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Research Paper

Improving the Hardness and Microstructural Properties of Piston Alloy Using the FSP Method

Mostafa Akbari[1*], Parviz Asadi[2], Hossein Rahimi Asiabaraki[1]
[1]Department of Automotive, Technical and Vocational University (TVU), Tehran, Iran
[2]Department of Mechanical Engineering, Faculty of Engineering, Imam Khomeini International University, Qazvin, Iran
[*]Email of Corresponding Author: mo-akbari@tvu.ac.ir
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Abstract
Al-Si alloys are widely used in the manufacture of automotive parts such as pistons and cylinders. Although it has desired properties for use in pistons, some microstructural properties of this alloy, such as dendrites or the presence of needle-like silicones, reduce the performance of the parts produced. In this research, to modify the microstructural properties and thus improve the mechanical properties of the alloy, the friction stir processing (FSP) method is used. Also, the effect of process parameters such as rotational and traverse speeds as well as the shape of the pin on the microstructural and mechanical properties of the samples, are studied. The results show that the FSP process improves the microstructural properties of the base metal, and thus improves its mechanical properties. Furthermore, by increasing the rotational speed or decreasing the traverse speed of the tool, the silicon particles become finer, and consequently, the microstructural properties are improved.

Keywords
FSP, Microstructure, Piston Alloy, Pin Shape

1. Introduction

Al-Si alloys are among the alloys that, due to their widespread use in industry, especially in the automotive industry, have attracted the attention of researchers to modify and improve the performance of these alloys [1-3]. These alloys are widely used in the production of internal combustion engine components such as pistons. In order to improve the performance of internal combustion engines, such as increasing the compression ratio of these engines, which increases their efficiency, it is necessary to increase the performance of these alloys to withstand high temperatures and friction. Even though these alloys have good wear resistance, some defects of these alloys, such as cavities, dendritic structure, and non-uniformly dispersed acicular silicon particles, have limited the use of these alloys in many applications[4, 5].

Friction stir processing (FSP) has recently been developed to modify metal microstructure based on the basic principles of friction stir welding (FSW) [6, 7]. The basis and parameters of these two processes are similar, and there are slight differences between them. In terms of microstructural changes and material properties, there is no difference between the two methods. The goal of the FSP process is not to connect the two samples but to modify the structure, change the grain size, increase the strength, make the structure uniform in terms of grain size, distribute the sediments and create surface composites as the achievements of this process. In friction stir processing, the tool pin penetrates the integrated workpiece to create local microstructural modifications to enhance the desired properties in the metal [8]. So far, research has been done to improve the microstructure of these alloys. Cheng et al.[9] processed Al-Si alloys through rolling and FSP to optimize the mechanical properties of these alloys. They stated that FSP resulted in the fragmentation and uniform distribution of Si particles in the base alloy and then eliminated Al-Si alloys' preferential crack propagation channels during tensile tests. Charandabia et al. [10] employed the FSP method to modify the microstructure and hardness of an automotive-grade Al-Si alloy after friction stir processing. In this study, the parameters of the FSP process, which plays a significant role in the final performance of the samples produced, were not studied, and only a rotational and linear velocity of the tool was used.

In the FSP process, process parameters such as traverse and rotational speed and the shape of the tool pin have a huge impact on the properties of the sample produced [7, 11-13]. As the rotational speed increases or the traverse velocity decreases, on the one hand, the temperature produced in the samples increases, and on the other hand, the plastic strain also increases. Increasing the temperature causes deterioration of microstructural properties due to increased grain growth rate. Also, increasing the strain rate increases the recrystallization, which improves the microstructural properties. Also, the shape of the tool pin, as the main factor determining the material flow, plays a vital role in the properties of the produced samples. In this research, first, the microstructural properties of the base metal are investigated. Then, using the FSP method, the microstructure of the base metal is modified to eliminate dendrites, needle-shaped silicones. Then the various process parameters are examined to achieve the best microstructure.

