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Effect of Microstructure on Fatigue Behavior of Heat-treated Aluminum 7075 Alloy

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***Abstract*: Al 7075 is a lightweight, non-toxic, and heat-conductive material with excellent corrosion resistance. It can be easily casted, machined, and shaped. Moreover, it is non-magnetic and non-sparking. The study focused on testing the fatigue life of Al 7075 under high cyclic loads using an axial fatigue device. ANSYS software was utilized for analyzing fatigue life, comparing experimental results with ANSYS data. The impact of heat treatment processes (annealing, HTPP, and T6 artificial aging) on Al 7075 alloys was also investigated. Fatigue tests and microstructure analysis were conducted on heat-treated specimens, and conclusions were drawn based on the findings.**

***Keywords*: Fatigue life, Ansys, Al 7075, Axial fatigue universal testing machine, Heat treatment, Microstructure.**

1. Introduction

Failure due to repeatedly applied load is known as fatigue. The physical effect of a repeated load on a material is different from that of a static load, failure always being brittle fracture regardless of whether the material is brittle or ductile. Mostly fatigue occur at stress well below the static elastic strength of a material.

In the axial fatigue machine, a specimen with a 12mm outer diameter and a gauge length of 206mm was subjected to fatigue testing. The machine applied cyclic axial loads to the specimen, simulating real-world cyclic loading conditions. The goal was to evaluate the specimen's fatigue behavior and durability. During the testing, the machine recorded the applied loads and monitored the specimen's response. This data was used to construct an S-N curve, which represents the relationship between the applied cyclic stress (S) and the number of cycles to failure (N). The S-N curve provides valuable insights into the material's fatigue strength and endurance limits. By drawing the S-N curve, it became possible to visualize the fatigue performance of the specimen. The curve showcases the stress level required to cause failure at different numbers of cycles. This information helps in determining the specimen's fatigue life under specific loading conditions.

Usually, the purpose of a fatigue test is to determine the life span that may be expected from a material subjected to cyclic loading, however fatigue strength and crack resistance are commonly sought values as well. The fatigue life of a material is the total number of cycles that a material can be subjected to under a single loading scheme. A fatigue test is also used for the determination of the maximum load that a sample can withstand for a specified number of cycles. All these characteristics are extremely important in any industry where a material is subject to fluctuating instead of constant forces.

Aluminum has the reputation of being the strongest grade aluminum alloy among many widely used aluminum alloys for various industrial purposes. It delivers a similar level of strength as many steel alloys while also possessing the benefits of easy machinability, corrosion resistance, and a lightweight metal. 7075 alloy has a reflective characteristic and produces a visually appealing finish when polished – this often eliminates the need for painting and reduces the weight of the object, which is an important necessity in aerospace applications

Fig. 1. Al 7075 alloy prior to the turning operation

2. Methods

A. Fatigue Experimentation

According to ASTM E466 standard, the fatigue testing specimens were manufactured from Aluminium 7075 alloy as shown in figure 1. Axial fatigue universal testing machine is a specialized testing equipment used to determine the behavior of a material under cyclic loading conditions. In axial fatigue testing, a sample of the material is subjected to cyclic loading in the axial direction, i.e., along the longitudinal axis of the sample. The loading is applied in a sinusoidal waveform, with a specified frequency and amplitude, until the sample fails.

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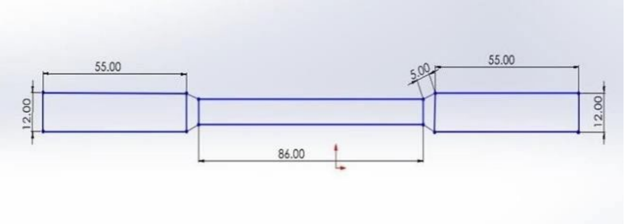

Fig. 2. Specimen for fatigue testing

Fig. 3. Specimen mounted in an AFUTM device

The following are the general steps involved in conducting an axial fatigue test using a universal testing machine:

1) *Sample preparation*

The first step in axial fatigue testing is to prepare the sample according to the required specifications. The sample should be carefully machined or prepared to ensure it has the required dimensions and surface finish. The sample is then mounted onto the grips or fixtures of the testing machine.

