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Investigation of surface hardness and roughness on formability of aluminum alloy sheet AA2024-T3 subjected to the shot peening process by silica shots

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Abstract

Shot peening is one type of modified surface treatment that produces a residual compressive stress on the material subsurface and improves surface properties while generating plastic deformation on the surface. This research work aims to improve surface properties, which include the enhanced material formability of aluminum alloy 2024-T3 sheet having 1.2 mm of thickness, by providing residual compressive stress on the surface using the shot peening process, which uses silica particles of 0.1 mm in diameter. First, shot peening was performed using various process parameters: compressed air, distance from nozzle to target, and duration time. Based on the obtained peening sheet, the surface hardness and roughness tests were experimentally performed on the peened surfaces. Additionally, the residual tension created in the sheet after the shot peening is calculated using the X-ray diffraction technique. Consequently, the shot-peened and unpeened sheets were put through hole expansion and Erichsen cupping tests to compare the results of the formability between the shot-peened and unpeened sheets. It was found that peened sheets had a low surface roughness and increased surface hardness, which is better than the unpeened sheet. Moreover, the residual compressive stresses were higher than on the original sheet. Last, the shot peening condition, which changed the surface properties the most, was tested on the hole expansion and Ericshen cupping tests, where the formability results were very significant.

1. Introduction

In the manufacturing of aerospace parts in the twenty-first century, lightweight materials have replaced standard steel in a variety of applications. Aluminum alloys are widely utilized to manufacture load-bearing components since they are among the lightest metals available. Currently, the aluminum AA2024-T3 sheet alloy has established itself as a competitive player in the aerospace sector. However, from a production standpoint, its limitation of formability is a major issue. It suddenly fractures after the maximum acceptable loading at room temperature. This reason induces us to study how to improve the formability of the AA2024-T3 sheet aluminum alloy. Clearly, shot peening (SP) is a kind of cold work that provides a residual compressive stress layer on the material subsurface and enhances material properties like surface hardness and roughness. When compressed air is used to drive media impact onto a surface, the surface layer of the base material is stretched, resulting in plastic deformation. This results in an improvement of their surface properties, which favorable properties can improve sheet material formability processes that prevent early failure during the sheet metal forming process.

In the industrial application, Mehmood *et al*. [1], Primee [2] and Rajesh *et al*. [3] reported and described an example of the manufacturing parts from the aluminum alloy AA2024-T3 that have been peened by media on their surfaces to produce the fuselage skin, wing ribs, bulkheads, landing gear beam and wing lower skin of aircraft and are being used in the production of helicopters like some of the rotor turbines. This is an aircraft part where fractures occur after the bending process. Therefore, it is important to study to improve the material so that it has the mechanical properties of the AA2024-T3 sheet material before it is put into production. For this reason, it is an important way to reduce the time and production costs, fix the problem as quickly as possible and support the aerospace industry. Therefore, the material surface improvement has been developed by using the shot peening process as reported in [1,2,4-6]. They have widespread use in the automotive and aerospace sectors. Shot peening is a strain hardening procedure that potentially improves fatigue life by increasing surface residual stresses. [2,6-9]

Mehmood *et al*. [1] utilized nickel as a particle medium in the shot peening process to enhance the surface residual stress of the material for improving the mechanical properties of the AA2024-T3 sheet. In the experiment, the selected process parameters are the distance between the specimen and the nozzle and the pressure. The enhancement of the modified surface is evaluated by surface hardness and fatigue strength. It can be concluded that increasing the pressure generates higher hardness on the workpiece surface, and the bending strength has increased accordingly. Otherwise, increasing the distance reduces the surface hardness and flexural strength, but the values obtained were not much different than the values prescribed. Additionally, Alalkawi and Shafiq [10] investigated the effect of shot peening on the mechanical properties of AA2024-T4 sheet material. It was found that that contribution enhances the surface hardness and yield strength values. In experimental tests, the bending strength is examined and results in an improvement of 3% to 5% of the original one. Subsequently, the particle process exposes the specimen surface to residual stresses, whereas the material has better mechanical properties. Furthermore, Mehmood *et al*. [1], Rajesh and Varthanan [4], and Otta and Sato [7] proposed that the stress produced after the shot peening process is higher than that of the unpeened workpiece. Concurrently, the peening process established the increasing flexural strength of the modified surface as reported in [4,5,12,13]. It was observed that the shot peening process increased the bendability. From the research mentioned above, it was found that if experiments were modified or used different parameters, they would affect the results of the mechanical properties of the material. This is because every parameter plays a part in the change in material properties after testing. Several researchers have dedicated their work to investigating the effects of the shot peening process on the mechanical properties and modified surface treatment as described in [4,14-20].