2. Experimental method

The A356 alloy is one of the most widely used Al-Si series alloys in auto parts production. In this study, to modify the microstructure of this alloy, A356 ingots were cut into sheets with a thickness of 10 mm. The chemical compositions of the alloy used are also shown in Table 1.

Table 1: Chemical composition of as-cast A356 aluminum plates (wt. %)

Si	Fe	Cu	Mn	Mg	Zn	Ti
7	0.31	0.2	0.1	0.3	0.1	0.25

Rotational speed, traverse speed, and pin shape are the most critical process parameters FSP, that the correct selection of these parameters improves the properties of the produced sample. In this study, rotational speeds of 800, 1200, and 1600 rpm were used to produce samples. Moreover, traverse speeds of 8, 32, and 80 mm / min were also selected as linear speeds of the tool. In order to investigate the effects of tool pin shape on the properties of the produced samples, cylindrical, square, triangular, and threaded pins, which are widely used in this process, were selected. The dimensions of the tools used in this research are shown in Figure 1. The pitch distance of the threaded pin profile tool was 1 mm. In all the experiments, the FSP tool tilt angle and the penetration depth were kept constant at 3 and 3.5 mm, respectively.

The microstructural properties of the FSPed specimens were studied using an optical microscope (OM). The FSPed samples were mechanically polished and etched with Keller's reagent to reveal the micro-structures. Moreover, the size of Si particles was measured using image analyzing software.

Vickers micro-hardness of the FSPed specimens was determined on the cross-section perpendicular to the FSP direction at 200 g load at various locations in the stir zone (SZ).

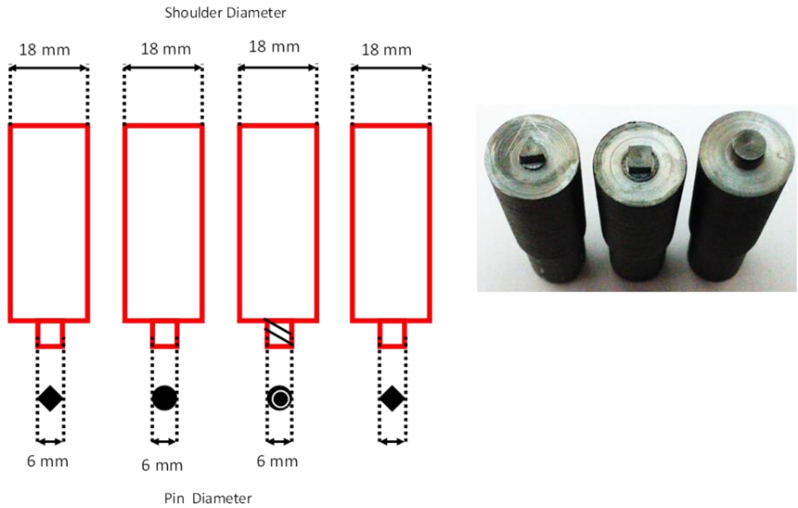

Figure 1. Dimensions of the tools used.

3. Results and discussion

3.1 Microstructural properties

The microstructure of the base metal is shown in Figure 2. As can be seen, needle-shaped silicon particles are heterogeneously distributed in the base metal. On the one hand, these needle-shaped particles and their uneven distribution in the base metal, on the other hand, reduce the mechanical properties of this alloy due to factors such as stress concentration. The brittle behavior of this metal is due to this observed microstructure [14]. Other defects such as cavities or α-Al dendrites are also seen in the base metal. The average size of silicon particles in the base metal is about 10 microns with an aspect ratio of 4.67.

Figure 2a shows the different areas of the FSPed sample. As can be seen, in the SZ, the silicon particles become much finer and are homogeneously distributed in the base metal. The excessive strain created by the tool pin causes these particles to be crushed and redistributed in the base metal. Also, the cavities and dendrites in the base metal structure have been destroyed due to the intense material flow created in this area. The formation of this microstructure eliminates the fundamental problems of the base metal, and it is expected that the mechanical properties will improve.