2) *Setup and calibration*

The testing machine are then set up and calibrated to ensure it is functioning correctly. This includes verifying the load cell or force transducer is calibrated, the grips or fixtures are securely attached, and the testing machine is programmed with the required testing parameters.

3) *Test initialization*

Once the machine is set up and calibrated, the testing is initialized by starting the machine's software or controller, which activates the actuator and begins applying the cyclic load to the sample.

4) *Data collection*

During the test, the testing machine records the load, displacement, and time data. The data is collected at regular intervals throughout the test, and the testing machine software typically displays a real-time graph of the load versus the number of cycles.

5) *Test completion*

The test is continued until the sample fails or reaches the required number of cycles. The sample failure is typically indicated by a sudden drop in load or a visible crack in the sample. The testing machine software records the data at the point of failure.

6) *Data analysis*

After the test is complete, the collected data is analyzed to determine the material's fatigue strength, endurance limit, and other properties. The data is typically plotted as a stress versus number of cycles graph, which allows researchers or engineers to analyses the material's fatigue behavior and predict its performance under real-world cyclic loading conditions.

B. *Fatigue Simulation using ANSYS*

ANSYS is a general-purpose, finite-element modeling package for numerically solving a wide variety of mechanical problems. These problems include static/dynamic, structural analysis, heat transfer, and fluid problems, as well as acoustic and electromagnetic problems. The fatigue's life has been calculated in ANSYS for AL 7075 and Al 7075-T6 specimens at different loads.

- Step 1: Select Static Structural from Analysis system
- Step 2: Select Engineering data and add Al 7075 material property
- Step 3: From Geometry Option Import the model of Al 7075 specimen
- Step 4: Select the Model tool then Workbench appears
  Step 5: Select the Model, Mesh Sizing is given as 1mm
- Step 6: Boundary Conditions are given as per the requirements

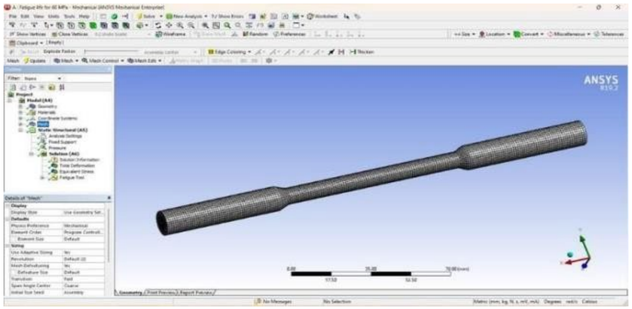

Fig. 4. ANSYS specimen model

C. *Heat Treatment*

Many materials may have to go through procedures that change their grain structure during the manufacturing process. Heat treatment is a technique of changing the physical properties of metals, such as their ductility, and then improving them to meet different industry demands by utilizing controlled heating and cooling procedures. These heat treatments differ based on the metal form and the mechanical properties needed for the required strength specifications, the proper heat treatment procedures must be followed. The hardness and strength of some aluminum alloys (e.g., the 2xxx, 6xxx, 7xxx, and 8xxx series) can be increased through heat treatment. Natural aging, artificial aging, annealing, solution heat treatment, homogenizing is some of the aluminum heat treatments. Heat treatment of the samples is done in electric muffle furnace and then cooled in an open environment. Aging and water quenching is done. Four samples of Al 7075 Specimen were tested to each heat treatment.

In T6 heat treatment, samples were water quenched after they were solution treated for 2 hours at 485° C and then a 5-hour aging process was performed at 120° C. In HTPP heat treatment, samples were solution treated for 2 hours at 485° C, after samples were solution treated. The samples were cooled inside the furnace, a pre-precipitate formation process was carried out for 3 minutes at 450° C and samples were aged for 5-hour for 5 hours at 120° C. In Annealing (O) heat treatment samples were solution treated for 2 hours at 500° C, and then the samples were cooled inside the furnace aging process is not applied to Annealing heat treatment.

