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PAPER

Study of the effect of nano ZrO_2 and TiO_2 and rotation speed on friction behavior of rotary friction welding of HIPS and PP

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Keywords: friction welding, mechanical properties, welding surface, HIPS, P.P, ZrO_2 TiO_2 nano particles

Abstract

The purpose of this project was to introduce a way to improve the mechanical properties of dissimilar welded material, which provides benefits such as affordability, high speed, and a suitable bond property. This experimental project applies the friction welding method, including combining parameters, such as a numerical control machine, two different speeds, and three different cross sections, including flat, cone, and step surfaces. When the welding process was done, samples were implemented and prepared via a bending test of materials. The results have shown that, besides increasing the machining velocity, the surface friction increased, and so did the temperature. Considering the stated experimental facts, the melting temperature of composite materials increased. This provides the possibility of having a better blend of nanomaterial compared to the base melted plastics. Thus, the result showed that, besides increasing the weight percentage of nanomaterial contents and machining velocity, the mechanical properties increased on the welded area for all three types of samples. This enhancement is due to the better melting process on the welded area with the attendance of various nanoparticle contents. Also, the results showed that the shape of the welding area could play a significant role, and the results also change drastically where the shape changes. Optimum shape in the welding process has been dedicated to the step surface. The temperature causes the melting process, which is a significant factor in the friction welding process.

1. Introduction

Rotatory friction welding (RFW) is a solid joining process for plastic also recognized as spin welding. In order to weld these materials, two chucks held the materials; one was fixed, while the other was rotating. The friction of joining the partner generates the required heat [1]. RFW is a solid joining process, which is also recognized as spin welding for plastic. To weld these materials, two chucks held the materials [2]. The driving motor continuously drives the chuck along with the heating and rotating stages. In IFW, the driving motor is disengaged, and two components are forced together by friction welding force [3]. The flywheel's stored kinetic energy can be dissipated as heat at the weld surface while the flywheel speed decreases. Linking different components is essential in engineering design; the welding process must be done due to tremendous engineering applications. Linking different materials using the FSW method improved engineering applications. As a result of the study, it was found that joint quality is defect-free [4]. In 1991 the Cambridge University Welding Institute conducted a study; the outcome was the invention the FSW method. In that project, they joined aluminum alloys. It must be mentioned that in the auto and aerospace manufacturing industries, FSW is essential. High impact polystyrene (HIPS) is a tough and rigid material that can be used in different industries. If the working environment is included with the impact, then HIPS is a wise choice. In order to join material with a thermoforming process, HIPS is suitable [5]. Polypropylene (PP), due to its tremendous mechanical and chemical behaviors, is widely used in engineering and industrial applications. PP is produced from monomer PP, which is a member of the polyolefin group. They are partially crystalline and non-polar, and have characteristics similar to those of polyethylene, but in the case of toughness, they show better behavior. PP color is white, and it must be noted that PP is the second most utilized commercial material, even more than polyethylene. FSW is a reliable method that can improve mechanical features to link different types of materials. In order to join two workpieces, FSW is an excellent choice to produce a large number of components to improve and increase plastic joining's mechanical features. The FSW technique is popular due to the higher strength of the plastic-based material join [4, 6]. Due to smaller surface energy, the presence of release agents from the last step of the process, and poor weldability, will remain the main reasons that makes the joining of polymers or plastic-based materials more difficult [7]. By utilizing some of the particle reinforcements, mechanical features of welding plastic-based materials can be successfully developed [8, 9]. By employing some particle reinforcement techniques with the origin material, welding of plastic-based materials was successfully achieved [10]. The ability to intermix plastic-based materials has been analyzed accurately before welding dissimilar polymer materials [11, 12]. Thermodynamically, most of the dissimilar polymers are not homogeneously mixed [13]. FSW of polyethylene has been performed using a different milling setup to advance its effects on the morphological properties of welds. This paper studies the reviewed particles based on the influence of mechanical performances on FSW low-density polyethylene and high-density polyethylene (HDPE), with reinforcing Fe metal powder considered [14]. A couple of different plastics can be welded to implement good mechanical properties. Current research has found that the glass transition temperature and melt flow index rheological properties of polymeric materials can be generated with metal powder reinforcement [15]. Multiple employments of FSW and PS processing in several industries is investigated. Polyethylene sheets including HDPE and HIPS were welded with FSW, and their mechanical features were examined; consequently, an innovative procedure to produce nanocomposite polymers is recommended. The strength and weakness of PS-welded polymer materials has been investigated [16]. The tool and shoulder profile plays an essential role in the FSW process [17, 18]. Before welding, one of the work parts is fastened to the rotatory chuck simultaneously with the drive flywheel of a supplied weight. Next, the other piece was rotated up to a high proportion of rotation to deposit the needed energy in the flywheel. Once rotating obtained the normal speed, the motor is switched, and the pieces were compressed together under pressure. The process was continued until it was completed [15, 19]. Due to the unique characteristics of nano TiO_2, such as high mechanical features that strengthen the structure, it has attracted much attention from researchers [20]. he effect of nano TiO_2 on cementation material has also been widely studied.

2. Experimental details

2.1. Material characteristics

Pure HIPS and PP were purchased from the National Petrochemical Company located in Mulla Sadra St, Tehran in this investigation, tand wo types (TiO_2–ZrO_2) of nanoparticles were acquired from US Research Nanomaterials Houston, TX, USA. The amount of employed nanoparticles comprises 0.7% of the total weight of the specimens. ZrO_2 nanoparticles have a purity of 99% and a size of 20–30 nm. Also, TiO_2 nanoparticles have 99% purity and sizes of 10–30 nm.

