Journal of Solid and Fluid Mechanics (JSFM), 13(3): 1-4, 2023

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/JSFM.2023.12573.3684

Manufacturing Engineering of Iran

An experimental investigation on the influence of geometrical configuration of copper patches on mechanical strength of cracked titanium components using diffusion method

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Received: 01/05/2023 Revised: 05/12/2023 Accepted: 07/25/2023

Abstract

The orientation and shape of joints in cracked structures significantly impact the mechanical behavior of components and the optimization of the construction process. This study investigates the mechanical behavior of titanium grade 2 cracked components under quasi-static tensile loads, considering the crack length (central cracks of 1, 2, and 3 cm) and patch type (rectangular, oval, and hexagonal shapes) parameters. patch connections to the 50 × 40 × 0/5 mm titanium grade 2 base plate are examined according to ASTM E 8/E 8M – 08 and ASME SA-370 standards. A novel approach to patch connection is employed using the advanced diffusion method (SPS) at a temperature range of 820-850 degrees Celsius and a pressure of 47-50 megapascals, with potential applications in the aerospace industry. A scanning electron microscope (SEM) is used to investigate the quality of the joint area of the cracked pieces joined together. Results show that an increase in crack length leads to a decrease in component resistance under static tensile loading. The hexagonal patch demonstrates better resistance with averages of 0/534 and 0/691 compared to rectangular and oval patchs, respectively, due to its superior stress distribution along the entire length of the cracks.

Keywords: Diffusion bonding; Copper patch; cracked plate; Titanium.

1. Introduction

This research investigates an innovation involving the diffusion bonding of cracked titanium sheets with central crack lengths of 2.1 cm and 3 cm, using copper patches for repair. Three types of patches with rectangular, elliptical, and regular hexagonal geometries are utilized to mend the cracked sheets. The strength of the repaired pieces under a quasi-static load perpendicular to the crack direction is examined to investigate the effectiveness of the copper patches in increasing the strength of the repaired pieces while focusing on evaluating the tensile strength in cracked sheets. This study distinguishes itself from recent research by connecting different geometrical shapes of copper patches (rectangular, elliptical, and regular hexagonal) to the central cracked sheet with the mentioned crack lengths.

Furthermore, the study explores the influence of pressure, temperature, and duration on optimizing the test piece, as well as the impact of the geometric shape of the patches (rectangular, elliptical, and regular hexagonal) on the strength of the repaired sheet. To ensure the experiment's reliability, the titanium sheet's surface, which is prone to rapid oxidation and the formation of TiO2, undergoes a chemical process involving cleaning with oxidation-reducing acids, followed by a mechanical process of surface abrasion prior to the experiment. The experiment is conducted under a complete vacuum to prevent oxidation, especially at the connection site.

The primary objective of this research is to evaluate the tensile strength of the repaired cracked titanium sheets using the diffusion bonding method employing the SPS apparatus. This evaluation involves altering the copper patches' geometrical shapes and the lengths of the major cracks in the base sheet [1].

2. Laboratory Method

2.1. Raw Materials

This study used grade 2 titanium (Ti) to fabricate a cracked piece, while copper (Cu) metal was used as a patch. The experiment conducted in this study involved conducting tensile strength tests on the repaired piece with patches in rectangular, elliptical, and hexagonal shapes. The cracked titanium sheet samples had dimensions of 50 mm × 40 mm × 0.5 mm, following the ASTM E 8/E 8M – 08 and ASME SA-370 standards [2]. To create three significant cracks, which served as notches, in the center of the piece, a wire-cutting machine with a 50 µm diameter wire was utilized. The lengths of these cracks were 10 mm, 20 mm, and 30 mm. The properties of the materials used in the cracked sheet can be found in Table 1, while the composition of the titanium alloy elements, obtained using a spectrometer, is presented in Table 2.

Table 1. Mechanical Properties of Grade 2 Titanium [3]

Modulus of Elasticity (GPa)	Poisson's Ratio (dimensionless)	Fracture Toughness (MPa)	Ultimate Strength (MPa)
105	0.37	66	345

Table2.Composition of Alloy Elements of Grade 2 Titanium

Ti	Fe	Cr	Mn
99.92 %	0.08 %	0.04 ≤%	0.01 ≤%

2.2 Method of Sample Fabrication

In order to achieve optimal repair of titanium parts with cracks using the diffusion method, we conducted a diffusion test utilizing the SPS method. The procedure involved a series of sequential operations at four different temperatures: 820°C, 830°C, 840°C, and 850°C. Corresponding pressures of 48 MPa, 47 MPa, 49 MPa, and 50 MPa were applied, while the durations were defined as 573 minutes, 581 minutes, 592 minutes, and 601 minutes, respectively. It is worth noting that all experiments were carried out under conditions of relative vacuum.