Shot peening can be induced to improve the surface properties because the process is powered by a collision and the energy generated by the impact between the particle media and the workpiece surface creates a very small dent [19,20], a plastic transformation. For the above reasons, residual stress is created on the surface by shot peening particles. The effect of the dimple on the modified surface: the plastic deformation is generated by the impact energy, which the particle size produces the small dimple after shot peening treatment. Apparently, Ongtrakulkij and Khantachawana [19] studied the fine shot peening process (FSP) and found that it enhances mechanical and surface properties using various media sizes. The experimental results demonstrate that the surface hardness and bending strength are strongly and slightly affected by media size, respectively. Ongtrakulkij *et al.* [20] investigated the influence of type and size of media on surface hardness and roughness of modified surface treatment. It can be described that the higher hardness and larger media provide more residual compressive stress, surface hardness, and roughness than those with lower hardness and smaller media. Those parameters produce higher strain hardening on the modified surface.

Previous research has devoted their efforts to studying the effects of shot peening process parameters on mechanical properties and modified surface treatment. These studies, however, did not place an emphasis on the characterization of the formability of modified surface sheets, which have increased surface hardness and residual compressive stress, including strain hardening behavior, occurring on the surface. Therefore, this novelty work aims to investigate the effect of surface hardness and roughness on the material formability through the various process parameters of the shot peening process, such as pressure air, distance from nozzle to specimen surface, and duration time. Then, during the formability evaluation, hole expansion and Ericshen cupping tests are done experimentally, and the drawing depths from these tests are used to figure out how well the modified sheets can be formed as a formability evaluation.

2. Experimental and material tests

The AA2024-T3 sheet with a thickness of 1.2 mm was investigated for this research. The main objective of this study is to look into the influence of shot peening on surface properties induced to increase sheet metal formability. To prepare for shot peening test conditions, square specimens of 30 mm × 30 mm are cut by a shearing machine. Experimental peening conditions were performed for peening with silica media with a size of 100 μm and a distance of 150 mm to 300 mm between the nozzle and the test specimen. There are two pressure settings, 0.35 MPa and 0.5 MPa, and the firing shot angle is always 90º. The media shutter was used to control the peening time, which ranged from 5 s to 10 s. Hardness, roughness, and residual compressive stress were all considered after shot peening. The digital microscope was utilized to investigate the surface roughness measurements and observe material surfaces to compare the surfaces with shot peening and without shot peening. Additionally, the surface roughness was measured using a roughness average (Ra). The residual stress was then determined via an X-ray diffraction (XRD) technique. The Vickers hardness (HV) test was also conducted in this investigation to determine the hardness of the top surface. Obviously, many researchers have hypothesized and reported that mechanical properties and plastic deformation on material surfaces have been modified by peening the specimens under different process conditions. So, this work is mostly about how the parameters of the shot peening process affect the ability to be shaped.

2.1 Material

Aluminum-alloy sheet AA2024-T3 is an appealing base material for lightweight aerospace applications. However, it has low formability and, more importantly, cracks suddenly just after the ultimate loading point. This material has a 148.3 HV surface hardness and a 0.16 μm surface roughness (Ra) before performing the shot peening process. Table 1 shows the important mechanical properties of the AA2024-T3 employed in this work. Tensile testing in the rolling direction (0°) resulted in the greatest results, with an ultimate tensile strength of 489.08 MPa, a yield stress of 378.66 MPa, and a percentage uniform and total elongation of 11.8 and 12.8, respectively. These mechanical

Table 1. Mechanical properties of AA2024-T3 aluminum alloy.

Direction	Yield strength (MPa)	Ultimate tensile strength (MPa)	Uniform elongation (%)	Total elongation (%)
0º	378.66	489.08	11.8	12.8
45º	340.22	465.45	11.4	11.7
90º	349.53	476.27	11.2	12.1

properties exhibit sudden cracking after reaching the maximum force of the investigated material. In particular, the small percentage difference between uniform and total elongation in each direction from the rolling direction demonstrates the low formability of the examined material sheet. This information will lead to the next step in the improvement method of surface properties using the shot peening process. Shot peening could improve the surface and mechanical properties by creating layers of residual compressive stress and plastic deformation on and under the surface.

