



Article A New Approach to Direct Friction Stir Processing for Fabricating Surface Composites

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Abstract: Friction stir processing (FSP) is a green fabrication technique that has been effectively adopted in various engineering applications. One of the promising advantages of FSP is its applicability in the development of surface composites. In the current work, a new approach for direct friction stir processing is considered for the surface fabrication of aluminum-based composites reinforced with micro-sized silicon carbide particles (SiC), eliminating the prolonged preprocessing stages of preparing the sample and filling the holes of grooves. The proposed design of the FSP tool consists of two parts: an inner-threaded hollow cylindrical body; and a pin-less hollow shoulder. The design is examined with respect to three important tool processing parameters: the tilt angle of the tool, the tool's dispersing hole, and the tool's plunge depth. The current study shows that the use of a dispersing hole with a diameter of 6 mm of and a plunge depth of 0.6 mm, in combination with a tilting angle of 7°, results in sufficient mixing of the enforcement particles in the aluminum matrix, while still maintaining uniformity in the thickness of the composite layer. Metallographic examination of the Al/SiC surface composite demonstrates a uniform distribution of the Si particles and excellent adherence to the aluminum substrate. Microhardness measurements also show a remarkable increase, from 38.5 Hv at the base metal to a maximum value of 78 Hv in the processed matrix in the surface composites layer. The effect of the processing parameters was also studied, and its consequences with respect to the surface composites are discussed.

Keywords: direct friction stir processing; in situ composites; surface composites

1. Introduction

Wrought aluminum alloys are considered one of the most significant metallic materials in today's fabrication and manufacturing production, especially in the transportation industries [1,2]. In general, many aluminum alloys offer an excellent combination of properties such as high strength-to-weight ratio, corrosion resistance, good formability, and weldability. However, in specific applications where dynamic loading is imposed, aluminum alloys' fatigue performance is considered a significant drawback. Other properties such as wear resistance are also of concern. Surface treatments such as coating, shot peening and induction friction stir processing (FSP) have been developed as solid-state processes capable of enhancing the surface properties of aluminum alloys [3]. The FSP process was developed based on the principles of friction stir welding (FSW) [3–5]. It involves the use of a relatively high-speed rotating non-consumable tool, which consists mainly of a shoulder with/without a pin to process the sheet/plate surface of the metal. During FSP, a localized heat produced by friction is generated at the interface of the rotating tool and the workpiece, resulting in metal softening and plasticization; the rotating pin, on the other hand, allows significant stirring and mixing, leading to severe plastic deformation and thus producing microstructure refinement in the stirred zone (SZ) [6–10]. The high-speed rotating tool then traverses along a specified path of interest to process and modify the material's matrix.



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). The microstructural alterations are characterized by equiaxed and ultra-fine grains for many metals and alloys [4,11]. Such grain refinement by FSP has been shown to enhance mechanical properties in several Al alloys, including tensile strength, ductility, and creep and fatigue strength [4,7,12–16]. The processing of other high-temperature materials such as steels [17] and Ti alloys [18] with FSP has also been reported.

The application of FSP for the development of surface composite matrixes was first introduced by Mishra et al. [4]. An in situ surface composite was produced by smearing the aluminum surface with reinforcement SiC particles and methanol and applying FSP to produce a surface composite layer. Since then, different methods for adding reinforcement particles have been reported [4,12,19–24]. For example, several studies proposed a new FSP method for making in situ composites, known as the groove method, by filling the reinforcement particles into a machined groove in the base material's top surface using FSP [25–28]. The groove method can be divided into three different steps: (1) machining the groove with the desired dimensions, (2) processing with a pin-less tool to pack the reinforcement particles, and (3) processing the entrap reinforcement particles by a tool with a pin in the desired processing parameters. The last two steps can be substituted by placing a thin sheet on the groove of the same materials and then applying the process using a tool with a pin to process the reinforcement particles entrapped in the groove by the thin sheet. Another approach for adding reinforcement particles, which eliminates the need for pin-less tool processing, is drilling several holes in a line or lines and then packing them with reinforcement particles, followed by processing with a tool with a pin to develop the surface composites [27,29]. The dimensions and number of grooves and holes play a vital role in acquiring the second phase's desired volume fraction [7,9]. All the previous methods have used a non-consumable tool. However, a consumable rod can be used [27] with drilled holes placed at different positions along a radial line filled with reinforcement particles to provide excellent results. The aforementioned methods require rigorous preparations of the surface or the consumable rod. More recently, Huang et al. [30] fabricated a surface composite by direct friction stir processing (DFSP) using a hollow tool without preprocessing to add the reinforcement particles. This design allows the in situ implementation of reinforcement particles.

