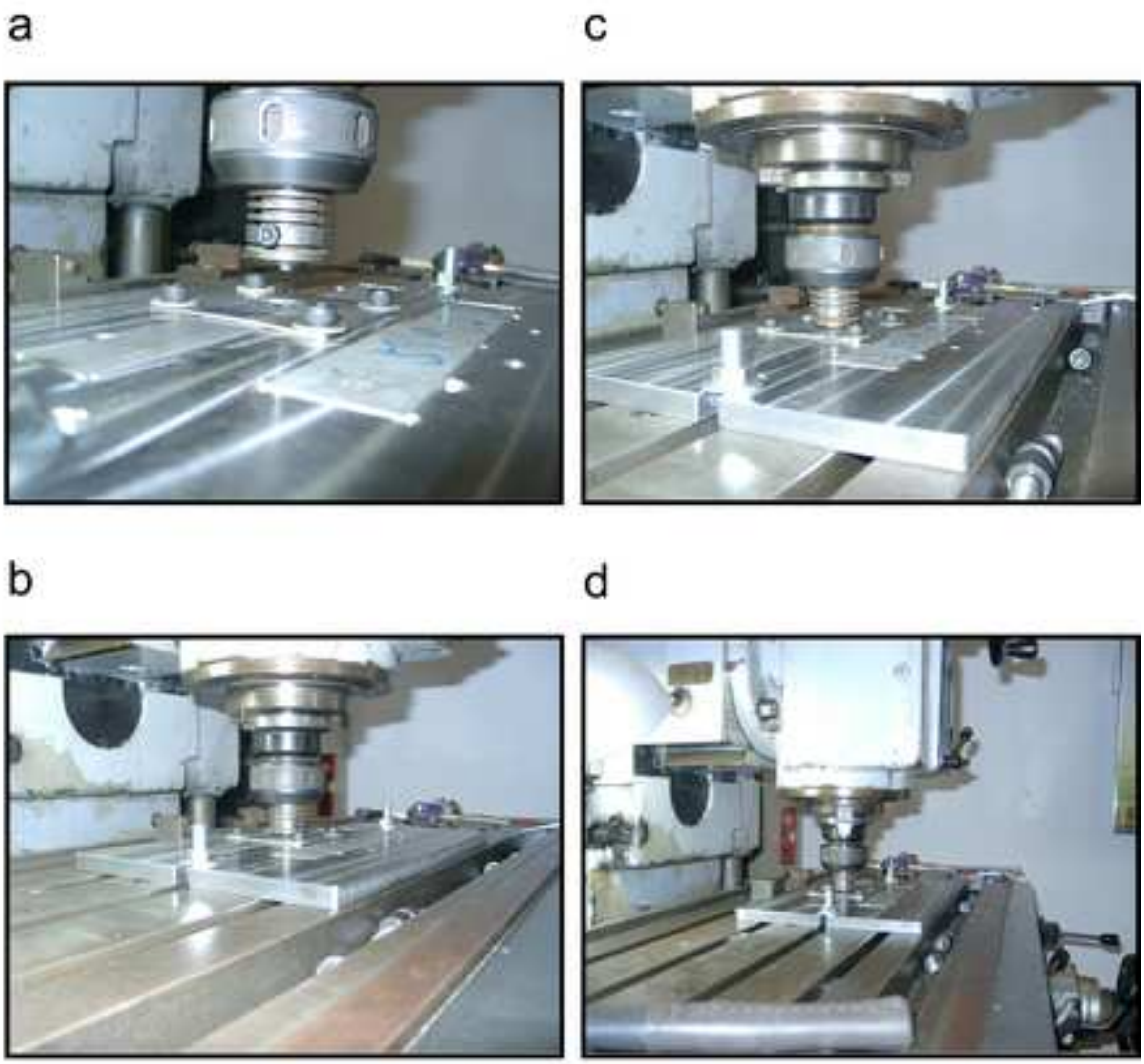

Figure 4

Figure 5

Figure 6