2.2 Shot peening process

Shot peening is a cold-working technique that changes the surface properties of a material by hitting the surface with small media under compressed air [16]. Shot peening leaves dimples on the material, which serve as points for plastic deformation [18,20]. Surface and subsurface areas with these dimples have increased hardness and residual compressive stress [21-23]. In addition, the shot peening parameters of pressure, distance between nozzle and material, nozzle angle, media type, and media size all contribute to the enhanced hardness and residual stress. [19-21,24]. This study investigated the influence of 100 µm silica media on AA2024-T3 sheet specimens with a thickness of 1.2 mm. The shot peening was performed on the peening machine as shown in Figure 1, with the silica media confined in the bottom hopper prior to the process setup. Obviously, Table 2 depicts the various levels of each process parameter for duration, time, pressure, and distance from the test specimen to the nozzle as experimental conditions. Before beginning an experiment, it is important to test and ensure that the silica media flow is stable so that each specimen produces the most accurate and consistent results under various conditions. First, the pressure in the spray test was controlled at 0.35 MPa and 0.5 MPa, which were the limitations of this peening machine. The ejected silica media was collected from the bottom hopper for use in the next cycle test. Shot peening was experimentally performed on both sides of the specimen surface in order to improve the mechanical and surface properties such as surface roughness and hardness, including plastic deformation and the residual compressive stress near the surface. This is to compare a workpiece with no reinforcing surface (none shot) to a workpiece that has been shot peened.

Figure 1. Shot peening machine.

2.3 Hardness testing methodology

Another approach for evaluating mechanical properties on the sheet surface and comparing the effects of shot peening on specimens is room temperature hardness testing. Vickers hardness has a wide range of hardness scales that are appropriate for evaluating the hardness of the aluminum sheets utilized in this study. The Vickers test method employs a square pyramid-shaped diamond indenter with an angle of 136º, pressed perpendicular to the area on the specimen's surface, resulting in hardness conversion with a test load of 294 kN. Each time the hardness was tested, the load on the surface above the specimen was applied for 10 s. All the hardness tests were directly repeated three times to guarantee experimental test reliability. The hardness of the specimen is 148.33 HV in the absence of shot peening as shown in Figure 5.

Table 2. Experimental conditions of shot peening process.

Time (s)	Pressure (MPa)	Distance (mm)
5	0.35	150
		200
		250
		300
	0.5	150
		200
		250
		300
10	0.35	150
		200
		250
		300
	0.5	150
		200
		250
		300

2.4 Surface observation and roughness measurement methodology

A digital microscope is a non-contact surface roughness measurement tool that can also record all of the photos required to produce a 3D phase. The 3D profile process also provides sharper images with a greater depth of field and a wider field of view than the 2D profile. For the roughness measurement, the roughness analysis was divided into two parts: the roughness profile and the arithmetic mean deviation (Ra).The average of these lines that observe the 3D phrase is obtained for each condition received to obtain an accurate value of surface roughness. The surface roughness of specimens that have not been peened is 0.16 Ra as shown in Figure 6. A digital microscope with a high depth of focus and a long observing distance that can study surface features and three-dimensional objects with quality pictures. The digital microscope uses optics and a digital camera to transmit acquired pictures to a computer monitor. The light source in this microscope is an LED. In an optical microscope, the light source is reached through an eyepiece on the outside of the microscope.

2.5 Determination of residual stress

The residual stress is estimated by X-ray diffraction (XRD). In this study, the volume of material characterized by the irradiation area and the XRD machine depicted in Figure 2 determines the arithmetic mean stress. The XRD is a largely non-destructive technique for measuring residual stresses in all material. The X-ray diffraction residual stress measurement was applied to determine the residual element on the surface after shot peening and without shot peening. XRD has very high sensitivity to changes in the crystal lattice spacing of a material and can measure the residual stress of a material in relation to the incident X-ray beam to determine the location of a suitable diffraction peak in a specific area. The residual stress of the specimens was evaluated with an x-ray diffraction meter by a portable X-ray machine (μ-x360), to measure the residual stress on the elements using XRD. Furthermore, XRD can measure thin layers near the surface, with a depth of roughly 10 μm on the specimen surface. The X-ray incidence angle was angled at 35 degrees throughout the inspection, and the distance between the XRD instrument and the specimen was 67 mm.

