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Influence of tool pin profiles on the filler added friction stir spot welded dissimilar aluminium alloy joints

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Abstract

Dissimilar metals are pretty challenging to attain enhanced mechanical properties in the conventional friction stir spot welding (FSSW) process. In this research, a new filler added friction stir spot welding (FAFSSW) process is adopted for welding dissimilar aluminium alloys of AA5052 with AA6061 by using five different tapered tool pins to enhance the mechanical and metallurgical properties of the joints. Magnesium (Mg) powder with 4.5 mg in volume fraction is considered filler material to fabricate the joints. Mechanical properties of the spot weldments like tensile shear strength test, microhardness test, and metallurgical characterizations like microstructure analysis were carried out for FAFSSW joints. The results show that a tool pin profile with 5 mm upper diameter, 2 mm lower diameter and a pin length of 1.2 mm produce a sound joint with 202.85 MPa tensile shear strength and 119.9 HV microhardness. The FAFSSW joint shows 34% higher strength than the normal FSSW joints. The microstructure analysis indicates that the Mg filler mixes well in the weld zone, and a fine grain structure is gained without any defects.

1. Introduction

Aluminium Alloy lap joints are widely used in the aerospace and marine industries. In AA5052, the primary alloying element is magnesium (Mg) and chromium. Magnesium plays a significant role to improve strength without compromising ductility, and chromium improves corrosion resistance properties. These all properties make the AA5052 eligible to use as a skin metal. When it comes to the AA6061, the major alloying element is magnesium which provides good strength; hence mostly AA6061 is used for structural applications. The glossy surface of the aluminium alloy made it difficult to weld material. Therefore it is pretty tricky to weld aluminium alloys with fusion welding; many industries adopted fasteners or rivets to connect these metals. Besides, these practices increase the weight of the joint and reduce strength as well, and these practices are not recommendable for marine or space applications. The best remedy for these problems is friction stir welding (FSW); its solid-state joining property is widely applicable for metals with high thermal conductivity. This method can eliminate all the defects encountered with fusion welding, and this method can enhance the joint strength compared to fusion welding; moreover, it is economical. A non-consumable rotating tool with a designed pin profile is used to join the metals. This tool will plunge into metals and create frictional heat and making the region into the plastic stage. Thus coalescence between two workpieces was obtained. This plastic region will form a joint by the axial force given by the tool shoulder.

Resistance spot welding was widely applied for spot welding. While comparing with FSSP, this resistance spot welding exhibits poor joint strength and metallurgical characters. In the resistance spot welding method, typical electrode wear leads to defects in the weld zone. Moreover, the power consumption is high in resistance spot welding compared to FSSP. In all aspects, FSSP is superior to all fusion spot-welding methods. This friction
stir spot welding (FSSW) is derived from the traditional friction stir welding (FSW) method. The only difference from the FSW method is the tool does not have a tool travelling speed or lateral tool movement in this FSSW.

The effect of SiC reinforcement nanoparticles on AA6061—T6 friction stir spot welds were studied by Morteza Asadollahi et al [1]. The study shows that 28% of enchant in the tensile strength by SiC reinforced FSSW joints compared to filler less FSSW. Moreover, the microhardness of the joint was enhanced to 24% due to the dynamic recrystallization in the weld zone. Aluminium alloy AA7039 was friction stir spot welded, and the effect of tool profile was investigated by Gyander Ghangas et al [2]. Four different profiles have adopted this work; they are cylindrical, conical, triangular and square with three different diameters, 5 mm, 6 mm and 7 mm, respectively. The results show that the pin profile with 6 mm diameter and square profile was the best tool for this similar metal friction stir spot welding. The microstructure examination shows different grains sizes across the different weld zones. The high plastic deformation that happened in the stir zone resulted in dynamic recrystallization. The effect of tool rotation speed in Mg and Al friction stir spot welding was studied by Bo Zheng et al [3], the tool rotation speed selected for this experiment was 700, 900, 1100, 1500 and 1500 rpm, respectively, and the welding speed kept constant that is 50 mm min⁻¹. This study reveals that at 900 rpm tool rotation speed, a sound defect-free Mg/Al joint was achieved. At the lower tool rotation speed, coarse grains were found in the nugget zone, and similarly, while using higher tool rotation speed over 1100 rpm, tunnel defects were found.