The next region created in FSPed samples is TMAZ. This area experiences less stress than the SZ [15]. As it turns out, the silicon particles have shifted around the SZ region (Figure 2a). The size of silicon particles in this region is larger than the particles in the SZ region and smaller than the particles in the base metal. This area can be called the transition zone from SZ to the base metal.

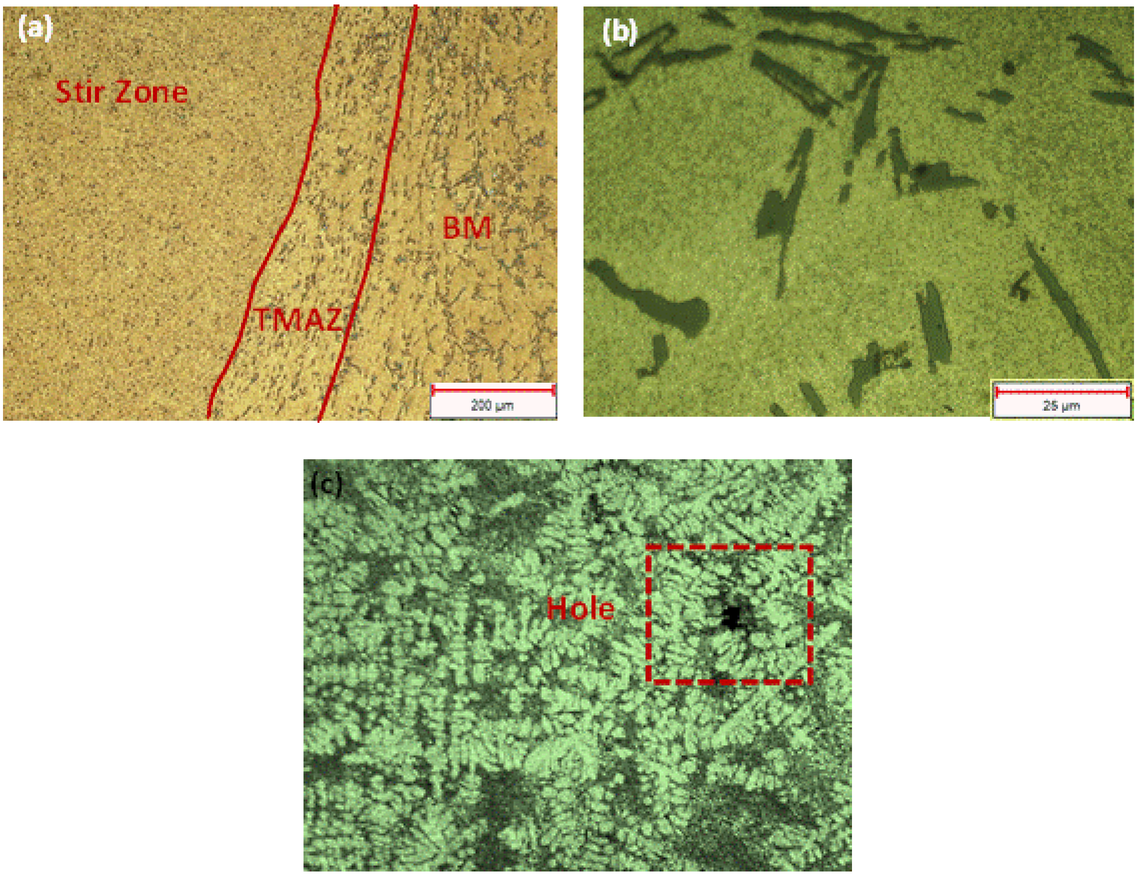

Figure 2. Microstructure of a) Different areas of FSPed samples b) Silicon particles of base metal c) Cavities and dendrites in base metal

As mentioned, the selection of optimal process parameters plays a significant role in modifying the base metal microstructure. We first examine the effects of linear and rotational velocities on the microstructure of FSPed specimens. Figure 3 shows the microstructure of the SZ of samples produced with different rotational and traverse velocities. Table 2 also shows the average size of silicon particles in these samples. Note that the samples are produced with threaded pins. As it turns out, the size of silicon particles of all samples produced at different speeds is smaller than the base metal silicon particles. This shows that the use of the FSP process, even without the use of optimal parameters, improves the microstructural properties. Also, the particles in all samples are out of the needle shape.