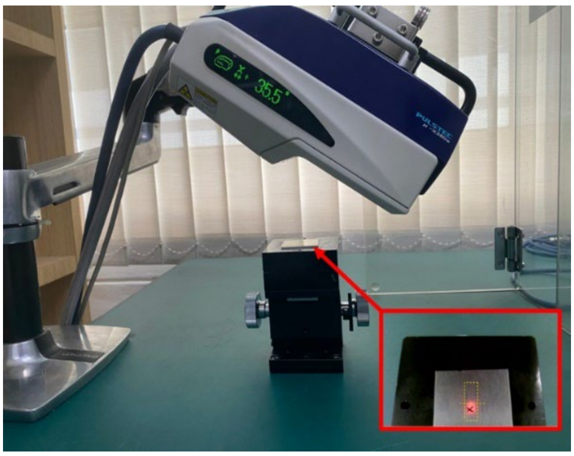

Figure 2. Portable X-ray shot machine.

2.6 Formability testing

Formability is a fundamental material property that describes material deformation limits. There are many tests of formability for sheet material. Formability refers to the ability of sheet metal to be formed into a desired shape without necking or cracking. The considered design of the part for manufacturability using formability information and materials is chosen depending on the complexity of the features. For the purposes of this study, then, formability corresponds to the ability of a given metal workpiece to undergo plastic deformation without suffering damage. Metallic materials have a limited capacity for plastic deformation, beyond which tearing or fracture can occur. The properties of sheet metal were various types of forming, which included case of specimen shot peening and case of specimen none shot, which can be used to compare the cold formability results of the aluminum alloy sheet AA2024-T3 test by hole expansion test and the Erichsen cupping test. An Erichsen formability testing machine model 102-60 was used to examine sheet metal formability.

2.6.1 Hole expansion test

The stretch flange-ability of a sheet metals is currently of great importance in the production of automotive parts. The hole expansion test, one of the formability tests that establishes a method for measuring the stretch flange-ability of circular hole sheets, has examined this behavior. In this study, the hole expansion test was conducted in accordance with ISO 16630 [25] standard. The test is a local formability evaluation where the material is subjected to intensive deformation along the circumference of a hole until it fractures. It measures the elongation capacity of a sheet edge or the sensitivity of an edge fracture. Several researchers, like Akela *et al.* [26], Kim *et al.* [27], and Choi *et al.* [28], investigate sheet formability through the hole expansion test. In this work, the hole expansion test has been selected to perform the test and evaluate the investigated sheet material since the stretch flange-ability has more high effect to edge crack occurred around the hole edge of sheet metal stamping and it will affected to production line of automotive parts. In the beginning, the shot peening was conducted again by using conditions such as compressed air with a pressure of 0.35 MPa and 0.5 MPa, the nozzle to target distance of 150 mm and 250 mm, and a duration time of 10 s. They were experimentally performed again on both sides of the specimen surfaces, which had a size of 100 mm × 100 mm. The peened specimens were conducted on the Erichsen formability testing machine model 102-60 by using a hole expansion, punch and die set. During the experimental test,

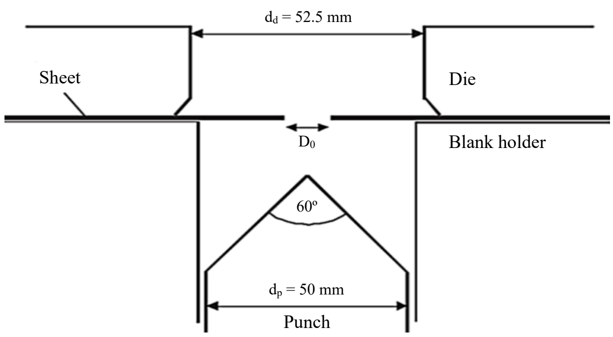

Figure 3. Schematic diagram of hole expansion test.

the peened specimens with a wire cut hole in the middle were drawn with a pointed punch of diameter 50 mm. applied the force to the specimens until the first crack appeared. A punch speed of 5 mm·min^{-1} and a blank holder force of 8 kN were totally employed. The experimental tests were totally repeated three times to ensure the test reliability and reproducibility. The setup schematic of the hole expansion test is presented in Figure 3. In this investigation, the formability can be evaluated from the drawing depth of the deformed peening specimen at the initial crack that occurred.