2.2. Experimental procedures

For a friction welding process, the sample with a circular surface was fixed, and then the second sample was moved with the desired rotating motion. When the final step of the welding process was completed, the rotation stopped, and the pressure continued to form the joint. All samples had a length of 40 mm and a diameter of 22 mm. Then, the machining process was applied to form the specimens (flat, cone, step). The whole welding period lasted 15 min. As shown in figure 1, the ledge's diameter for the step surface selected was 11 mm. Then, the drilling process was applied on another piece to equally distribute the force and welding process to prepare the groove side. The step ledge and groove length considered were 10 mm, and the desired angle of the cone surface assumed 45° with a 10 mm length. As shown in figure 2, this project was conducted on samples with three different surfaces (flat, cone, step), the test was performed with two rotational speeds (1200 and 2400 rpm) and 0.05 mm/round feed rate. The rest period for the welding process was 15 s, and it also must be mentioned that the test was applied on specimens with reinforcing TiO_2, ZrO_2 nanoparticles and without reinforcing nanoparticles. At first, the sample nanoparticles were attached to the spindle, and the other sample was attached to the fixture. After the rotation speed reached its desired speed, the two tangent surfaces of the samples and the automatic feed rate started the welding procedure. The time for the welding process in all samples is assumed to be constant. When the restrained period reaches its limitation, the welding process was terminated, and the welded specimens were cooled to room temperature. The mentioned process was implemented for all samples. Welded specimens are significant as shown in figures 1–3 while the welding operation was completed, the Bending test was applied. As shown in figure 4,

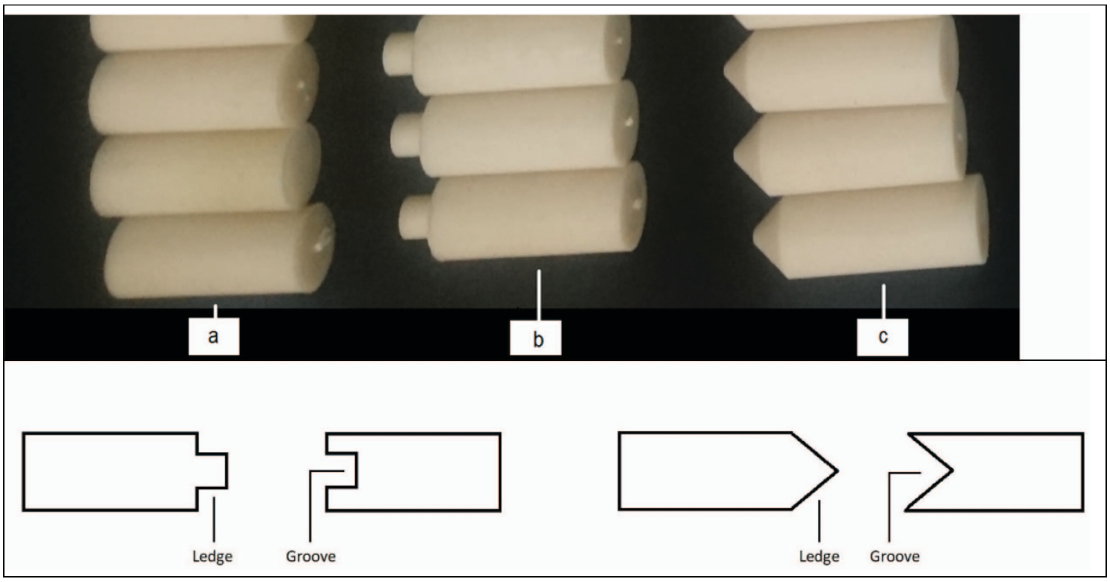

Figure 1. Flat surface (a), step surface (b), cone surface (c).

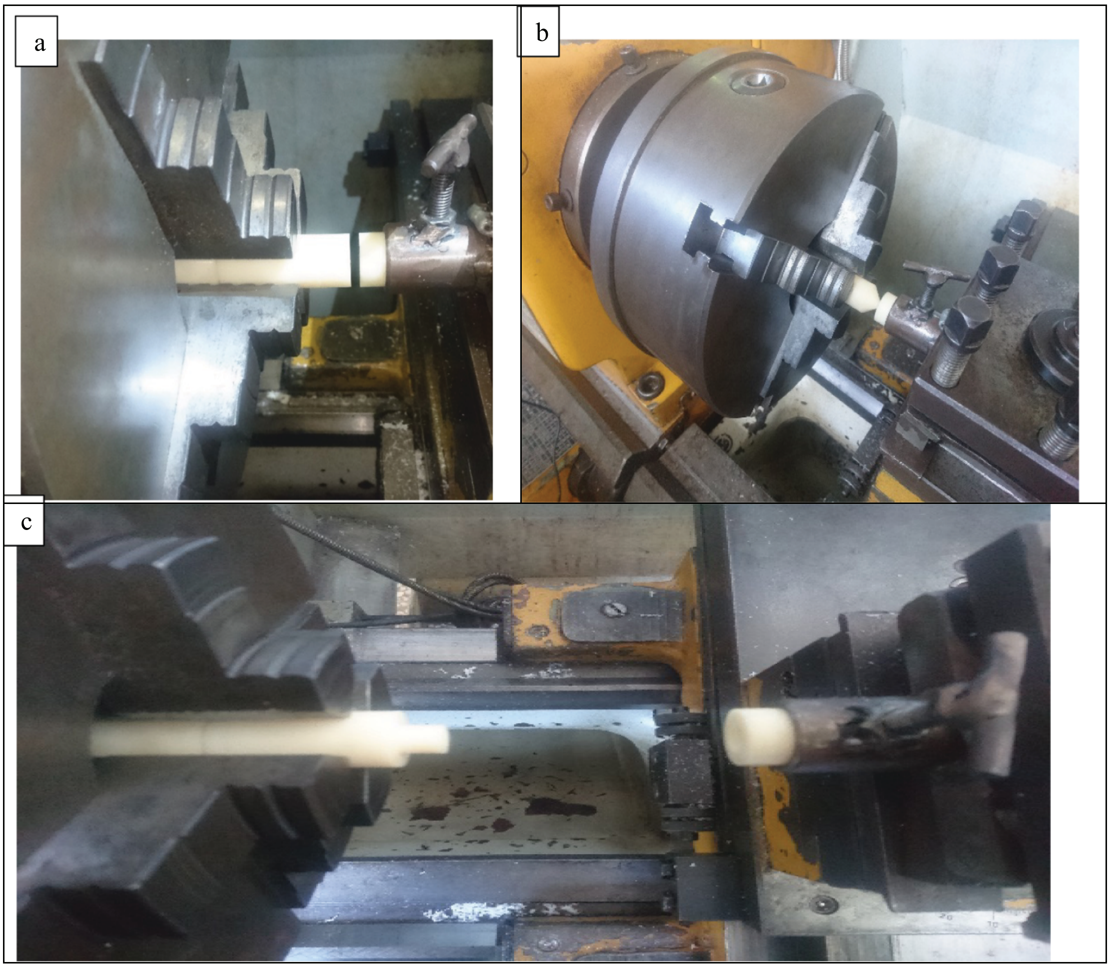

Figure 2. (a)Flat surface. (b)Cone surface. (c)Step surface are respectively the steps of the welding process for 3 different welding area.