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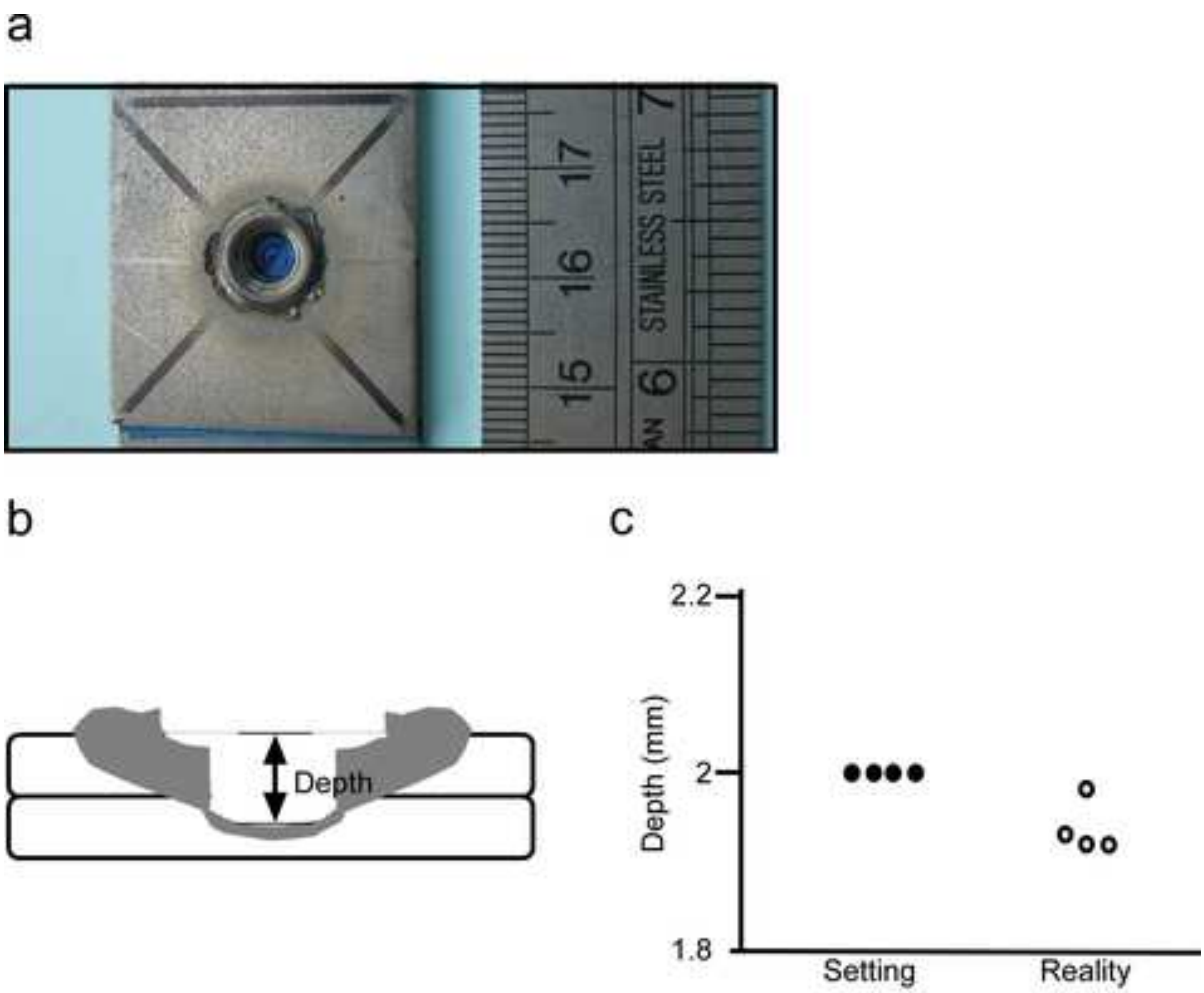