2.6.2 Erichsen cupping test

Formability is the ability of a material to plastically deform before to fracture. There are various methods for determining the draw-ability of metal sheets, including bending, scratching, coining, drawing, etc. The Erichsen cupping test for sheet metal is a widely used method for evaluating the formability of sheet metal subjected on bi-axial loading which is often applied to the sheet metal forming of automotive panels. This test's developing method is directly comparable to stretch-forming and bulge elimination. The edge zones (borders) are held and therefore are not affected, or are only slightly affected, by forming. The specimen is spherically pressed until a crack occurs that runs the full thickness of the specimen and is just wide enough to allow light to pass through part of its length. The formability of the examined AA2024-T3 material was illustrated by the biaxial stress on the sheet during the forming process, as measured by the Erichsen cupping test in accordance with ISO 20482 [29]. Singh *et al.* [30], Vemula *et al.* [31], and Hamada *et al.* [32] conducted experiments and reported on the formability of the analyzed sheets based on their bi-axial tension behavior. Obviously, the schematic of the Erichsen cupping test set up is presented in Figure 4. In the same condition as the peened specimen of the hole expansion test, the shot peening process was conducted on the square specimen size of 80 mm × 80 mm. First, the peened specimens were performed on the Erichsen formability test machine by using a spherical punch and die set. Then, the spherical punch was pressed to peened specimens at a speed of 5 mm·min^{-1} and applied force of 8 kN to hold the specimens by the blank holder and die. Each test variant was repeatedly taken three times to warrant reliable consequences which was conducted until fracture initiation appeared. Eventually, the drawing depth of the fractured cup sheets was evaluated through the spherical punch displacement at the fracture state. The depth of the fractured cup (drawing depth) can be used to be the formability index.

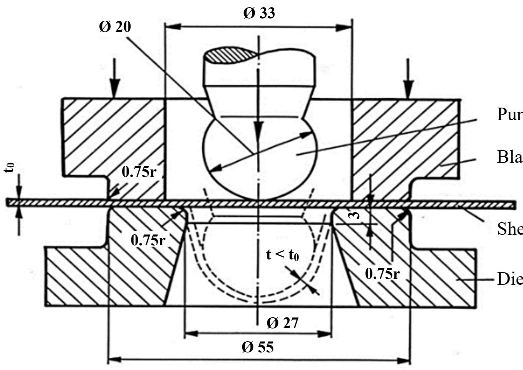

Figure 4. Schematic diagram of Erichsen cupping test.

3. Results and discussion

3.1 Vickers hardness investigation

From the shot peening process with a specimen size of 30 mm × 30 mm, the experimental conditions were carried out following the information in Table 2. Definitely, Figure 5 demonstrated the results of the relationship between the surface hardness of AA2024-T3 sheet alloy with and without shot peening. Simultaneously, the results show the surface hardness has been raised after shot peening treatment. Therefore, the higher hardness could be interpreted by plastic deformation generated from dimples on the surface after shot peening [22,23]. The hardness is also increased with the impact energy from the collision of silica media on the surface specimen due to generating more dumpers on the surface [18-20,24]. The plastic deformation generated by silica media collisions could be successfully accumulated if the quantity of media was increased. Subsequently, shot peening may effectively develop a changed microstructure with particle elements and better mechanical characteristics [2,14]. The lamellar microstructure possibly improves the hardness value on the surface. In the experiments, the silica media size of 100 μm in diameter was used in the test, which means that small holes can be created on the specimen that can help to increase the hardness of the specimen. In Figure 5, it was found that using a pressure of 0.5 MPa increased the hardness value higher than the pressure of 0.35 MPa since the higher pressure established more impact energy on the material surface. Then, the distance between specimen and nozzle was observed to be longer, producing the lower hardness value after the test. In particular, at a distance of 300 mm, at a pressure of 0.35 MPa and 0.5 MPa, they exhibited a hardness less than all other tests. The parameters used in the test that results in the highest hardness value is pressure at 0.35 MPa and the distance from a nozzle of 150 mm, with time shot peening of 5 s and 10 s, and the hardness values are 166.00 HV and 166.67 HV, respectively. It is a reason since the closest distance between nozzle and specimen established higher impact energy and a smaller dimple, which induced a higher level of plastic deformation produced on the material surface. Otherwise, the duration time of the peening process is given the difference between the hardness value response and the quantity of silica media collision on the surface depending on the duration time.