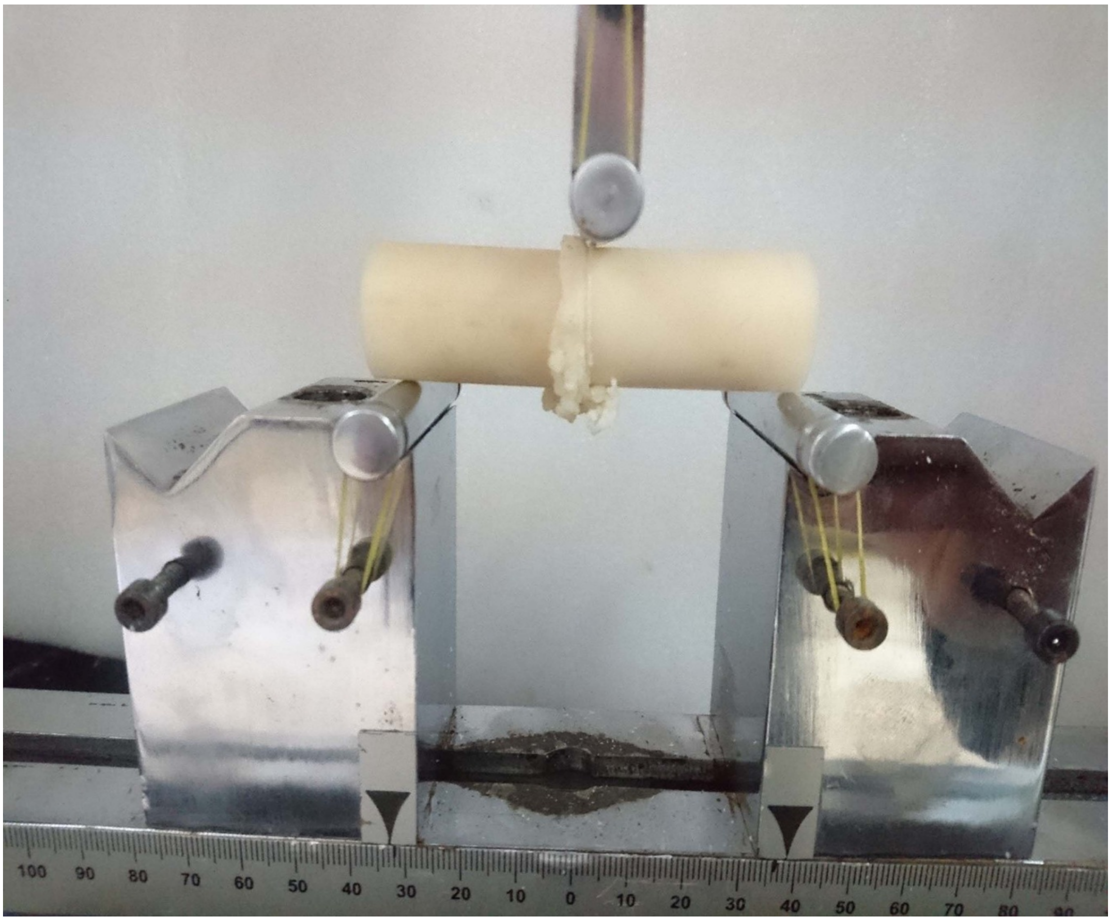

Figure 3. Bending test of joined HIPS and PP.

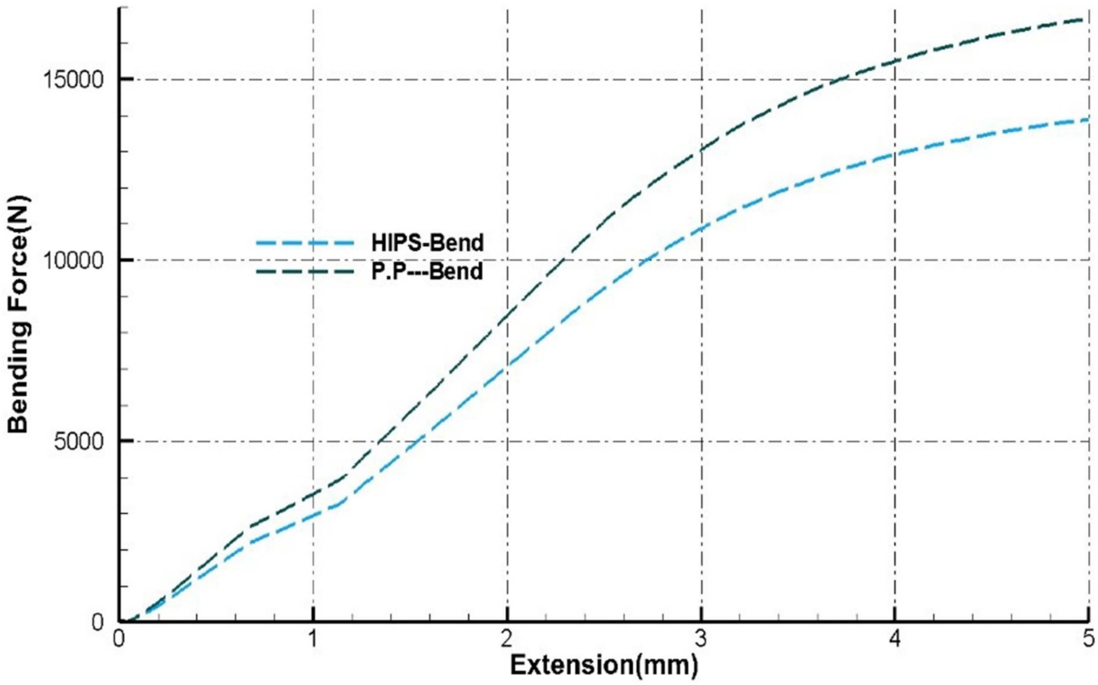

Figure 4. HIPS-PP bending results.