Figure 6

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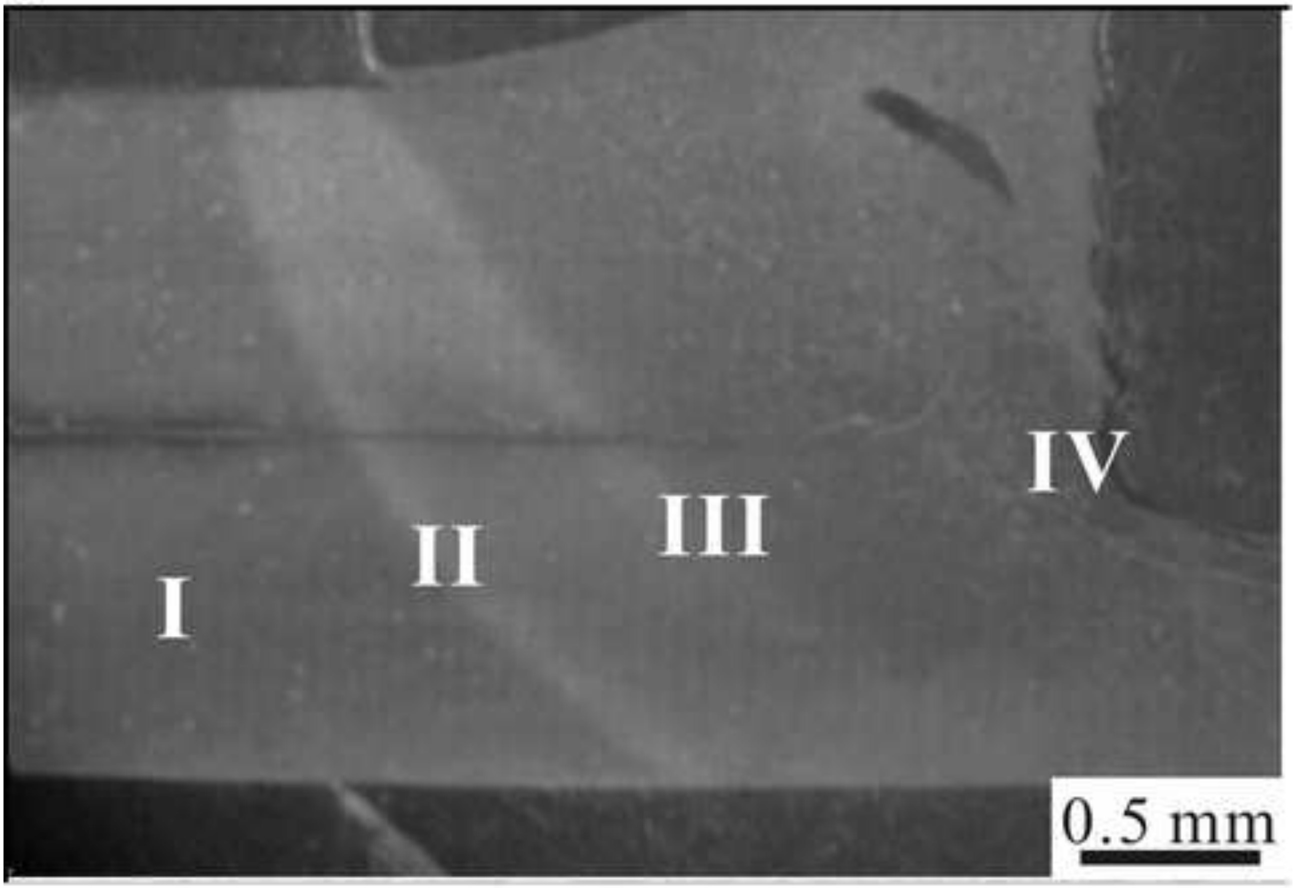