Furthermore, the tool's design in FSW/P plays a critical and decisive role in the welding and processing, as well as the fabrication, of materials and surface composites. Different tool designs have been reported in previous studies [4,9,13,31–33]. Types of tools used for FSW/P are generally categorized into three types, namely, fixed, adjustable, and self-reacting [10]. The first type is the fixed-pin tool, where the tool is a single piece that includes the pin and the shoulder. The second type is the flexible tool with an adjustable pin, which can also be made from another material. The third type is the self-reacting tool, which is similar to the second type but with the addition of a bottom shoulder, and which acts as a backing anvil for the processed piece during the process. These three tool types have been used in FSW/P to weld and process several metallic materials.

The work of Huang et al. [30] proposed an efficient tool design for making in situ surface composites. The tool design consists of a pin-less hollow shoulder that is tapered at its lower end. This design was shown to allow the efficient spread and mixing of the reinforcement particles into the matrix surface during FSP. The shoulder is tapered from the center of the tool to minimize unnecessary frictional contact between the shoulder and the metal surface. In this study, a modified design of the FSP tool is proposed for making aluminum-based surface composites reinforced by SiC particles, based on the concept of the tool design reported in [30]. The modification includes several alterations to the tool design, including a two-part design, several hole sizes, and shoulder shape. A new approach for the fabrication of in situ surface composites by FSP has also been proposed in this study. It aims to reduce the probabilities of clogging the hole in the shoulder or any back extrusion during the processing. The role of the new design and technique on the microstructure and microhardness of the matrix surface are studied.

2. Materials and Methods

2.1. Tool Design and Processing Approach

In this study, a new design for the tool and a new processing approach are proposed to carry out the friction stir processing to develop surface composites. A two-part tool is fabricated where the two parts are the top part of a hollow cylindrical body and the lower part of a tool head, as schematically illustrated in Figure 1a,b.



Figure 1. Schematic illustration of the FSP tool and design and processing procedures: (**a**) upper part, and (**b**) lower part of the FSP tool; (**c**) sectioned views of the tilting of tool head with respect to the processed aluminum plate; and (**d**) processing setup. All dimensions are in mm.

The top part consists of a body made from H13 steel with an outer diameter of 25 mm and a 13.5 mm hollow body with 15 mm of threading at the 30 mm end. The height of the top portion of the tool is 60 mm; half of the distance is prepared for clamping, and the other half remaining is used as a casing for the lower part. The lower portion is the head, containing a shoulder with a hole in its middle instead of a pin. Three different sizes of holes were used in experiments 2, 4, and 6 mm. The head also contains threading that fits into the top part of the tool's body. The upper portion of the lower part consists of a

15-mm thread with a diameter of 11 mm, and then the head body is 25 mm in diameter and 12 mm in thickness for the lower portion of the lower part, as depicted in Figure 1b. The total length of the whole body, assembled from the two parts, is 72 mm. Two bolts are also used to add more stability to the tool during processing by secularly tightening the lower part's threaded part and the top part. The tool can be fabricated as one part; however, the two-part design is easier to manufacture and allows for more extension of the tool; thus, more powder can be loaded inside the tool from the top part, as illustrated in Figure 1c. The two-part tool also has many benefits with respect to the flexibility of the tool's use, as well as advantages such as the ability to use different materials and designs for the head, such as the different hole sizes used in this experiment. The new design also facilitates head/tool body reuse, reduces the materials needed, and reduces the associated costs.