To address this issue, we repeated the experiments at 850°C and 50 MPa, extending the duration to 1500 seconds to achieve better bonding of the samples. The optimal sample was selected through empirical observation based on its quality and stability. By conducting further experiments and extending the duration beyond 1500 seconds, we determined that the temperature and pressure range required for successful bonding was 850°C, 50 MPa, and beyond 1500 seconds. Establishing the point at which the diffusion bond was considered acceptable clarified the matter

To validate these findings, we subjected ten additional test samples to the same temperature, pressure, and time range, and all of them yielded positive results. Consequently, all primary samples were bonded using the parameters mentioned above. This temperature and pressure range provided stability, facilitating the complete merging of the patch and the base plate [4].

3. Discussion and Results

This research used copper patches of various geometric shapes to make nine connections with titanium sheets containing different lengths of cracks. Each sample underwent tensile testing, and the tensile strength of the repaired pieces was analyzed. The comparison of force-displacement graphs from the static tensile test of Grade 2 titanium sheets repaired with a copper patch in a regular hexagonal geometric shape, with crack lengths of 1 cm, 2 cm, and 3 cm, revealed some significant findings.

As the crack length increased from 1 cm to 2 cm, the tensile strength of the repaired pieces decreased by approximately 0.3305 units. Additionally, there was a further decrease of approximately 1.012 units as the crack length increased from 1 cm to 3 cm. Moreover, an approximate decrease of 0.5125 units in tensile strength was observed when the crack length increased from 2 cm to 3 cm. It is worth noting that similar trends were observed in rectangular and oval shapes, where shorter crack lengths resulted in a more significant increase in length during the tensile test. These factors can be attributed to the higher resistance of the piece and a wider elastic region in the graph.

The relatively softer copper patch connection on the titanium sheet during the rupture while being stretched leads to higher resistance and non-brittle behavior of titanium during the break, which is one of its characteristics. Therefore, increased crack length decreases tensile strength, as observed in the tensile test. Notably, the decrease in tensile strength was more pronounced in the hexagonal geometry compared to the rectangular and elliptical geometries when the crack length increased from 1 cm to 3 cm.

In another comparison, the tensile strength of repaired sheets with identical crack lengths but different geometric shapes and those without a patch with a similar crack length was evaluated. We compared the force and displacement diagrams obtained from the tensile test of Grade 2 titanium sheets that were repaired using copper patches with different geometries (rectangle, ellipse, and hexagon) and had a 1 cm crack length.

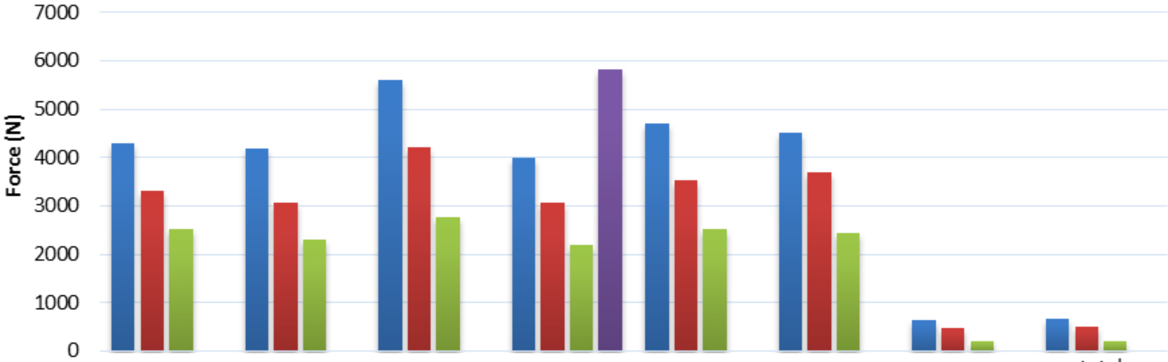
The results indicated that the tensile strength of the sheet with a hexagonal patch was higher than that of the rectangle and ellipse, respectively. This observation was held when the test was repeated for sheets with crack lengths of 2 cm and 3 cm. Therefore, the cracked titanium sheet with a hexagonal patch exhibited higher tensile strength than the repaired sheet with rectangular and elliptical patches. The suggestion of more significant overlap and less stress concentration on the surface implies a positive outcome.

Therefore, according to the obtained results, the tensile strength of the sheet repaired with a rectangular patch is higher due to better overlap and less stress concentration on the surface than the sheet repaired with an elliptical patch. Based on these two points, one can infer the effect of the number of corners in the geometric shape on the improved strength of the repaired sheet. The criterion for selecting the geometric shape of the patches in this experiment was to encompass the entire crack, and the length of the patch was equal to the width of the the strength of the repaired sheet.