As can be seen in the figure and table, increasing the rotational speed causes the size of the silicon particles to become smaller. As the rotational speed increases, the strain rate around the rotating pin increases, which increases the stress on the silicon particles and makes them smaller. As the rotational speed increases from 800 rpm to 1600 rpm, the average size of silicon particles in the SZ decreases by about 60%.

Increasing the traverse speed has the opposite effect of increasing the rotational speed in determining the size of silicon particles. As the traverse velocity increases, less time material is subjected to strain, resulting in less stress on the silicon particles, resulting in an increase in particle size. With increasing traverse velocities from 8 mm/min to 80 mm/min, the size of silicon particles in the SZ region has increased by about 460%.

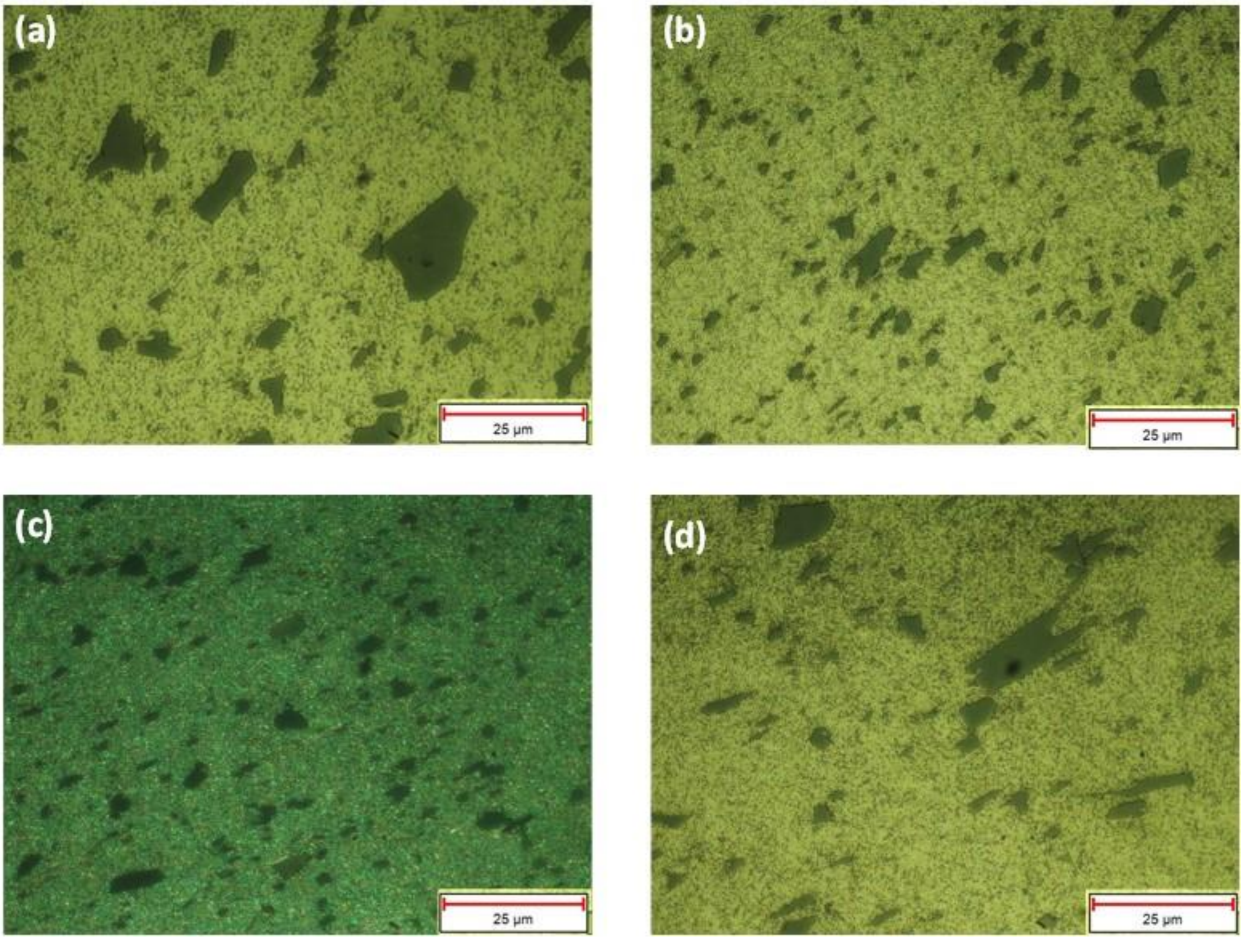

Figure 3. The microstructure of the SZ at various tool rotational, and traverse speeds of a) 800 rpm, 32 mm/min, b) 1600 rpm, 32 mm/min, c) 1200 rpm, 8 mm/min, d) 1200 rpm, 80 mm/min.

Table 2. Silicon particle size changes with traverse and rotational speed changes

Tool Speed	1200 rpm-8 mm/min	1200 rpm-32 mm/min	1200 rpm-80 mm/min	800 rpm-32 mm/min	1600 rpm-32 mm/min
Si Particles size (μm)	1.1	3.1	6.2	3.7	1.5

Another influential parameter on the microstructure of FSPed samples is the shape of the tool pin. The tool pin is the main factor in the formation of material flow during the process. The use of different shapes of tool pins causes a change in the material flow and, as a result, the microstructure produced. As it turns out, the cylindrical tool has produced the worst microstructure with the largest silicon particle size compared to other tools (Figure 4). The use of threaded tools reduces the size of silicon particles compared to cylindrical tools. Silicon particles are trapped between the threads of the tool and will be crushed as the tool rotates. The tool