Commercial silicon carbide (SiC) particles with an average size of 20 µm were used as the reinforcement particles, as shown by the secondary electron image in Figure 2. The SiC particles were poured into the cavity of the lower part of the tool. The two-part tool was assembled and clamped into a vertical milling machine to conduct FSP. The processing was carried out with a constant tool rotating rate of 3000 rpm, using a clockwise rotation and a 20 mm/min travel speed. The reinforcement SiC particles were fed into the matrix via gravitational force. A ball bearing of 11 mm in diameter was placed on the top of the powder inside the hollow tool to facilitate the dispersion of the reinforcement particles into the metal surface to produce surface composites at the top of the metal matrix. To allow the use of different hole sizes, the tool was tilted by 7° , as illustrated in Figure 1c. By doing so, it was possible for a part of the tool, less than half of shoulder surface, to be in contact with the workpiece. Offset distances of 6 and 7.5 mm were used between the point of contact of tool with the workpiece and the center of the tool (Figure 1c). Two main processing parameters, namely the offset distance and the tilting angle, were evaluated to provide the best possible combination of plunge depth required to enhance the particle dispersion processes with minimum back extrusion effect or tool hole blockage by the processed material. The use of the two offsets of 6 and 7.5 mm, in combination with a tilting angle of 7° , was shown to result in plunge depths of approximately 0.9 and 0.6 mm, respectively.



Figure 2. Secondary electron images of the as-received commercial silicon carbide particles in aggregate state.

2.2. Material and Experimental Procedures

T6 tempered aluminum alloy 1100 plates were purchased in hot extrusion condition. The chemical composition of the alloy is given in Table 1. The aluminum plates were used as the base for fabricating the surface composite. The plates were sectioned perpendicular to the extrusion direction. The dimensions of the FSP plates were $100 \times 150 \times 6.5$ mm, as schematically illustrated in Figure 1d. Coupons were cut transversely from the middle of the processed plate for metallographic investigations. A standard metallographic procedure was used to prepare the sample for examination. The cross-section of the coupons was examined by a metallurgical microscope (AxioImager A1M, ZEISS, Oberkochen, Ger-

many). Additionally, a field emission scanning electron microscope (FESEM) (JEOL, model: JSM-7001F, Tokyo, Japan), equipped with an Energy Dispersive X-Ray Spectroscopy (EDS) detector (Aztec-Energy, Oxford, High Wycombe, UK) was used to examine surface composite layer development in the FSP zone and to identify the elemental distribution across the surface composite/matrix interface. The EDS analysis was carried out at an accelerating voltage of 20 kV and a working distance of 11.5 mm to allow for a sufficient depth of penetration (1–2 μ m). The surface composite's elemental analysis was acquired from the top surface to the alloy matrix toward the plate's bottom, and horizontally at the center of the processed zone.

Table 1. Chemical composition of the 1100 aluminum plate used in the study.

	Composition (wt.%)							
-	Si	Fe	Mn	Cu	Ti	Cr	Zn	Al
Al 1100	0.140	0.250	0.001	0.051	0.019	0.001	0.002	Bal.

Vickers microhardness measurements of the polished samples were conducted. Indentations were carried out using an Innovatest Falcon 500 Hardness Tester (Innovatest, Maastricht, The Netherlands) with a load of 100 gf and a dwell time of 20 seconds. Microhardness measurements were taken along two lines from the top surface toward the bottom of the samples. The first line is vertical in the middle of the SZ from the upper surface toward the bottom, and the indentations were carried out with increments of 0.1 mm in the processed area and 0.25 mm in the alloy matrix for a total distance of 3 mm. The other line is a horizontal line on the processed area at a distance 150 μ m away from the top surface of the SZ, with increments of 0.5 mm, as schematically illustrated in Figure 3.