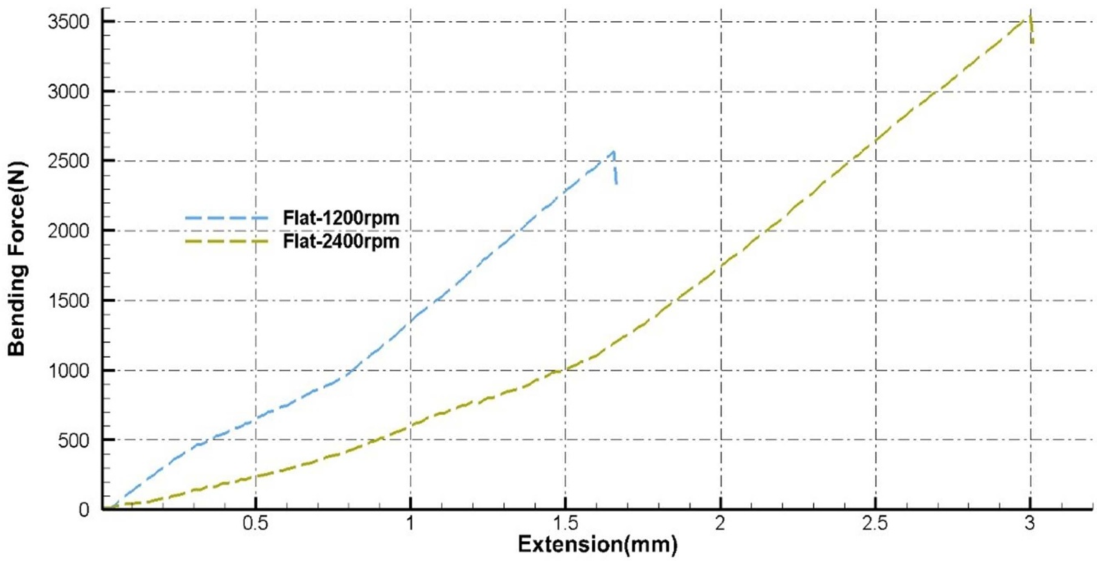

Figure 5. Flat surface of joined HIPS-PP bending results without nanoparticles.

based on ASTM D5934, the standard for the bending test of polymers, the test was implemented three times. According to the mentioned standard, the test speed should not exceed 0.5 mm $\min^{-1}$.

3. Discussion

3.1. Pure HIPS and PP

As shown in figure 4, no deformation or stress concentration was observed according to the force and extension variation graph for neat samples. All the unexpected factors were caused by surface variations or alterations on the surface areas of the samples that have not been observed. The machining process was not applied to these samples [12], so the samples were assumed to be fixed and uniform. With this assumption, the samples were applied for the mechanical test. According to the diagram of force/extension, all tests were repeated two times and were then analyzed. The sample is pure HIPS and PP (without nanoparticles or not welded); the elastic range is expected. These data showed that HIPS and PP samples have a frequently uniform structure that holds less porous structure and can help make a better bond in the welding structure. Considering certain conditions, calculating the safety factor for structural strength and the critical point must be studied. Also, for all samples at this test level, test factors are considered constants. Therefore, these samples are assumed to be uniform in engineering design [3, 18]. The engineering piece functions under various conditions. It must be mentioned that PP presented better mechanical behavior than HIPS. The higher bending strength is due to its higher density and more robust bonding structure, making this material more challenging.

3.2. Flat surface without nanoparticles

As can be seen in figure 5, a welding process applied to HIPS and PP at 1200 and 2400 RPM without the presence of nanoparticles has been conducted. The lower speed of the welding process caused residual stress, and residual stress can further turn into fatigue stress; compared to the welding with higher rotation, the yield stress reached a lower state of strength. According to this detail, this method could be used in conditions where more flexibility is required. It must be mentioned that the main reason for selecting the higher speed in the welding process is, firstly, it can create a better bonding structure in the polymeric chain; this chain held the whole structure and prevented failures. The speed of the rotation can also play a fundamental role in the strength of this bonding. Increasing the speed in the mold zone, temperature increases, and increasing mold zone temperature can better bond the thermoplastic structure. The obtained results revealed that by strengthening the bonding structure, the force and extension rate are increased, lower speeds cause less temperature, and increasing rotation speed causes a higher melt quality. As shown in figure 5, the welded sample in the lower rotation speed produces lower strength, indicating why the heat created by spindle welded samples at higher rotation speed has higher strength and extension. The welded samples in the lower rotation speed suffered accidental breakage, so higher rotation speeds in the friction

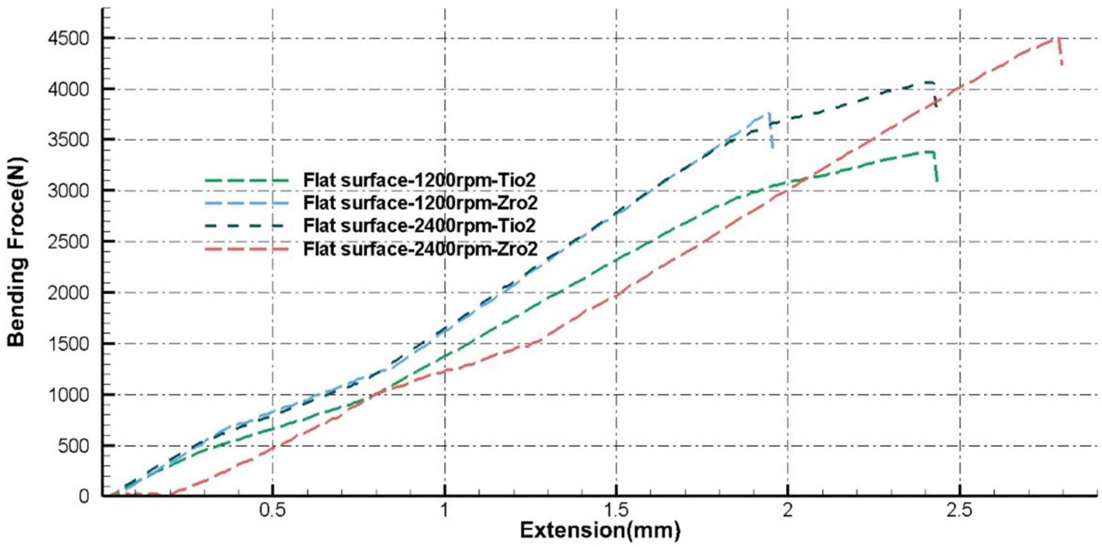

Figure 6. Results of flat surface joined by HIPS-PP bending with nanoparticles.

welding process caused the fracture point improvement because it creates high temperature. The mechanical results of the melted welding surface at a higher speed were more significant than those of the lower state.