threads also cause a vertical flow of material in the SZ region, which increases the strain and thus the finer silicon particles compared to the cylindrical tool. Figure 4c&d shows the microstructure of samples produced with square and triangular tools. As it is known, the size of silicon particles produced with these tools has been significantly reduced compared to cylindrical and threaded cylindrical tools.

Square and triangular tools have flat surfaces that cause a kind of eccentricity when rotating the tool. This eccentricity is defined as the ratio of the dynamic volume swept to the static volume of the tool pin. This ratio is equal to 1.5 and 2.41 for square and triangular tools, respectively. In addition, the eccentricity of the pin shape is associated with dynamic orbit. The dynamic orbits of all pin profiles utilized in this study are demonstrated in Figure 5. The pin profiles with flat faces produce a pulsating stirring action in the flowing material because of flat faces. Triangular and square pin shapes produce 62.5 and 83.3 pulses/s when the tool rotates at a speed of 1250 rpm (Table 9). There is no such pulsating action in the case of cylindrical profiles.

The presence of two factors, eccentricity and pulse generation during tool rotation, produces better microstructure when using triangular and square tools. These two factors cause pressure waves to form around the tool pin, which causes the silicon particles to become more refined.

As shown in Figure 4 and Table 3, the triangular tool performed better than the square tool and produced finer silicon particles. It illustrates that the pulsation effect of the square pin is severe than the triangular, and the number of pulses generated by the square pin is 33% more than the triangular pin; however, the rotating arm is bigger for the triangular pin. The better microstructure produced by the triangular tool indicates that the rotating arm length is a more critical parameter than the number of pulses.