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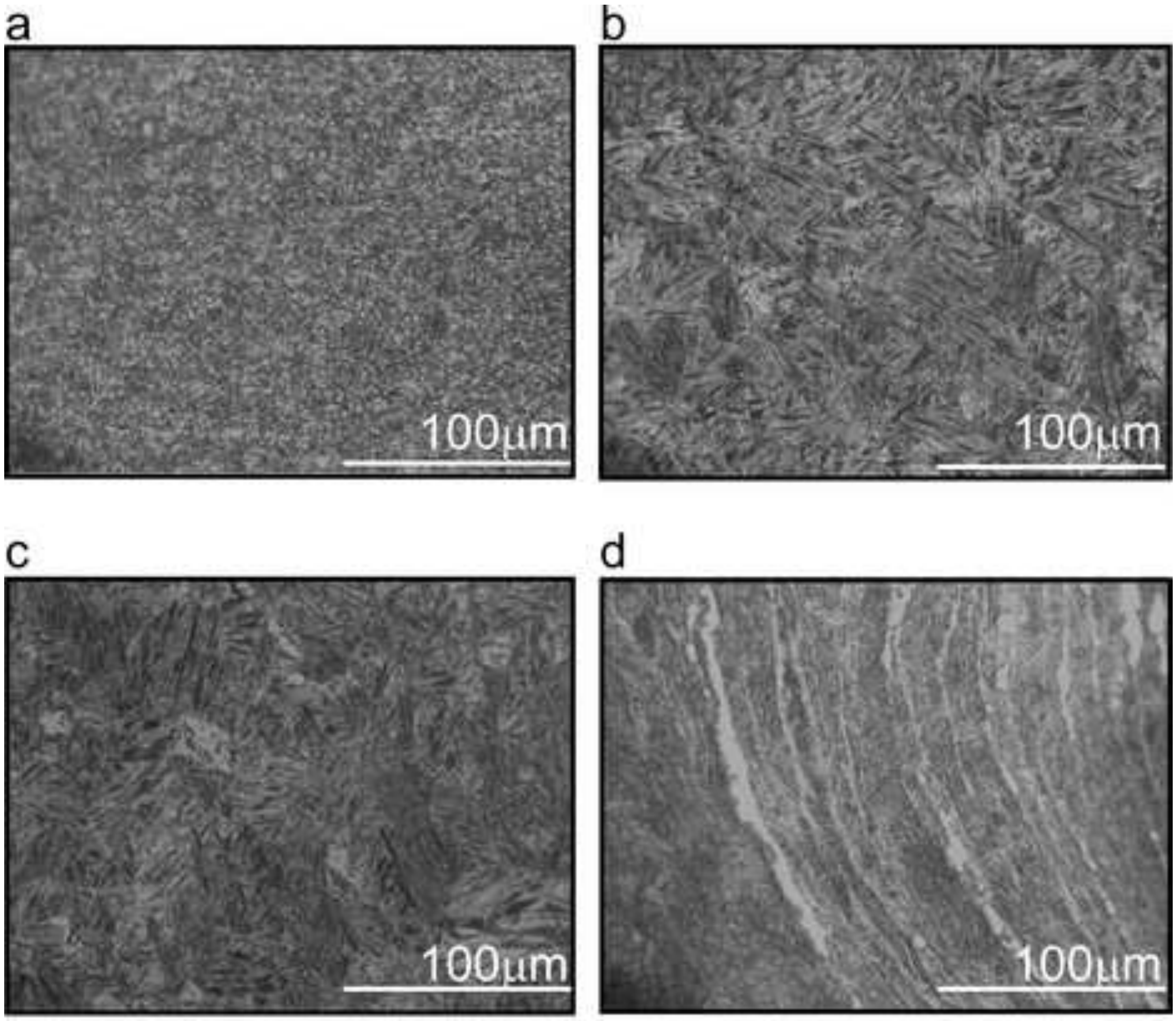