3.3. Flat surface with TiO_2 and ZrO_2 nanoparticle

As shown in figure 6, based on experiments conducted on the mechanical properties of titanium oxide, it was found that compared to the non-reinforced nanoparticles, the mechanical strength and extension in the elastic zone increased due to the reinforcing agent nanoparticles. TiO_2 played an essential role in strengthening the polymeric chain in the weld zone, which activates the recent polymeric structure flux features. Nanoparticles covered the gaps in the dissimilar joining of thermoplastic. Further studies had shown that when higher rotational speeds were adopted, the sample's surface was completely melted and combined with nanoparticles. Also, these nanoparticles are deposited in the welding zone as a filling agent. As shown in figure 6, samples with ZrO_2 particles had greater ultimate strength than welding with TiO_2 and without nanoparticles. A UTS comparison was conducted on the welded samples at 1200 RPM. By surveying the graphs, it can be seen that the ZrO_2 nanoparticles integrated with the HIPS structure due to their adhesion and crystalline properties. Because of the ZrO_2 nanoparticle's nature, it makes the bonding of the chain stronger. When nanoparticles combine with the thermoplastic mold, the size of the nanoparticle polymeric chain becomes stronger. At the polymeric structure, microcracks are created by the molding process. These microcracks are caused by heat tension that can be healed or covered by nanostructures, which can improve the polymeric structure. The nanoparticles played an essential role. This article could be added and cover the weld area to prevent failure in the polymeric chain, nanoparticles strengthening the chain, and attempting to hold the structure during early or unexpected failures. The materials' behavior and the mechanical behavior are improved by the nanoparticles, which improve the welding quality and boosts mechanical performance. Also, with a different look at the ZrO_2 properties, it can be concluded that cracks or microcracks (as seen in figure 11) appeared in the weld zone; these cracks are filled with these nanoparticles and prevent pre-joint failure.

3.4. Cone surface without nanoparticles

As shown in figure 7, the welding geometry's temperature played an essential role in the joints' welding strength. Furthermore, after a survey was done on the geometry, the surface type showed an essential responsibility for the weld strength. According to the graph, samples without nanoparticles in linear growth reached a lower yield strength. This revealed that samples with this geometry have a greater chance of increasing the level of polymerization of the joints. Furthermore, the rotational speed played an essential role in the welding process; the rotational speed increased, and the melt zone temperature for both materials increased. The bonding strength improved drastically at the higher rotational speed due to the lower porosity accrued in the polymeric structure. Also, yield points improved; this improvement assists in the engineering design to predict or analyze the work condition to find the best utilization of the material design. Finally, regarding the equivalence parameters, it should be considered that the higher velocity causes high temperatures; it also causes better integration of the surface's connection.

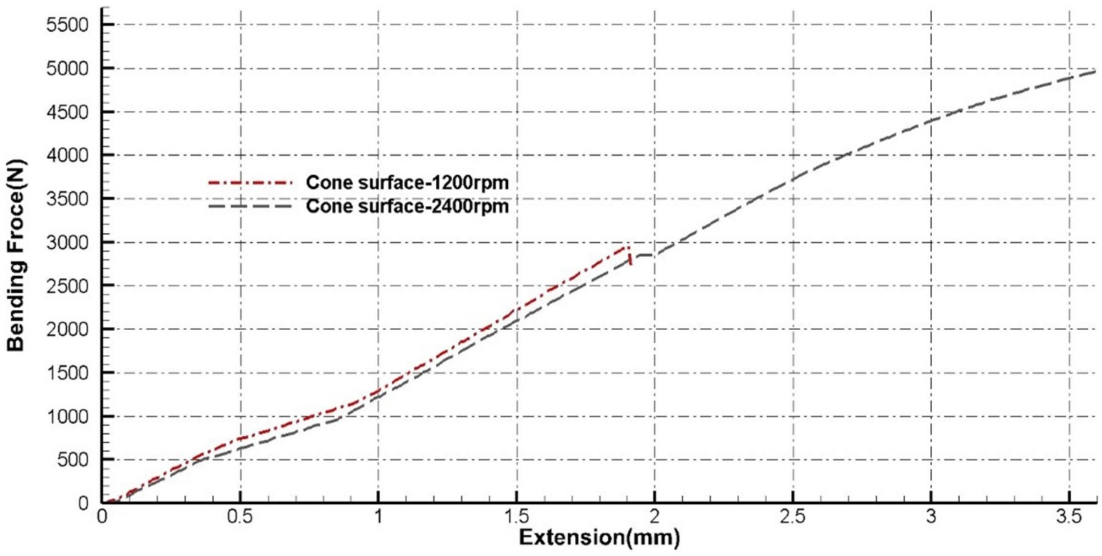

Figure 7. Results of cone surface joined by HIPS-PP bending without nanoparticles.

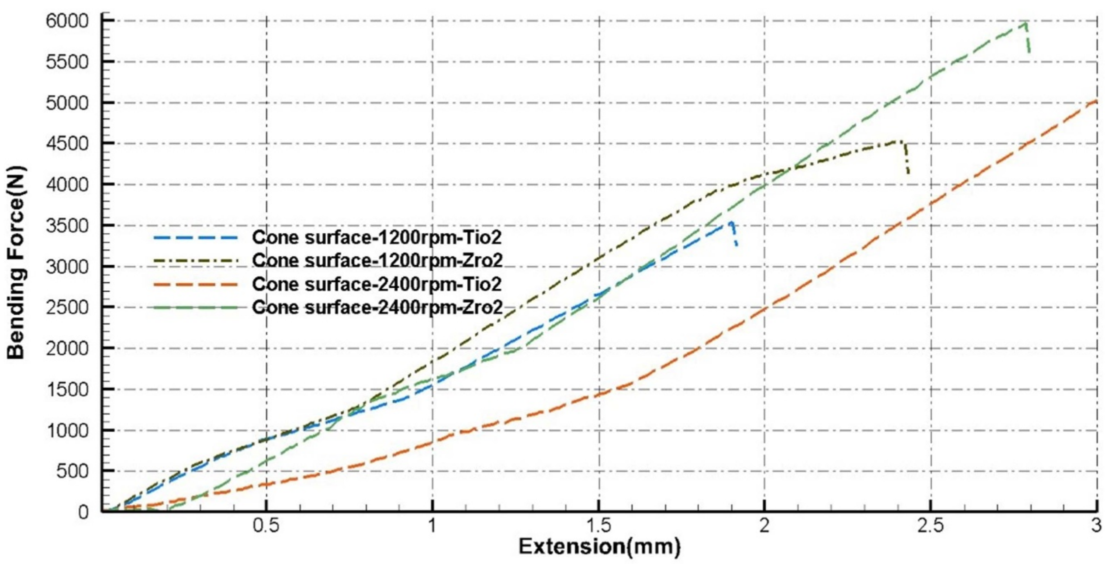

Figure 8. Results of cone surface joined by HIPS-PP bending with nanoparticles.