Figure 3. Schematic illustration of the microhardness measurements vertical and horizontal lines.

3. Results and Discussion

3.1. Processing of the Surface Composite

As a result of the two-part tool's flexibility, different hole sizes of the lower part of the tool (2, 4, and 6 mm) were used to examine particle dispersion efficiency. Visual examination showed that there was a noticeable change in the dispersion characteristics with increasing the hole size. Apparently, there was a flow discontinuity of the enforcement particles into the workpiece when processing with a 2-mm hole size since there was a blockage of the tool hole by a large amount of the SiC particles, as shown in Figure 4b. This discontinuity can most likely be attributed to the small size of the hole used and the enforcement particles adhesion characteristics. The blockage might be assisted by the high rotational speed, which might enhance the material flow due to the presence of significant centrifugal forces. Therefore, the workpiece processed by the tool with a 2-mm hole size showed no signs of reinforcement particles for plunge depths of either 0.6 or 0.9 mm. In addition, the use of a tool with a 4-mm hole size resulted in flow irregularity of the enforcement particles into the workpiece. This led to the non-uniform distribution of the enforcement particles in the upper region of the matrix. On the other hand, processing with a 6-mm hole size was shown to promote a continuous flow of the enforcement particles into the workpiece. This resulted in uninterrupted feeding of SiC particles into the aluminum matrix. However, there were back-extruded pieces of aluminum formed in the hole when

using a tool with hole sizes of 4 and 6 mm, as shown in Figure 5. This was particularly evident with an offset distance of 6 mm, i.e., a plunge depth of 0.9 mm. The occurrence of back extrusion is believed to occur due to the buildup of friction-stirred material into the hole by the forging action of the tool. The easy access to the hole due to the short distance between the processed material and the hole opening aids in back extrusion, as do the softness and the quantity of the materials, as a result of tool rotation and plunge depth.



Figure 4. Photographs of (**a**) the tool before processing, and (**b**) blockage of 2 mm hole after processing using 2 mm hole size.



Figure 5. Photographs of the back-extruded aluminum during processing when the offset between the hole and the processing material is low during processing using 4- and 6-mm hole sizes.

In general, the processing and tool design parameters, such as the dispersion mechanism, the tool hole's size, the tilting angle, and the offset distance, were shown to significantly contribute in the blockage of tool hole and back extrusion buildups. Besides that, the characteristics and size of the SiC enforcement particles might have an effect on the flow and dispersion of enforcement particles. However, only one enforcement particle type and size were used, and consequently, the current study was focused on the critical processing parameters that significantly control the flow and dispersion of the SiC particles, i.e., hole size and plunge depth; both parameters were shown to affect the SiC particle blockage in the tool hole and the buildup of the back-extruded material during processing. Therefore, to avoid excessive amounts of back-extruded aluminum, a balance is required between the processed area and the offset distance between the tool's hole and the processed workpiece surface. This was achieved by adopting a tool design with a 6-mm hole size, using an offset distance of 7.5 mm, resulting in a plunge depth of 0.6 mm. This was shown to provide the best processing parameters for the development of a surface composite layer in the current study.

Figure 6a shows the aluminum matrix's processed area reinforced with SiC particles as a surface composite at the upper surface using a tool with a 6-mm hole size and a 0.6-mm plunge depth. A well-distinguished layer of surface composites of Al/SiC was shown to develop, with no evidence of porosity in the processed zone, illustrating a good mixture and adherence to the aluminum substrate. However, as previously mentioned, using a tool with a hole size of 4 or 6 mm combined with a plunge depth of 0.9 mm resulted in limited dispersion of the Si particles into the aluminum matrix and non-uniform surface composite layer, as illustrated in Figure 6b. This is due to the enforcement particle flow's irregularity, and more aluminum material is back extruded rather than being mixed with the SiC particles. The high rotational speed and the tilting degree hence plunge depth, aids