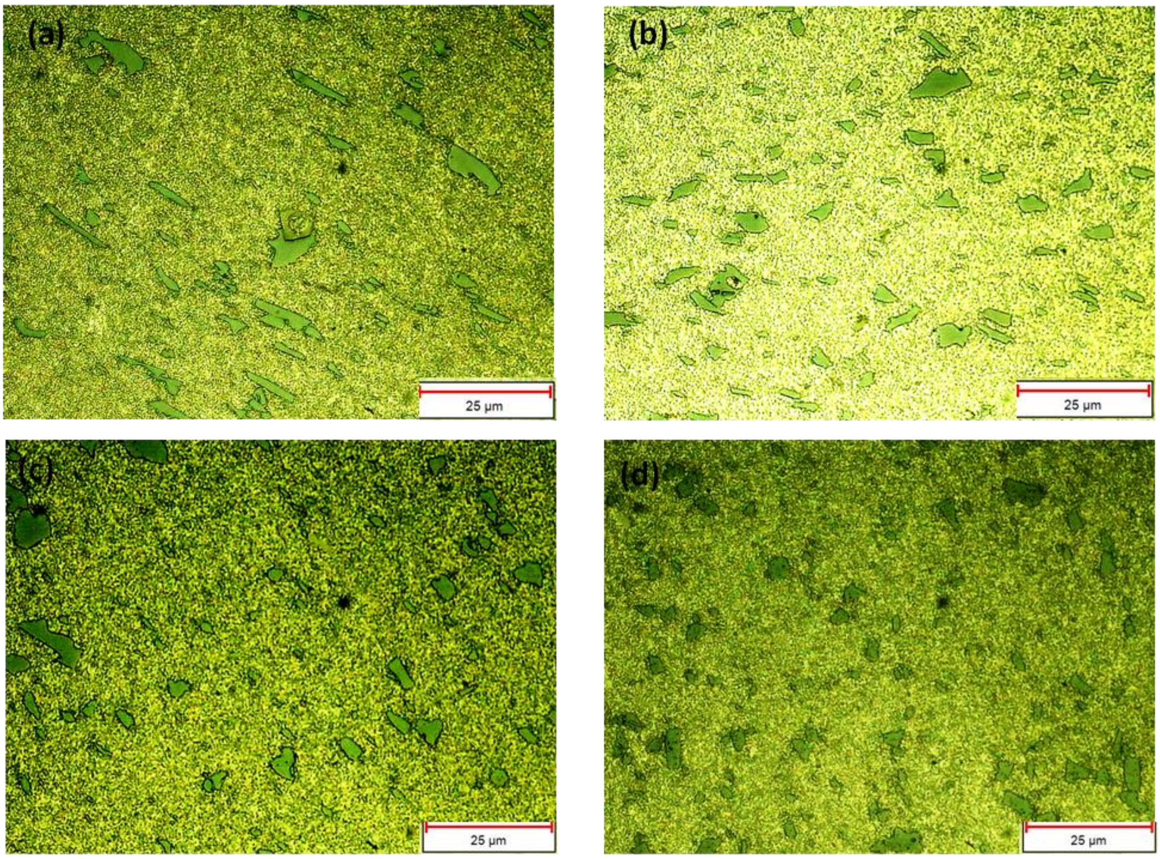

Figure 4. The microstructure of the center of the SZ at various pin profiles of a) Cylindrical pin profile, b) threaded pin profile, c) Square pin profile, d) Triangular pin profile

Table 3. Silicon particle size in samples produced with different pins

Pin Shape	Cylindrical	Threaded Pin	Square	Triangular
Si Particles Size (μm)	6.2	3.7	2.4	2.1