3.5. Cone surface with TiO_2 and with ZrO_2 nanoparticles

As mentioned in figure 8, the cone shape welding area improved the weld strength; also, nano TiO_2 plays an essential role in improving the weld zone's mechanical properties. Nanoparticles can play an essential role in strengthening the weld structure, and it is also noteworthy that nanoparticles cover porous structures; also, at 2400 RPM, due to the positive effect of temperature on the welding process, the fracture failure occurred at a higher level. Adding TiO_2 through the structure improved the adhesion in the polymeric chain. TiO_2 nanoparticles improved the polymeric chain elasticity. TiO_2 nanoparticles strengthen the polymeric chain by covering the microcracks, and porosity was created in the weld zone body. Porous areas are a probable incident that occured during the polymeric molding process. Nanoparticles can strengthen the structure against the external force loaded. These nanoparticles try to cover the gaps or even provide more elasticity to the structure. As can seen in figure 8, the welding depends on the shape and rotational speed by surveying the joint diagram's behavior and slope at 2400 RPM. Due to the properties of the ZrO_2 particle, such as adhesion and higher strength, the polymeric chains in the weld area improved. Considering that the effect of temperature created some thermal tension on the weld zone, residual stress created some microcracks. As can seen in figures 12(a)–(f), the beginning of crack growth is highly dependent on residual stresses. Also, the welding process is highly dependent on speed and heat, and the residual stresses on the weld area applied by

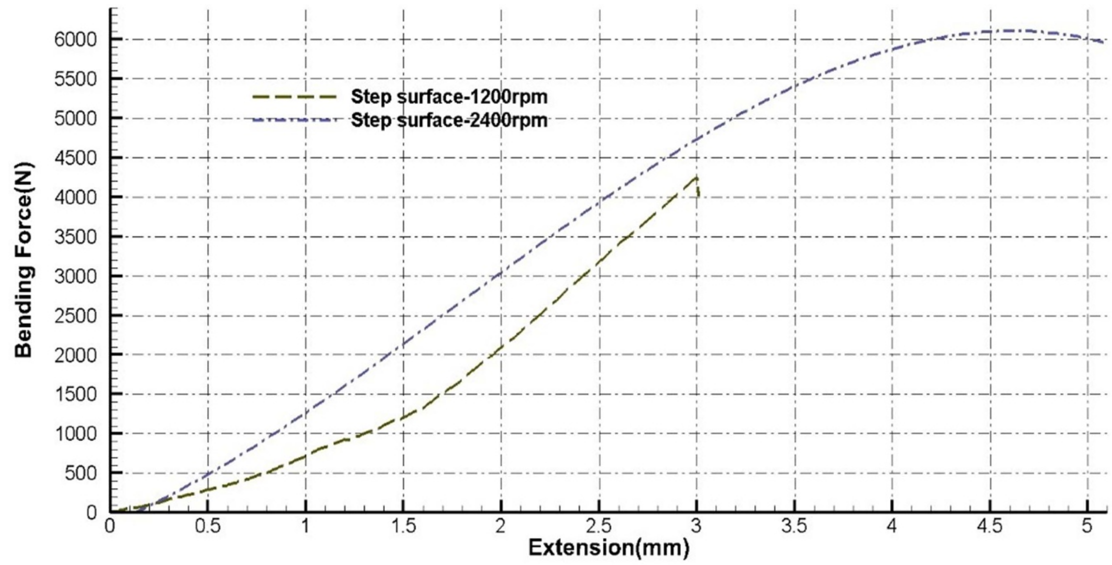

Figure 9. Results of step surface joined by HIPS-PP bending with nanoparticles.

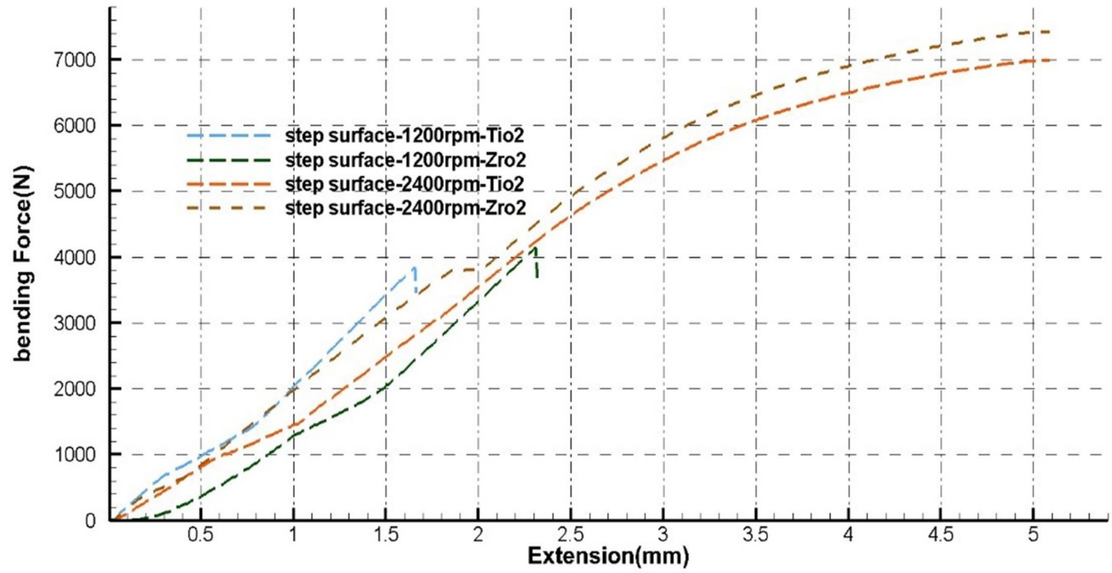

Figure 10. Results of step surface joined by HIPS-PP bending with nanoparticles.

the mentioned factors. The main aim studied in the current situation is finding a solution to decrease microcracks and improve mechanical properties. Here, adding particles is essential due to the healing and improvement characteristics, by which the mechanical properties on the weld structures improved.