In this research, a comparison has been made based on the results obtained from the tensile test for titanium sheets with major cracks of lengths 2 cm, 1 cm, and 3 cm (without patches) and those repaired with rectangular, elliptical, and hexagonal geometrically-shaped patches as shown in Figure 1. The average tensile strength and standard deviation of the sheets repaired with patches (repaired sheet for each crack length and the three patches mentioned above) and the overall average and standard deviation (sheets with cracks repaired with patches and sheets without patches) have been presented. From the average results with the three geometric shapes of the patches and the overall average (sheets repaired with patches and sheets without patches), it can be demonstrated that the tensile strength of the pieces mentioned above with a crack length of 1 cm is higher compared to those with crack lengths of 2 cm and 3 cm. Moreover, the tensile strength of pieces with a crack l

base piece. In this comparison, the regular hexagon, due to encompassing a larger surface area and having a more significant number of corners, has significantly impacted 3 cm. These tests conclude that the length of the central crack in Grade 2 titanium sheets has an inverse relationship with tensile strength, meaning that a shorter crack length will result in higher strength. Furthermore, based on the results of the standard deviation with patches and the overall standard deviation as shown in Figure 1, and considering the number of tested pieces and the parameters mentioned above (crack length and geometric shape of the patch), it can be inferred that as the crack length increases, the standard deviation decreases. This statement indicates that the tensile strength of the pieces approaches the average strength of the samples as the crack length increases.

Therefore, it can be concluded from the obtained standard deviation that Grade 2 titanium sheets with a central crack, with or without the aforementioned geometrically-shaped patches, will have tensile strength closer to the average strength of the samples as the crack length increases.



	Restored sheet with rectangular patch	Restored sheet with oval patch	Restored sheet with hexagonal patch	Titanium sheet without patches	Average with patches	Total average (with patch and without patch)	Deviation with patches	total standard deviation (with patch and without patch)
1cm	4307	4200	5595	3988	4700/66	4522/5	633/8	658/4
2cm	3312	3080	4205	3075	3532/33	3700/5	484/9	513/3
3cm	2524	2295	2780	2200	2533	2449/75	198/1	214/8
without crack				5823				

1cm 2cm 3cm without crack

Figure1. Results of the quasi-static tensile test accompanied by the mean tensile strength of the samples and standard deviation.

4. Conclusion

In this research, the maximum tensile force endured by a Grade 2 titanium piece with cracks, repaired using regular hexagonal, rectangular, and elliptical patches through the Spark Plasma Sintering (SPS) diffusion method, was experimentally determined. The piece underwent varying pressures, temperatures, and time durations. The following results were obtained:

1. The SPS device underwent testing under relative vacuum conditions at four different temperatures (820°C, 830°C, 840°C, and 850°C), pressures (48 MPa, 47 MPa, 49 MPa, and 50 MPa), and time durations (573 min, 581 min, 592 min, and 601 min) to determine the optimal repair method for cracked titanium pieces using the

diffusion method. The optimal sample was selected at a temperature of 850°C, pressure of 50 MPa, and time duration of 1500 s. These conditions resulted in a stronger connection and increased bond strength between the repaired piece and the patch. Complete fusion prevented the separation of the patch and base piece during the quasi-static tensile test. Thus, the diffusion bond was deemed acceptable under these optimal conditions.

2. By carefully observing the appearance of the deformed samples in the fusion zone and the base plate after the tensile test, it is possible to infer the optimal diffusion bond by considering various temperature, pressure, and time parameters. A detailed examination of the geometric parameters of rectangular, elliptical, and regular hexagonal joints revealed that an increase in the crack resistance of the base plate led to a decrease in joint strength. Among the three types of joints, the regular hexagonal joint exhibited superior resistance throughout the entire crack region due to better overlapping. According to the tensile test results, the tensile strength of the regular hexagonal joint was 0.2302% and 0.2493% higher than that of the rectangular and elliptical joints, respectively, for a 1 cm crack length in the base plate made of titanium. Similarly, the tensile strength of the rectangular joint was 0.2408% higher than that of the elliptical joint for the same crack length. For a crack length of 2 cm, the tensile strength of the regular hexagonal joint was 0.2123% and 0.2675% higher than that of the rectangular and elliptical joints, respectively.

3. Additionally, the tensile strength of the rectangular joint was 0.0700% higher than that of the elliptical joint for the same crack length. Finally, for a crack length of 3 cm, the tensile strength of the regular hexagonal joint was 0.0920% higher than that of the rectangular joint and 0.1744% higher than that of the elliptical joint. Furthermore, the tensile strength of the rectangular joint was 0.0907% higher than that of the elliptical joint for the same crack length. Based on these results and the comparisons mentioned above, it can be concluded that the regular hexagonal joint exhibits better overlapping than the other joints.

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