in developing the required forging and frictional forces that produce the heat required for plasticization and the implementation of reinforcement particles into the matrix's upper surface, especially when enough enforcement particles are available. The reinforcement particles are stirred and bonded to the upper part of the SZ during FSP. Although the presence of SiC is expected to cause wear to the H13 tool, the H13 tool was visually inspected, and there is no evidence of tool wear. This can be attributed to the soft nature of the processed material examined in the current study, i.e., aluminum alloy 1100. This is also supported by the fact that the FSP tool used in this study had no pin, and thus the friction stirring action occurred at a shallow depth, resulting in a maximum thickness of $300 \mu m$ at the center of the processed zone.



Figure 6. Panoramic image of the cross-section of the processed samples showing the composite surface using: (**a**) a tool with a hole size of 6 mm and a plunge depth of 0.6 mm; and (**b**) a tool with a hole size of 6 mm and a plunge depth of 0.9 mm.

In addition, the results show that some variation in the thickness of the developed surface composite layer had occurred. Although the surface composite approximately covered the main width of the shoulder, which is around 21 mm, the thickness of the processed layer varied slightly, reaching a maximum thickness of 300 µm at the center of the processed zone, i.e., near the hole, and minimum thickness of approximately 50 μ m near the edge of the tool shoulder. The maximum thickness at the center of the processed zone was most likely achieved due to the high quantity of enforcement particles dispersed at the center during the processing. Some layer depth uniformity can be noticed around the center of the tool, which can be attributed to the high rotational speed of 3000 rpm and the moderate forging force generated from the tool's shoulder with a tilting angle of 7° and plunge depth of 0.6 mm. On the other hand, the workpiece processed with a plunge depth of 0.9 mm exhibited a large variation in thickness along the width of the processed zone. Unlike for the 0.6-mm plunge depth, the center of the processed zone (near the hole) exhibited the minimum thickness. This is a direct indication that back extrusion adversely inhibits the dispersion process at this center region. Additionally, the surface irregularities (inclinations) of the composite are evident, which suggests that the increase in the plunge depth was unnecessary to process the soft aluminum matrix.

The dispersion uniformity of the reinforcement particles generally depends on several factors, such as the vertical pressure on the base metal, number of passes, tool rotational direction, travel speed of the rotating tool, and the traverse tool speed. The vertical pressure on the base metal is reported [34] to develop a better forging and improve material flow and particles dispersion. Additionally, the increase in the number of passes plays a role in developing a better uniformity of the distributed second phase particles in addition to eliminating the porosity and developing refined microstructure [17,21,34,35]. Furthermore, significant homogeneity in the dispersion of SiC particles into the composite matrix has been reported [36] to occur as a result of changing the tool rotational direction between passes. Other factors such as the travel speed of the rotating tool and the traverse tool

speed have various effects depending on the heating cycles developed during processing, as a result of deformation processes similar to extrusion and forging [20,35,37].

3.2. Elemental Analysis of the Surface Composite

Only the samples developed using the tool with a hole size of 6 mm, a tilting angle of 7° and a plunge depth of 0.6 mm were studied. Figure 7 presents the EDS elemental mapping of the surface composite region, illustrating the distribution of major elements in the processed zone (Al, Si, C, and O). No noticeable Fe content was detected in the cross-section of the surface composite. The processed area was mainly a mixture of aluminum matrix and dispersed microsized SiC particles, as well as some other oxides. The dispersed microsized SiC particles can be seen to be uniformly distributed in the aluminum matrix. The presence of oxygen is evidence for the possible formation of silicon or carbon oxides during FSP. Small pockets of oxygen are also present. Moreover, the concentration of silicon seems to be well distributed throughout the processed zone, indicating a sufficient dispersion of SiC particles in the matrix and a lack of clustering or agglomerations of SiC particles.