Only a few researches are conducted on sheet metal to plate lap welded joints with dissimilar metals, and for those all joints, the strength gained was not up to the mark. Hence, in this research work, magnesium (Mg) powder is considered a filler material and sandwiched between the lap interfaces of the metals. This magnesium filler is placed on the knurled surface of the metal plate. The literature shows that the increase in the dwell time and tool rotation speed will increase the frictional heat in the spot weld zone and reduce the joint’s shear strength.
due to the induced excess heat affected zone [4]. The hook shape formation in the weld zone is related to the tool pin profiles, so selecting tool profiles has paramount significance. Hence, in this FAFSSW work, five different tool pin profiles are considered to evolve their influence on joint strength. The effects of the filler powder and tool pin profile are portrayed in this paper. Tensile shear strength and microhardness tests were conducted as per ASTM standards. A 0.71 mm thick AA5052 sheet and 3 mm thick AA6061 dissimilar metals were selected for performing FAFSSW. The significance of the parameters is well studied and presented.

### 2. Materials and methods

Aluminium alloys are widely used in the automobile, marine and aerospace industries as skin and structure applications like AA5052 and AA6061 for skin and structure, respectively. These aluminium alloys are friction stir spot welded using an FN2V vertical numerical controlled milling machine with 20 kN capacity. Tin snips cut AA5052 sheet with thickness of 0.71 mm, 200 mm length and 100 mm width and AA6061 with 3 mm thickness,

Table 1. Chemical compositions of aluminium alloys in weight percentage (%).

| Alloys  | Si         | Cr      | Mg | Mn   | Fe | Cu   | Zn   | Ni | Ti | Al     |
|---------|------------|---------|----|------|----|------|------|----|----|--------|
| AA5052  | 0.051      | 0.189   | 2.64 | 0.015 | 0.188 | 0.006 | 0.009 | —  | 0.012 | Balance |
| AA6061  | 0.620      | —       | 0.97 | 0.517 | 0.340 | —     | 0.031 | 0.18 | 0.022 | Balance |

Table 2. Mechanical properties of aluminium alloys.

| Alloys  | USS (MPa) | YS (MPa) | Elongation (%) | Hardness (VHN) |
|---------|-----------|----------|----------------|----------------|
| AA5052  | 213       | 164      | 17.5           | 85             |
| AA6061  | 308       | 278      | 13             | 95             |

Table 3. FAFSSW working condition and parameters.

| Tool rotational speed (rpm) | 1200 rpm |
|-----------------------------|----------|
| Dwell time (s)              | 10 s     |
| Plunge depth (mm)           | 0.15 mm  |
| Magnesium powder (mg)       | 4.5 mg   |
| Tools                       | Tool—1, Tool—2, Tool—3, Tool—4, Tool—5 |
| Tool Material               | High-speed steel |

Figure 3. Schematic representation of the FSSW/FAFSSW tools with dimensions.
200 mm length, and 100 widths cut using a band saw [5]. Figure 1 shows the schematic representation of the FAFSSW joint configuration, and figure 2 shows the sample FAFSSW specimen with front and bottom surface. The AA6061 plates overlapping area for spot welding was knurled about 25 mm from the edge with a depth of 0.4 mm. Both the plate and sheet are cleaned with acetone solution. The magnesium powder of 4.5 mg is dispensed in the knurled area about 15 mm diameter locally where the tool gets into penetration [6]. The chemical composition and mechanical properties of the AA5052 and AA6061 are tested on their receipt of purchase. The chemical composition of AA5052 and AA6061 are given in table 1. The mechanical properties of AA5052 and AA6061 are shown in table 2.

Several trial experiments were conducted with different parameter ranges before fixing the parameters. The parameter ranges adopted for trail experiments where tool rotational speed from 900 rpm to 1300 rpm, plunge depth from 0.00 mm to 0.25 mm, dwell time 6.00 s to 15.00 s and magnesium (Mg) powder range from 0.00 to 15 mg. Irrespective of the tool pin profiles, the results show that a sound joint without any defect can be fabricated using 1200 rpm tool rotational speed, 0.15 mm plunge depth, 10.00 s dwell time, and 4.5 mg magnesium powder. This research focused on studying the influence of tool pin profile, so apart from tool profiles, all the parameters are kept constant [2, 7]. The process parameters selected for this experiment is given in table 3. Five different tapered tool pin profiles are chosen; all the pin profiles have a base diameter of 5 mm, a pin length of 1.2 mm and a shoulder diameter of 15 mm. The varying pin tip diameters are 0.00 mm, 1.00 mm, 2.00 mm, 3.00 mm and 4.00 mm, respectively. The schematical representation of the tools in figure 3 and the tool images are shown in figure 4.