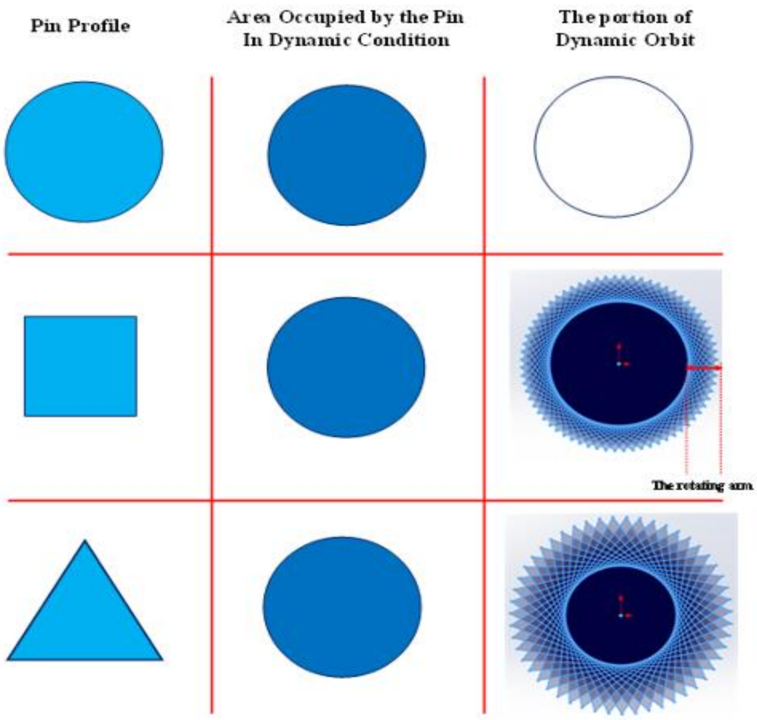

Figure 5. Impact of tool pin profile on perturbation area

3.2 Hardness

One of the problems with cast aluminum alloys is their low hardness. The FSP process is one of the processes that improve the mechanical properties by modifying the alloy's microstructure. Tables 4 and 5 show the average hardness in the SZ for samples produced at different speeds and with various pins. As it turns out, all produced samples have a higher hardness than the base metal, although the extent of this improvement in hardness depends on the parameters used. The hardness of the base metal used in this study was about 45 HV. As the traverse speed decreases or the rotational speed increases, the hardness of the samples increases. This increase can be related to the improvement of microstructural properties such as finer silicon particles. As seen, increasing the rotational speed or decreasing the traverse speed causes more crushing of silicon particles and reduces their size. These results are consistent with the results obtained by Sharma et al.[16] . In their research, they found that as the size of the silicon particles in the base metal decreased, the hardness of the samples increased. Smaller Si particles produced by the FSP exert an additional strengthening effect on the aluminum matrix through dislocation/particle interaction. Also, the use of triangular tools has produced the highest hardness among the samples. This improvement in hardness is due to the smaller size of the silicon particles in the SZ region.

Table 4. Hardness of samples produced using different tool speeds

Tool Speed	1200 rpm-32 mm/min	1200 rpm-80 mm/min	800 rpm-32 mm/min	1600 rpm-32 mm/min
Hardness (HV)	72	51	57	74

Table 5: Hardness of samples produced using different tools

Pin Shape	Cylindrical	Threaded Pin	Square	Triangular
Hardness (HV)	51	72	89	91

4. Conclusions

In this study, for modifying the microstructural and mechanical properties of A356 alloy, which is one of the most widely used alloys in the production of pistons, the FSP method was employed. Moreover, for producing FSPed samples, various process parameters such as different speeds and the shape of pins were used, and optimal parameters were introduced. In summary, the following results were obtained:

- The use of the FSP method significantly improved the microstructure of the base metal, such as crushing of silicon particles, homogeneous redistribution of these particles in the base metal, elimination of dendrites and cavities.
- Increasing the rotational speed or decreasing the traverse velocity causes the silicon particles to become finer and consequently improves the microstructural properties.
- The use of a triangular tool produces the best microstructure among the tools due to the presence of a type of eccentricity that generates pulses during the tool life.
- An inverse relationship was observed between the size of silicon particles in the SZ and the hardness of the sample in this region. As the particle size decreases, the hardness of the samples increases.
- The use of triangular tools produces the best sample in terms of mechanical properties.

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