Figure 7. EDS elemental mapping of the surface composite.

The through-thickness distribution of the silicon content is further examined in Figure 8. The spatial elemental concentration, presented in terms of counts per second, indicates that the aluminum content is uniform, and is rich within the base metal through to the composite/matrix interface. In the processed zone, the SiC content increases with lower aluminum content, which indicates good dispersion of SiC particles. On the other hand, the Si content is almost zero in the base metal, and increases toward the composite's outer layer. Other elements, such as oxygen and carbon, show a negligible change in content through the thickness.

The variation in silicon throughout the width of the processed zone was also examined, as presented in Figure 9. To eliminate the presence of foreign particles, the EDS measurements were carried out roughly 100 μ m beneath the top layer of the processed zone. The results show that silicon and aluminum are randomly present. The EDS spectrum generally indicates a larger number of counts for aluminum compared to silicon content for all points along the line of measurements. However, at a measurement distance of approximately 110 μ m, there is a large peak of silicon content presenting higher counts than those for aluminum. The higher silicon content might be a result of the clustering of

SiC particles. Other Si peaks are also shown in the spectrum, indicating small regions of SiC clusters throughout the processed zone. The presence of silicon is evident from the line of measurements, which indicates sufficient dispersion of SiC particles.



Figure 8. Vertical line EDS spectrum at the center of the surface composite starting from the top surface of the composite layer to the composite/matrix interface.



Figure 9. Horizontal line EDS spectrum of surface composite measured at 100 µm below top surface.

3.3. Microhardness

The widthwise microhardness profile of the processed zone, along with the average microhardness of the as-received 1100 aluminum, are shown in Figure 10 for three processing conditions. The microhardness indentations were measured at 150 µm below the top surface of the SZ. The average microhardness of the as-received 1100 aluminum was 38.5 Hv. In the case of FSP with negligible SiC dispersion, the results show a reduction in the hardness below the base metal value for all points measured in the processed zone. This indicates that the as-received aluminum, which was initially in cold-worked condition, was exposed to high frictional heat during FSP, resulting in a drop in hardness in the heat-treatable 1100 aluminum alloy. For the workpiece processed using a plunge depth of 0.6 mm, the surface composite's microhardness was, remarkably, higher than the base metal due to the dispersion-strengthening mechanism attained as a result of the presence of the reinforcement SiC particles in the processed zone [4,35,38,39]. High hardness values, approaching 76 Hv, were recorded near the center of the processed zone, which is consistent with the OM and EDS results, supporting the production of excellent SiC dispersion in the thick composite layer at the center of the processed zone. The increase of hardness extends roughly 5 mm from the center of the processed zone. Beyond 5 mm, a reduction in the hardness was shown to occur, reaching a minimum of approximately 24 Hv at the composite/matrix interface, which is lower than the hardness recorded for the as-received aluminum (38.5 Hv). The reduction in hardness demonstrates that the dispersion of SiC particles into the aluminum matrix became less effective as the distance from the tool center increases. Over such large distances, the hardness is strongly governed by the aluminum matrix.



Figure 10. Vickers microhardness profile of a horizontal line at the upper layer of the sample.

In addition, the hardness profile of the workpiece processed using a plunge depth of 0.6 mm was not symmetrical. The hardness was slightly higher on the retreating side. Additionally, the decrease in hardness below the base metal value was less present on the retreating side. Such non-symmetrical behavior can mostly be attributed to the temperature increase in the advancing side in comparison to the retreating side during processing, as reported by [40,41]. The hardness profile recorded for the workpiece processed with a plunge depth of 0.6 mm was reported by Sharma et al. [26], indicating steep fluctuations in the hardness are strongly related to the SiC agglomeration and formation of clusters/bands of and/or the number of dispersed particles. The volume fraction of SiC particles is expected to influence the microhardness in the processed zone. As the volume

percent of the SiC particles increases, the microhardness eventually increases. This was reported by Mishra et al. [4], where the microhardness of the surface composites increased by more than 50 Hv when the vol.% of SiC particles was increased from 13% to 27%. The measured microhardness values for the workpiece processed using a plunge depth of 0.6 mm were generally in good agreement with the results of the semi-quantitative elemental mapping presented in Figures 8 and 9.