3.6. Step surface without nanoparticles

According to the welding type and method shown in figure 9, samples with 1200 RPM have a more significant elastic region than those at 2400 RPM. This means that the samples with higher speeds and lower speeds increase or decrease elastic features on the weld zone. The plastic area decreases with relative strength and the temperature created; the pressure applied to the samples increases the surface friction. The sample's heat and melting levels increased more than the other samples with a lower welding speed by increasing the friction level. High rotational speed can increase friction, which can result in less porosity. The temperature factor is an influential factor on the fractures' stress and growing stress and force. Increasing the friction state improved the linkage durability on the weld zone; when the molding state increases, there are many opportunities to enhance the bonding structure. By increasing the temperature, two distinct parts are deeply welded, which can excite the linkage to participate in the welding process. It is concluded that increasing the

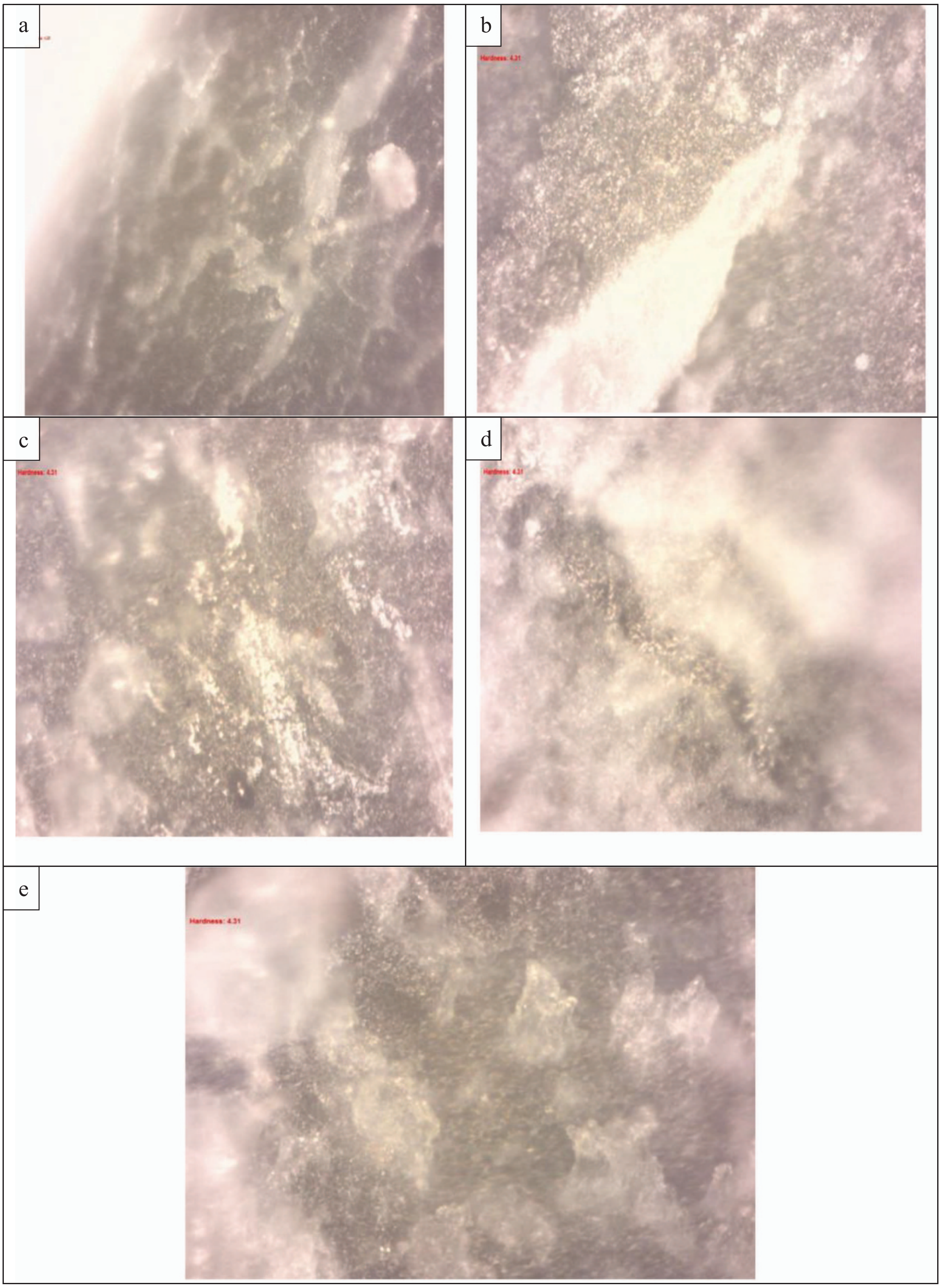

Figure 11. (a)–(e) are AFM images captured from the weld zone on different areas.

reach of the weld can create a better polymeric chain. By considering all factors, the welding process' rotational speed is classified as the main reason for the improvment in the mechanical features.

3.7. Step surface with TiO_2 and ZrO_2 nanoparticles

The conditions of the welding of non-nanoparticles shown in figure 10 show a similar behavior in nanoparticle welding, and properties have been observed in which nanoparticles can improve the nanocomposite joints performance; these advantages can be observed in figure 11. According to the mentioned figure, the yield stress reached its maximum limit. However, there is a significant difference in the