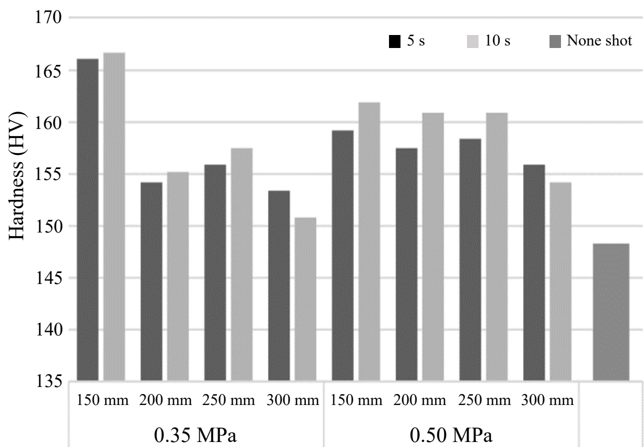

Figure 5. Hardness (HV) data at various experimental conditions.

3.2 Surface roughness investigation

Figure 6 presents the surface roughness values exhibited by different parameter shot peening conditions; it was discovered that the surface treatment of the specimen after shot peening has a fine surface and is shiny on the specimens, and the surface roughness of the peened sheets was reduced. Obviously, Figure 7 illustrates the specimen without shot peening and with shot peening processes. As shown in Figure 7(b), the surface discovered that media provided miniature dimples that are slightly deeper into the surface. After evaluating the material roughness, the arithmetic mean deviation (Ra) of the roughness profile was exactly determined. From the modified surfaces, they evaluated that shot peening was capable of producing the dimples on the surfaces. The impact of the shot media against the specimen could generate some fragments. Subsequently, continuous collision from other shot balls of silica media, the improved surface properties, and induced residual compressive stress and plastic deformation appeared on the investigated material surface. Figure 6 depicts the surface roughness profiles for various shot peening settings. The results demonstrated that the surface roughness was the lowest in conditions with a pressure of 0.35 MPa, a distance of 150 mm between the specimen and the nozzle, and a peening time of 10 s. The lowest surface roughness (Ra) value is 0.035. Moreover, in the same process parameters, the high pressure of 0.5 MPa generated a higher surface roughness than the one based on 0.35 MPa since the higher pressure gave bigger dimples on the surface. The comparison of the microstructure at the surface before and after shot peening is illustrated in Figure 7. The original surface in Figure 7(a) appeared to have more roughness than the modified surface in Figure 7(b). It meant that the surface roughness of peened specimens had significantly decreased, which was a reason for using small silica media of 0.1 mm in diameter, as silica media has higher hardness than the investigated AA2024-T3 sheet. Thus, in an experiment with conditions of pressure of 0.35 MPa, distance of 150 mm, and duration time of 10 s, the material surface was modified to obtain a fine surface with low surface roughness and a shiny surface. Finally, it can be concluded that the modified quality surface with a fine level also established a high level of plastic deformation, represented by the highest surface hardness.

3.3 Residual stress measurements

To confirm the plastic deformation developed after the shot peened by silica media, the residual compressive stress should be accumulated under the surface or subsurface. In this investigation, the residual compressive stress relied on the impact energy of peening shots, exhibited plastic deformation on the surface, and used the residual stress measurement method described in Section 2.5. Table 3 shows some examples of results obtained from XRD examination of specimens before and after shot peening. Depths from the top surface to 10 µm were precisely measured. As a result of the high impact energy, dimples, and plastic deformation caused by shot peening, the grains fracture into a multitude of smaller grains. ([1] The test results clearly show that the value of residual compressive stress increases dramatically with shot peening. Concurrently, silica shot peening produced a maximum residual compressive stress of 274 MPa on the subsurface (10 µm from the top surface), which was higher than in the case of on-shot peening. In addition, the results can be illustrated that higher hardness could be obtained when plastic deformation occurred and residual compressive stress was present. These findings demonstrate that shot peening may cause surface deformations while energy accumulates in the microstructure, leading to the creation of residual stress. The source of residual compressive stress, which is the interior structure's deformation, As a result, the residual compressive stress value is noticeably higher when compared to when the specimen surface was not shot peened. The pressure setting condition was 0.35 MPa, the distance between the specimen and the nozzle was 150 mm, and the peening time was 10 s. This gave the maximum residual compressive stress, the highest hardness, and the best surface roughness.