Figure 8

Figure 9

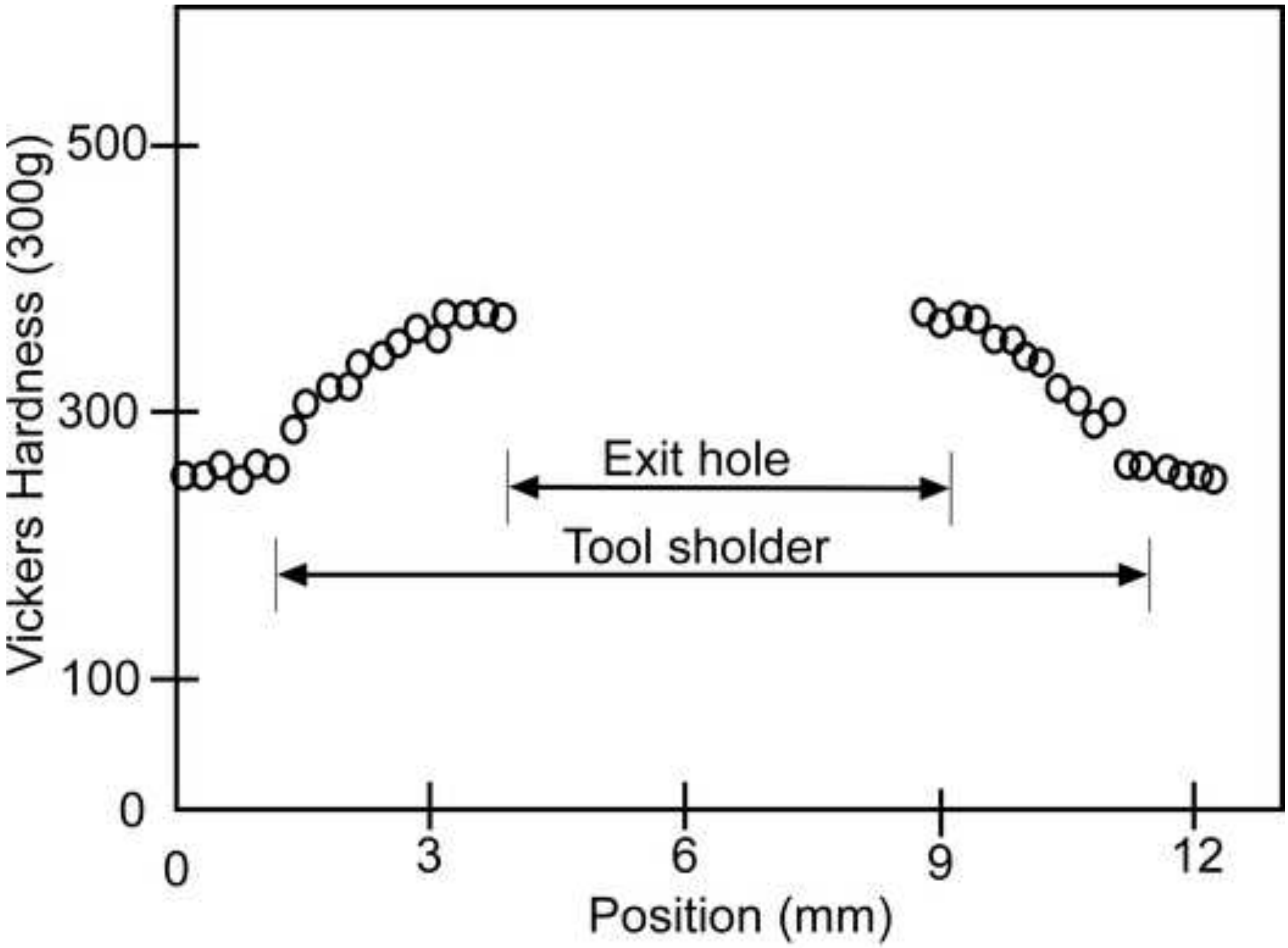

Figure 4

Name of Material/ Equipment	Company	Catalog Number	Comments/Description
anvil	MIRDC		made by MIRDC
DP780	China steel Corporation	CSC DP780	
stir spot welder machine	MIRDC		made by MIRDC
tool pin	KINIK COMPANY	DBN2B005B	

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Title of Article: Method of friction stir spot welding to generate lap joint on DP780 steel

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Date:	2018/06/15

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Reviewer #4:

I did not find this manuscript as a scientific paper. However, it is a good protocol for Friction stir spot welding of a specific still. Having read the requirement of your journal, i think you can publish this protocol.