Figure 11 presents the through-thickness hardness profile at the center of the three cases examined in Figure 10. For the workpiece processed by FSP without particle dispersion, there is a decline in the hardness below the as-received value, reaching a minimum of 28 Hv at approximately 0.4 mm below the top surface. The hardness values gradually increase at increasing depth, reaching the hardness of the as-received material at a depth of 3 mm. For the workpiece by a plunge depth of 0.6 mm, the dispersion of SiC particles at the top surface resulted in an increase in hardness to 76 Hv and a decrease at greater depths, dropping to approximately 45 Hv at the composite/matrix interface (0.5 mm from the top surface). The remarkable increase in the microhardness at the outer processed surface is most likely attributable to the presence of the reinforcement SiC particles, as demonstrated by the ESD mapping presented in Figures 8 and 9. In addition, a further reduction in hardness to 35 Hv was recorded at depths greater than the composite/matrix interface (between 0.5 and 1 mm). However, the hardness gradually increased to the hardness of the as-received material at a depth of 1 mm. Compared to the workpiece processed using FSP without SiC dispersion, the decrease in hardness in the aluminum matrix region next to the composite/matrix interface was less severe for the workpiece processed using SiC dispersion via FSP. This indicates that the amount of frictional heat absorbed by the aluminum matrix was greater for the workpiece processed by FSP without SiC dispersion, and thus the reduction in hardness was not only stronger, but also occurred at a greater depth below the processed surface. It can also be deduced that dispersion of SiC on the top surface of the workpiece acted as a lubricant, reducing the transition of frictional heat in the aluminum matrix due to FSP, and thus producing less loss in hardness in the base metal.

The plunge depth was shown to strongly affect the development of uniform thickness of the composite layer, as well as the uniformity of SiC particle dispersion and hardness development. For a given angle of tilt (°7), the increase in plunge depth resulted in an increase in the contact area between the shoulder and the workpiece. This eventually promoted greater depth in the composite layer, considering that the back-extrusion force was not sufficiently high to cause matrix plastic flow into the tool hole. However, the increase in plunge depth could have a deteriorating effect on the matrix microhardness due to the high amount of heat generated during processing, as previously reported by Rathee et al. [42]. However, the reduction in matrix microhardness was shown to be small when the plunge depth was carefully chosen at a value of 0.6 mm, as also demonstrated in Figure 11.



Figure 11. Vickers microhardness through-thickness profile of the FSP aluminum alloy.

4. Conclusions

A new approach and tool design for direct friction stir processing to eliminate the step of preplacing reinforcement particles into the base metal was proposed for developing a surface composite layer on 1100 aluminum alloy. The FSP tool consists of a two-part hollow body, i.e., a hollow shank and a shoulder. The new processing approach requires less than half of the tool shoulder to contact the surface, allowing the dispersion of reinforcement particles onto the workpiece's surface through the hole and mitigating the blockage of the hole during processing. Three different sizes of hole were used, but the 6-mm hole was the optimum. The high rotational speed rate, a tilting angle of 7° for the tool, and a moderate plunge depth produced the heat required for plasticization, leading to the application of reinforcement particles. These tool design and processing approaches were shown to effectively disperse the microsized SiC particles into the aluminum matrix during FSP, reaching a uniform distribution of SiC particles in the SZ at the top surface of the base metal with no porosity. The Al/SiC surface composite layer has a thickness ranging from 50 μ m, near the edge of the processed area, to about 300 μ m, at the center of the processed area. The microhardness increased remarkably from 38.5 Hv at the base to about 80 Hv at the composite's top layer.

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