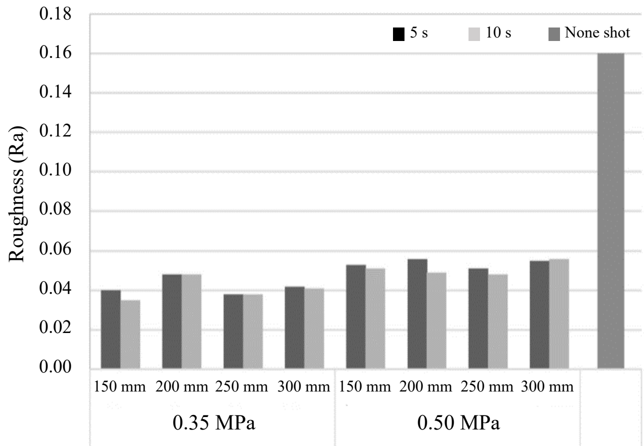

Figure 6. Surface roughness data at various experimental conditions.

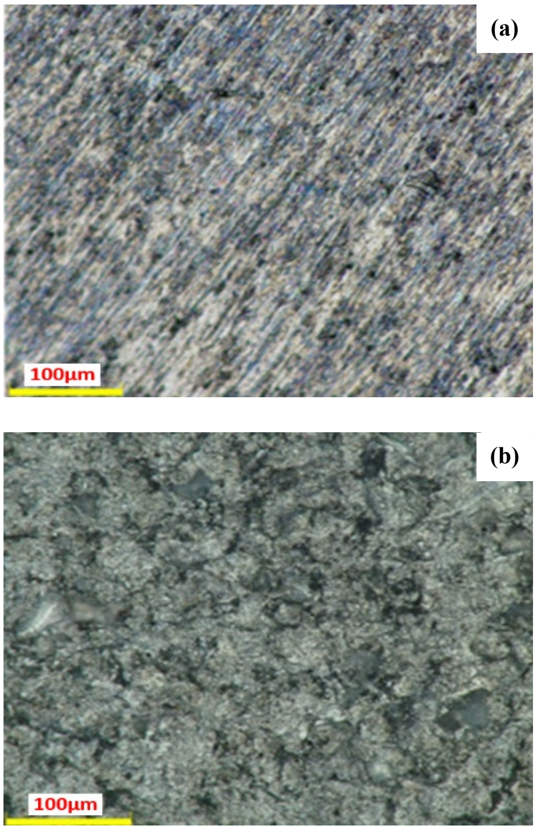

Figure 7. Appearances microstructure of specimen (a) before shot peening (b) after shot peening process.

3.4 Formability investigation

This section describes the experimental results collected using the procedures outlined in Section 2.6.1 and Section 2.6.2. The hole expansion test results presented in Table 4 illustrate the drawing depth of the hole expansion test at the fracture state of the specimens, as shown in Figure 8(a). Note that the hole expansion specimens were peened with the condition described in Table 4 before performing the tests. Apparently, the hole expansion test results showed that the conditions set up for the experiment, which set pressure at 0.35 MPa, distance between specimen and nozzle at 150 mm, and time pinning at 10 s, had the highest formability of the other ones based on drawing depth. This is a reason why the drawing depth developed from those testing conditions was higher than the one based on without shot peening and the other peening conditions. The drawing depth was measured at 9.44 mm with the mentioned testing conditions. Otherwise, without peening, it was evaluated as 9.10 mm. Additionally, the formability was tested again with a peened specimen under the same testing conditions: pressure of 0.35 MPa, distance of 250 mm between the specimen and the nozzle, and peening duration time of 10 s. It was observed that the measured drawing depth was 9.01 mm. In the last condition test, it can be explained that the residual compressive stress value was lower than the one based on the previous testing condition as presented in Table 3. The formability is also lower than the other one. They have a reasonable interpretation of the residual compressive stress obtained from the impact energy of shot peening with silica media on the material surface. They give the compressive force applied to the material sheets when they are applied in the forming process. Theoretically, the compressive stresses have improved the formability of sheet metal. It should be noted that the higher residual compressive stress is given the higher formability of sheet materials. Furthermore, originally, the strain hardening behavior from cold working by shot peening developed the higher hardness value on the material surface. On the other hand, unfortunately, they also exhibited early brittle crack with low formability as seen in Table 4. Exceptionally, the high residual compressive stress gave an improvement in sheet formability