Dear Reviewer,

Thanks for your valuable comments.

Dr. Vineeta Bajaj
Review Editorr

Manuscript ID: JoVE58633
Manuscript Title: Method of friction stir spot welding to generate lap joint on DP780 steel
Dear Dr. Vineeta Bajaj:

We would like to thank you for your kind consideration and helpful suggestions regarding our manuscript. We would like to resubmit our manuscript for thoughtful of publication in "*Journal of Visualized Experiments*". We have substantially revised the manuscript in keeping with the reviewers' comments and believe that we have answered most of the questions raised as listed below in a sufficient manner.

Thank you again for helping our manuscript preparation.

Meng-Hsiu Tsai, Ph.D.

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Dr. Vineeta Bajaj
Review Editorr

Manuscript ID: JoVE58633
Manuscript Title: Method of friction stir spot welding to generate lap joint on DP780 steel
Dear Dr. Vineeta Bajaj:

We have substantially revised the manuscript in keeping with the reviewers' comments and believe that we have answered most of the questions raised in a satisfactory manner. The change sentence in the manuscript has been highlighted with red color for easy to read. We have made major revisions in this new version according to yours and the reviewers' comments as follows:

Editorial comments:

1. Please employ professional copy-editing services. The language in the manuscript is very poor and cannot be understood. A thorough review can only continue when the language is fixed. It is unclear what is being said throughout.

   Answer: Thanks for reviewer's comment. The word in the manuscript is rewritten marked with green highline. In the revised version, the wrong words also have been corrected.

2. Please provide reprint permissions for Figure 9. We cannot publish this Figure without this permission?

   Answer: Thanks for reviewer's comment. Figure 9 is the new experiment for in this paper. .

3. Please highlight only 2.75 pages of protocol text for inclusion in the video. This is a hard production limit to ensure that videography occurs in a single day.

   Answer: Thanks for reviewer's correction. The yellow highline of the protocol will be present in the video

4. Please revise the following lines to avoid previously published text: 60-64, 223-232, 239-245, 297-301, 308-316,

Answer: Thanks for reviewer’s comments. The entire paragraph had been re-written. The new paragraph has used yellow color to label.

Editorial comments:

1. Please employ professional copy-editing services. The language in the manuscript is very poor and cannot be understood. A thorough review can only continue when the language is fixed. It is unclear what is being said throughout.
2. Please provide reprint permissions for Figure 9. We cannot publish this Figure without this permission.
3. Please highlight only 2.75 pages of protocol text for inclusion in the video. This is a hard production limit to ensure that videography occurs in a single day.
4. Please revise the following lines to avoid previously published text: 60-64, 223-232, 239-245, 297-301, 308-316,

Dear Editor,

Thanks for your valuable comments. We have already revised following your suggestions. Also we would like to updated the affiliation information in lines 9-10 as Department of Mold and Die Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, 807, Taiwan.

Reviewer #1:

Manuscript Summary:

This is an improved (reviewed) version of the manuscript, as compared to the original version.

Major Concerns:

None.

Minor Concerns:

Some informations remain not very clear, and should be revised:

-The data cited in item 2.5.1., lines 175-176, are different from those showed in Figure 3.

-Item 3.2.2., line 248, asks to "Press the Vickers diamond indenter with a 500 g test load sample and 0.5 mm per test" to perform the Vickers hardness tests. However, item 3.2.3. (lines 250-251) aks to "Conduct the microhardness testing of the DP780 steel sheet using a microhardness testing machine with a 300 g load and a holding time of 15 s.". These informations are not matching.