Bead geometry and microstructure evaluation of the weldment was analyzed using an optical microscope and Scanning electron microscope (SEM), respectively. For this, the specimens are polished with a 200 to 2000
grade belt polisher. Then the fine polishing is carried out with alumina powder in a disc polisher [8]. Finally, as per ASTM E407 standard, the specimen is etched in Keller’s solution for 30 s. In addition, the Energy-dispersive x-ray (EDX) analysis was carried out for elemental analysis. Also, as per ASTM D3163, the tensile shear test samples were prepared. Figure 5 shows the sample of tensile shear specimen images.

The tensile shear test was carried out on an electromechanical controlled universal testing machine with 100 kN load (FSA, Indian made M100 model). Three samples were prepared for each experiment, and the average value is taken into account for analysis. A 0.2% offset shear strength, weld efficiency, and elongation percentage were assessed from this sample. Microhardness testing was conducted on Mitutoyo Micro Vickers hardness testing machine (Model: HV 110), with a load of 50 g and a dwell time of 20 s.

Figure 6. Bead geometry for (a) Tool-1, (b) Tool-2, (c) Tool-3, (d) Tool-4, and (e) Tool-5.
3. Results and discussion

3.1. FAFSSW bead geometry

Figure 6 shows the FAFSSW bead geometry for five different pin profiles. A precise metal interface like unaffected base metals, heat-affected zone, thermomechanical affected zone and stir zone is clearly visible. The onion ring formations are visible and can be distinguished in figures 6(c), (d) and (e) with their respective pin.
profiles and their influence in those specimens. Figures 7(a) shows the stir zone, (b) shows the thermomechanically affected zone (TMAZ) at advancing size (AZ), and (c) shows the thermomechanically affected zone (TMAZ) at retreating size (RZ) of the FAFSSW joint produced by the tool—3. The grains formed in those zones reveal that the stir zone achieved a refined grain structure with a similar grain structure.

Tool 1, 2 and 3 produces spot welding without any defects in the top surface, i.e. the tapered pin with an end diameter of 0 mm to 2 mm can make a better weldment compared to endpin diameter of 3 mm and 4 mm, respectively. In contrast, by increasing the pin end diameter from 3 mm, the material will be overheated and over plasticized [9]. As a result, the skin metal will tear apart, and it is visible in the advancing side of figures 6(d) and (e). Figures 6(a) and (b) shows an unaffected bimetallic region without proper metal mixing. This poor intermetallic bonding in the nugget zone is due to the tiny pin end diameter of less than 3 mm. This cause the metals in the nugget zone to not agitate well or plasticize to create a bonding due to the less heat generation by the
tool pin profile at the stir zone [10, 11]. A single extruded mass of AA5052 material was visible in figures 6(a) and (b); a blunt and poor material flow is noticeable in the bimetallic joining region. Figure 6(c), in the nugget zone, i.e. from the pin plunged area, the onion rings were visible due to the alternative staking of an equal amount of AA6061 and AA5052. Figures 6(d) and (e), i.e. the Tool-4 and Tool-5, displays a lower amount of isolated mass of AA5052 in the thermomechanical affected zone, and a slight trace of AA5052 was visible in the tool plunge region [12]. The larger end diameter of the tool pin does not agitate both the metals well due to the excess heat generation and over plasticization of metal in the stir zone. Meanwhile, the specimen joined by the Tool-3, as shown in figure 6(c), exhibits a shrill transformation of material flow, and no extruded AA5052 or AA6061 materials were visible in the nugget zone. Moreover, the small size of onion rings is only present in the bimetallic region of the stir zone.

3.2. Effect of tool pin profile on microstructure

Figure 8 shows the microstructure of the specimen prepared by FSSW by Tool-3. The grains orientation, materials flow patterns and grain size were examined using a scanning electron microscope (SEM).