Table 5 shows the results of the Erichsen cupping test, and Figure 8(b) shows a picture of the cracked specimen. A drawing depth was used to assess the formability of the specimen after the shot peening process. In the same manner as the process parameters for the shot peening process for hole expansion test, the formability represented by the drawing depth at the fracture state of the Erichsen cupping test was depicted in Table 5. The test results show that they have a similar trend to the hole expansion test regarding the drawing depths at fracture state, which they have a larger distance during each process parameter. Since the difference in applied force with bi-axial tension has better formability than stretching along the circumference by hole expansion, this is the case. Similarly, only one process parameter developed the best formability of the Erichsen cupping test in the same process condition as the hole expansion test. Other results have decreased formability. It can be concluded that the test results should be interpreted in the same way that the previous formability test was.

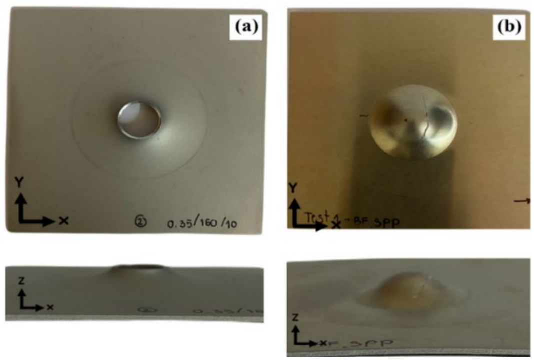

Figure 8. Deformed and fractured specimens (a) hole expansion (b) Erichsen cupping.

Table 3. Example of residual compressive stress values.

Condition	Time (s)	Pressure (MPa)	Distance (mm)	Residual Stress (MPa)
None shot	-	-	-	9
Shot peened	10	0.35	150	-274
Shot peened	10	0.35	250	-234

Table 4. Drawing depths of hole expansion test.

Condition	Time (s)	Pressure (MPa)	Distance (mm)	Drawing depth (mm)
None shot	-	-	-	9.10
Shot peened	10	0.35	150	9.44
Shot peened	10	0.35	250	9.01
Shot peened	10	0.5	150	9.00
Shot peened	10	0.5	250	8.85

Table 5. Drawing depth result of Erichsen cupping test.

Condition	Time (s)	Pressure (MPa)	Distance (mm)	Drawing depth (mm)
None shot	-	-	-	6.05
Shot peened	10	0.35	150	6.68
Shot peened	10	0.35	250	5.37
Shot peened	10	0.5	150	5.59
Shot peened	10	0.5	250	5.12

4. Conclusions

This research aims to investigate the aluminum 2024-T3 sheet specimens shot peened on both the front and back surfaces by silica shots. In air blast shot peening, the distance between specimen and nozzle, air blast pressure, and peening time are considered the major process control parameters. The improved effect of shot peening treatment is analyzed, which includes hardness, roughness, and residual compressive stress on the surface. The novel study of shot peening, in which the formability after shot peening is investigated with hole expansion and the Erichsen cupping test, In the experiment, silica media at 100 µm was utilized in the peening tests. Impact energy from shooting silica media generated small dimples on the surface, which induces the ability to reduce surface roughness and modify the surface with a shiny one. It was obviously seen that there was plastic deformation occurring through the digital microscope. Otherwise, the modified surface characteristics increase hardness and residual compressive stress, which induces an increase in crack resistance and directly obtains higher formability.

The high residual compressive stress can enhance the crack resistance and increasing formability. In formability tests, the residual compressive stresses in the modified surface compensated the tensile stress appeared during the formability tests. Originally, this investigated material sheets are kind of aluminum brittle crack but they can be improved the crack resistance by higher compressive force.

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