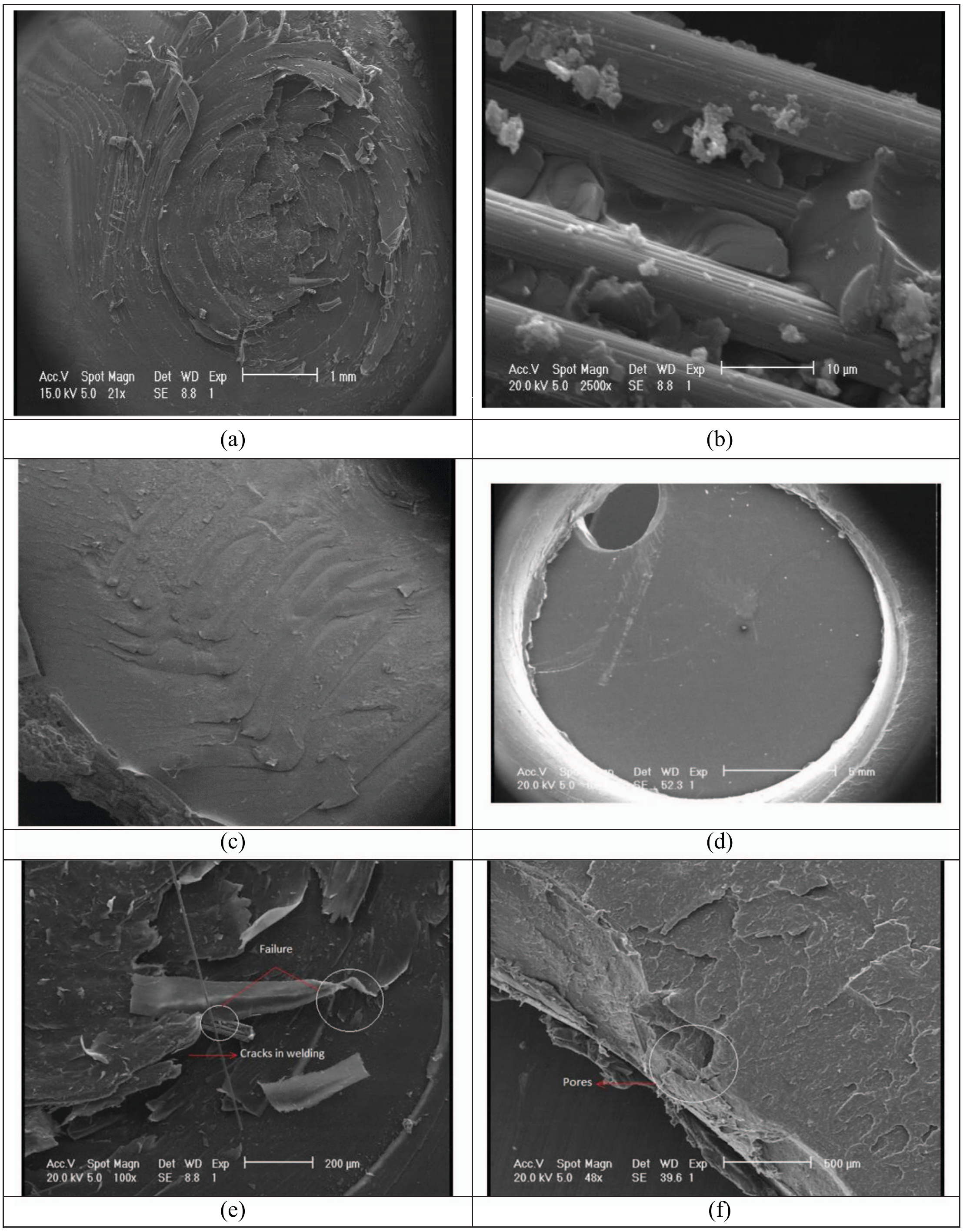

Figure 12. SEM shot of the welding area.

failure stress points, which reveals that the material's plastic behavior is less elastic based on the graph's curve. Nanoparticles are entirely mixed with HIPS and PP at the welding area. Nanoparticles showed an effective influence on the bonding structure strength. Porosity in weld areas has been created by the presence of oxygen in the welding process. As shown in figure 10, with the experiments performed at the welding of the step shape of the surface, the friction significantly affects the welding process. Because of the particles created on the ledge surface, ZrO_2 nanoparticles increased the fracture toughness resistance due to the filling role. Surveying the melting point of the component mixed in all directions also indicates that the main reason for the fracture resistance improvement and the residual force during welding operations are the ZrO_2 nanoparticles, which also prevent crack growth. As can be observed in figure 11, generally, nano ZrO_2 can be added to crystalizing structures that were just created during the molded process, which improves the samples' mechanical properties. In these structures at higher rotation speed, nano ZrO_2 is well distributed and placed between the gaps. With the increase of nanoparticles, the polymeric chain structure improved. As a result, nano ZrO_2 covered the polymeric chain and enhanced the mechanical properties. In this case, the effect of heat, which is generated by rotational speed, is considered.

4. Images of the result of AFM on the weld

It can be seen in figure 12 that the welded materials, and mechanical and frictional features are greatly affected by the microstructures and nanoparticles. As can be seen, the rotation speed is excellent and can be impacted in the weld zone, creating more porosity, weakening the weld. The effect of particles on strengthening the weld is considerable, and TiO_2 and ZrO_2 show different behaviors. ZrO_2 can mix well with a weld zone and create a massive crystalline structure with two dissimilar materials. Due to the high mechanical features of ZrO_2, better bonding in the structure was observed. The bonding in this structure, at higher work speeds, can improve the strength of the joined structure. As shown in figure 12, joining these dissimilar materials is highly dependent on the temperature of the weld zone, which at a higher spindle speed, strengthens the strength of the joint.

5. Conclusion

After conducting the tests and analyzing all the components that have been examined, the results are described below.

The rotation speed is a significant factor in the welding process because it develops with the increase of the temperature and causes the melting process to occur, which is a significant factor in the friction welding process. At the speed of 2400 RPM, which was the highest rate of speed employed in this project, better results even in samples without control nanoparticles were gained. Another parameter that affected the welding quality was the surface that predicted the increase in the cross-sectional area of the contact, increasing the welding surface, and, finally, the step surface showed the most substantial joining strength. Due to connection of two different directions, better welding quality was achieved due to the floor and the sample's rotating surface. After that, the step surface was analyzed, and the highest connection quality was revealed. Comparing the cone surface and step surface we found that the joint strength in the step surface improved because of the greater friction rate. Due to the unique properties of nanoparticles used in this project, a different effect on the discussed samples was achieved. According to the results, samples without nanoparticles differed substantially from those with nanoparticles used. In samples in which nanoparticles were used, higher quality and more UTS were recorded, in which nano ZrO_2 showed better mechanical behavior than TiO_2 nanoparticles due to their intrinsic properties. Also, this subject showed that nano ZrO_2 and step shape surface enhanced mechanical behavior.

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