The grain size orientation of specimen welded by FSSW, as shown in figure 8, reveals that the same parameters produce a sound joint with FAFSSW. This SEM image is taken from the nugget zone of the weldment, in which some AA6061 clusters and weld debris are found [13]. This weld debris and clusters are formed due to the improper mixing of parent metals. The heat generated by the tool pin in the nugget zone (pin plunged area) is insufficient and resulted in clusters forming. Moreover, the dwell time suitable for FAFSSW is not ideal for standard FSSW joining [14]. While examining the structure, the advancing side gained much-improved grain formation compared to the retreating side due to the dragging of the pin’s material. Still, the grain size achieved in the stir zone is much refined than the parent metals. Besides, this joint provides tensile shear strength of 133.88 MPa, which is 34% less than the FAFSSW joint [15]. Figure 9 shows the microstructure of the FAFSSW specimen fabricated with Tool-3 in 500x magnification.

The grain orientation and grain size of the FAFSSW joint fabricated by Tool-3 show refined grain structure in the weld zone. In this stir zone, the grains were arranged well without any stacking faults or kissing bonds. Magnesium powder was well blended due to the dynamic recrystallization that happened in the nugget zone [16]. This dynamic recrystallization was happened by the influence of pin profile as well as the shoulder plunging. Moreover, the perfect dwell time also influences the formation of refined grains by providing the appropriate heat to plasticize the metal.

In contrast, the tool rotation speed stirs the plasticized metals with the Mg powder and form a refined grain structure. The previous bead geometry analysis also shows a fine microstructure in the retreating size. The shoulder influence is more significant, and the grains are highly deformed in the thermomechanically affected region. Besides, the grain structure in the heat-affected zone is comparatively larger than the TMAZ and SZ due to the heat generated while joining and the poor mechanical influence of the tool in those regions [17]. Moreover, in the nugget zone, orbitally blended grains were found, and the sizes of the grains are smaller than...
the shoulder influenced regions. In the lamellar area, the thicknesses of both the parent metals are identical, and the densities of Mg powder in those regions are more or less similar. While comparing the pin-influenced region with the shoulder-influenced area, the downward flow of material is not substantial [18]. These examinations revealed that the tool pin profile plays a vital role in forming microstructure and eventually enhances the tensile shear strength.

3.3. SEM, EDX analysis with elemental mappings

Figure 10 shows the scanning electron microscopy (SEM) image of the weld specimen taken from the nugget zone of the weldment prepared by Tool-3. The stir zone examination reveals the presence of θ precipitates in the AA6061 in the nugget zone due to the age-hardening that happened while welding; this age hardening is related to the heat generated by the pin and shoulder in the stir zone. Besides, the thermomechanical affected zone does not have any θ precipitates but have some dislocations. Throughout the matrix, the skin metal AA5052 shows a structure with cell dislocations [19]. While comparing the FSSW with FAFSSW, the dissimilar joint fabricated with AA5052 and AA6061 exhibits coarse grains in the stir zone and throughout the matrix due to improper metal mixing.

Elemental mapping with the EDX analysis of the FAFSSW specimen is given in figure 10. Both AA5052 and AA6061 materials have a face-centred cubic (FCC) crystal structure. Therefore the substitutional diffusion mechanism of atoms will happen in the same atomic size elements [20]. The frictional heat generated by the shoulder and pin can provide the initiation energy for diffusing the Mg, Fe, Cr and C atoms to the parent
aluminium atoms of the base metals. From figure 11(a), the diffusion of each element with other elements is visible. The Mg atoms have only two electrons in the outer shell. They have a small structure; due to these atomic properties, Mg can move quickly, which results in the equal distribution of Mg throughout the nugget zone, shown in figure 11(b). While the Si atom has a diamond cubic crystal structure with a lattice parameter of 0.543 nm, which is slightly bigger than the FCC crystal structure, thus limits the movement of Si atoms and resulted in small accumulations; it is given in figure 11(d).

Similarly, the Fe atom has a BCC structure, and it has a more extensive crystal structure than Mg, Si and Cr. Due to this, the properties of Mg atoms required only lower activation energy to form a sound diffusion mechanism [21]. It is visible by the large concentration of those elements in figure 11(c).