-Lines 332-338: The authors cited that used a polycrystal diamond tool to carry out the FSSW to avoid tool wear. However, Figure 5 shows a tool used in the experiments, and is clear its wear - indeed, the authors cited in the Figure caption that "The pins are consumed at high temperatures.". These informations are not matching. Moreover, if tool wear took place in the experiments, would be expected some inclusion of this tool material in the joint?

Dear Reviewer,

Thanks for your valuable comments. The revised parts as follows:

1. Rotation speed 3000 rev/min, plunge rates 0.1 mm/sec and dwell time 4 sec are revised in Figure 3c which are constituent with lines 170-171 in the article. Also we updated figure 3c.
2. 300 g test load are corrected both in line 243 and 246.
3. Polycrystal diamond tool is more harder and stronger at high temperature compare to tool steel material. Therefore we use polycrystal diamond tool to increase the lifetime of the tool in line 332-333.

Reviewer #2:

It has been improved.

Major Concerns:

No

Dear Reviewer,

Thanks for your valuable comments.

Reviewer #3:

Manuscript Summary:

Well prepared.

Major Concerns:

The layout and content of the article are very complex.

Generally:

This manuscript is original and It is suitable for publication. All reports clearly show the scientific relevance of the results. It's been a pretty good job. The literature on handwriting has been studied.

Additional questions / Recommendations: Publish without major revision

For manuscript opinion and suggestion

The protocol part (Material preparation, Procedure, Mechanical property evaluation) are very complicated. The article was not fluent in terms of content because numbering was done in each section. Numbering within each section must be removed. (1. Material preparation 1 1.1. and 1.2.). 1 1.1. and 1.2 must be removed and created as 1. Material preparation only.

Since the contents of the sections are numbered in number, the sections should be revised separately. For example Therefore, these parts must be corrected again as a single section. In this way the article becomes more fluent.

Line 107

FSSW tool section: The diameter of the pin is 5 mm; the length is 2.5 mm, and the shoulder width is 10 mm. The real tool pin product is shown in Figure 1b. Figure 1 a shows dimension of the pin. What is the pin angle. not shown. Figure 1a and Figure 1b don't seem compatible with each other.

For figure 6: It would be better if there was an image on the cross section.

REPRESENTATIVE RESULTS was revised.

Minor Concerns:

Minor corrections are required for Figures 2 and 3.

Dear Reviewer,

Thanks for your valuable comments. The article has been revised more fluent.

1. The article has delete some numbering and make it fluently in line 101-106.
2. The pin angle is shown in updated figure1.
3. The cross section image is shown in Figure 7.

Editorial comments:

1. Please revise lines 307-310, 319-321, and 322-325 to avoid previously published text.

2. Please provide complete references for the following. We need authors, titles, publisher, and dates.

> 7 Feng, Z. et al. (SAE International, 2005).
> 13 Tarasankar DebRoy, S. A. D., John N. DuPont, Toshihiko Koseki, Harry K. Bhadeshia. Trends in Welding Research 2012: Proceedings of the 9th International Conference. (ASM 397 International, 2013).
> 15 R. A. Schultz, P. p. a. t. in Great Design in Steel Semina (American Iron and Steel Institute, South-field, MI, 2007).
> 16 Horvath, C. in Great Design in Steel Seminar (American Iron and Steel Institute, South field, MI, 2007).
> 21 Yan, B., Zhu, H., Lalam, S. H., Baczkowski, S. & Coon, T. (SAE International, 2004).
> 22 Wilson, R. B. & Fine, T. E. (SAE International, 1981).
> 26 <Friction Stir Welding.pdf>

Dear Editor,

Thanks for your valuable comments. We would like to reply as follows

1. The revised parts are shown in line 101-106, 306-309 and 317-324. Those are revised to avoid the previous study.
2. The references 7, 13, 15, 16, 21, 22, 26 are corrected and are shown in line 381-383, 399-401, 405-410, 424-427, 439-441.

AMERICAN JOURNAL EXPERTS

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DP 780 Steel with FSSW

Authors:

Tsai, Meng-Hsiu

Date Issued:

October 29, 2018

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