Besides, the concentration of the new alloying element Mg and other elements in the FAFSSW joint was evaluated using EDX analysis, given in figure 11(e). It reveals that the atom’s concentration in a specific area changes with time; this means an unsteady diffusion has happened in the nugget zone [22]. The diffusion is related to the temperature generated by the tool in the weld zone and dwell time. The temperature generation in

| Sl. no: | Tool number | Average tensile shear strength (MPa) | Percentage of elongation (%) in 50 mm gauge length |
|--------|-------------|--------------------------------------|-----------------------------------------------|
| 1      | Tool-1      | 186.52                               | 11.1                                           |
| 2      | Tool-2      | 198.76                               | 9.9                                            |
| 3      | Tool-3      | 202.85                               | 10.0                                           |
| 4      | Tool-4      | 174.03                               | 12.2                                           |
| 5      | Tool-5      | 147.82                               | 13.6                                           |
|        | Specimen without Mg Filler (FSSW) | 133.88                               | 12.2                                           |

Figure 12. Tensile shear testing.
this FAFSSW is associated with the tool pin profile. The EDX results show that Mg has a higher diffusion rate of around 2.69% (atomic weight %). In contrast, Fe and Cr have lower diffusion rates of 0.15% and 0.05%, respectively. The Mg has a higher diffusion rate due to higher atomic concentration by adding Mg powder as filler in the butt interface while joining and related to its small atomic size.

3.4. Effect of tool pin profile on tensile shear strength

The tensile shear testing specimens were prepared as per ANSI/AWS/SAE/D8.9-97 procedures. A sample image for conducting the tensile shear test was given in figure 12.

From each experiment, three samples were taken, and the average value is given in table 4. Tool-3 gained the best average tensile shear strength of 202.85 MPa in FAFSSW. The same Tool-3 and other conditions were used to fabricate the joint in normal FSSW, and the average tensile shear strength of that joint is also given in table 4.

Tensile shear test results reveal that the change in tool pin profile has a paramount influence on the tensile shear strength of FAFSSW joints. FAFSSW achieved the highest tensile strength of 202.85 MPa, with Tool-3 having the pin end diameter of 2 mm. This is 65.86% of the strength of AA6061 and 95.23% of the strength of AA5052. Earlier FSSW research on aluminium alloys exhibits around 91% of shear strength compared to the parent metals [23]. This higher strength results from the Mg precipitates and the refined grains formed in the weld zone. The proper tool pin dimension helps in achieving these results by providing adequate stirring for metals. These stirring results in the formation of ambient heat, and dynamic recrystallization took place. But the same tool produces tensile shear strength of 133.88 MPa with the FSSW joint, which is 43.47% of the strength of AA6061 and 62.85% of the strength of AA5052. Also, this tensile shear strength is 34% lesser than the joint produced by FAFSSW [24]. The specimen with the highest tensile shear strength was mainly due to the Mg precipitates than the grain growth in that region. Graph plotting the tensile shear strength of FAFSSW and FSSW specimens with the percentage of elongation in figure 13.

In contrast, in this FSSW specimen, the absence of Mg filler reduces the strength. Due to the lack of Mg, the heat generated by the tool super plasticizes the parent metals and resulted in the formation of debris and kissing bond defects. The Tool-5 produced the lowest tensile shear strength of 147.82 MPa with a pin end diameter of 4 mm, which is 47.9% and 68.43% of the base metals. The percentages of tensile shear strength of all the joints were below the base metals strength. Three FAFSSW joints produced by the first three tools exhibit comparatively the same percentage of elongation [25]. The fracture prolonged for the specimens prepared by Tool-3 and Tool-4 are at the advancing side of the heat-affected zone, and for Tool-1 and Tool-2, the fracture happened at the stir zone. For Tool-5, the fracture occurred at the thermomechanical affected zone in the retreating side due to the kissing bond defect in the joint.

In most cases, the frictional heat generated by the tool is sufficient enough to plasticize the weld zone. For Tool-1 and Tool-2, the pin end diameter and the contact area is not adequate to produce enough temperature in the stir zone and resulted in the formation of coarse grains. Also, the bimetallic region shows that the metals do
not bond well. Tool-4 and Tool-5 with a pin end diameter of 3 mm and 4 mm super plasticize the weld zone. It leads to the formation of worm defects and severe dislocations [26]. Tool-3 produces and exhibits a higher strength resulted from the proper mixing of bimetals in the stir zone. The age-hardening happens with the base metals while welding. The ambient heat generation in the nugget zone enhances the mechanical properties of the joint by dynamic recrystallization. The SEM analysis also proves that equiaxed refined grain structure was visible in this region [27]. The proper distribution of Mg filler also played a pivotal role in attaining better strength. In most of the weldments, the ductility was drastically reduced due to the strain hardening effect.

3.5. Effect of tool pin profile on microhardness

While performing the Vickers microhardness testing, the results show different microhardness across the weld profile. This fluctuation was happened due to the orbital stacking of Mg and the parent metal elements. Also, the entangled intercalated microstructure formed in the weld zone. This kind of dissimilar or fluctuating microhardness profile was already reported. Table 5 shows the average microhardness of the FAFSSW and FSSW specimens from the weld zones, and figure 14 shows the respective graph for microhardness. Microhardness in the heat-affected zone and stir zones exhibited higher microhardness than in other zones, 120 HV and 123.58 HV, respectively. The microhardness gained in the thermomechanically affected zone is higher than the base metals and lower than the stir zone. The tool shoulder plays a vital role in the enhancement of microhardness in the thermomechanically affected zone. The surface hardness of the tool influenced area is comparatively higher than the heat affected zone.

The microhardness examination shows that the maximum microhardness was visible in the retreating side of the FAFSSW joints. The skin area of the FAFSSW joint exhibits more microhardness than any other area due to the strain hardening that happened in the AA5052 and the formation of refined grains in the stir zone due to dynamic recrystallization [28]. Moreover, it is higher than the microhardness in the TMAZ region of both advancing and retreating sides. While considering the lower portion of the FAFSSW joint, the AA6061 exhibits lesser microhardness than AA5052. Because AA6061 is placed in the stinger region and AA5052 is in the skin.

**Figure 14.** Average Microhardness of FAFSSW and FSSW joints.

**Table 5.** Microhardness of FAFSSW joints.

| Specimen with Mg filler (FAFSSW) | Specimen without Mg filler (FSSW) |
|----------------------------------|-----------------------------------|
| Sl. No.  | Tool number | Average microhardness (HV) |
| 1 Tool-1 | 96.82       |
| 2 Tool-2 | 110.60      |
| 3 Tool-3 | 119.94      |
| 4 Tool-4 | 116.08      |
| 5 Tool-5 | 114.3       |
| Tool-3  | 116.48      |
region or strain hardening region [29]. So the addition of Mg particles and the frictional heat generated by the tool pin does not enhance the microhardness of AA6061 furthermore. The maximum microhardness gained by the FAFSSW specimen is 119.94 HV, and in the normal FSSW specimen, it was 116.48 HV.

4. Conclusions

The dissimilar alloy joint of AA5051 with AA6061 was successfully fabricated by considering the five different tool pin profiles through the FAFSSW process. The tensile shear strength test, microhardness test and microstructure analysis were carried out. The following conclusions were arrived from these testings and analyses.

(1) Among the five different tool pin profiles considered, the tool pin profile (Tool-3) with a base diameter of 5 mm, pin length of 1.2 mm, shoulder diameter of 15 mm, and a pin tip diameter of 2 mm produced a sound joint without any cross-sectional or surface defects.

(2) The higher tensile shear strength and microhardness are exhibited by the joint produced with Tool-3 in the FAFSSW process are 202.85 MPa and 119.9 HV, respectively.

(3) In contrast, the tensile shear strength and microhardness gained by the same tool pin profile (Tool-3) in the normal FSSW process are 133.88 MPa and 116.48 HV, respectively.

(4) The tensile shear strength gained in the FAFSSW process was 34% better than the joint produced by the FSSW process.

(5) The microstructure gained by Tool-3 compared with other tools reveals a fine refined and uniformly distributed grain structure. The same tool that joined the parent metals with the FSSW process shows weld debris and AA6061 clusters due to insufficient plasticization.

(6) The EDX results show that the diffusion of Mg atoms and the age hardening in the AA5052 parent metal played a vital role in enhancing tensile shear strength and microhardness.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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