D. *Fractographic analysis*

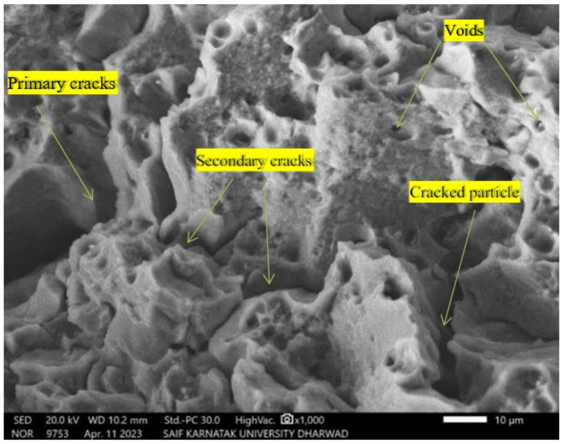

Fig. 5. Fatigue fracture surface of Al 7075 at Smax=370MPa

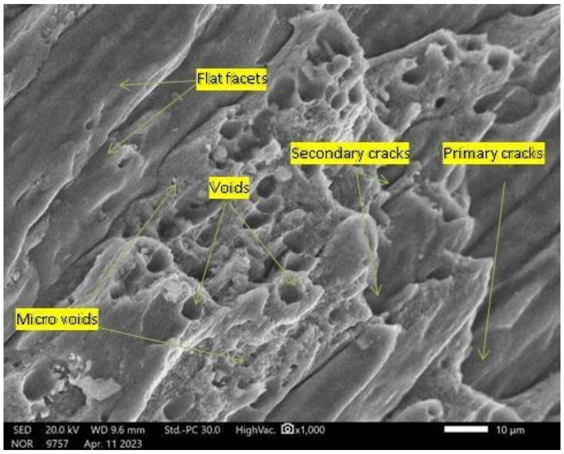

Fig. 6. Fatigue structure of Heat-Treated Al 7075-T6 at Smax=370MPa

The fatigue fracture surfaces of Al 7075 and Al 7075-T6 specimens were analyzed using scanning electron microscopy (SEM) at high magnification. The examination aimed to identify the locations where fatigue cracks originated. Fig. 5 and 6 shows the fracture surfaces of Al 7075 and Al 7075-T6 specimens, respectively. These surfaces consist of fatigue fracture regions. Notably, both figures indicate that fatigue cracks initiated from the corners of the fracture surfaces. The

Table 1
Heat treatment data

Heat Treatment	Solution Temperature and Time	Cooling	Pre-precipitating process	Aging
T6	485° C, 2 hours	Water, 25° C	Water, 25° C	120° C, 5 hours
HTPP	485° C, 2 hours	Furnace	450° C, 30 minutes	120° C, 5 hours
O	500° C, 2 hours	Furnace		

Table 2
Fatigue results for Al 7075

S.No.	Amplitude (mm)	Frequency (Hz)	Load P (N)	Bending Stress (MPa)	No. of Cycles
1	(±) 4	1	18588.8	370	933
2	(±)2	1	17081.6	340	1933
3	(±)1.5	1	10048	200	2933
4	(±)1	1	7033.6	140	3933
5	(±)0.5	1	3014.4	60	4933

Table 3
Fatigue experimental results for Heat-treated Al 7075-T6

S.No.	Amplitude (mm)	Frequency (Hz)	Load P (N)	Bending Stress (MPa)	No. of Cycles
1	(±)4	1	18507	370	1232
2	(±)2	1	16971	340	2232
3	(±)1.5	1	9838	200	3232
4	(±)1	1	6617	140	4232
5	(±)0.5	1	2814	60	5232

Table 4
Fatigue experimental results for heat-treated Al 7075-HTPP

S.No.	Amplitude (mm)	Frequency(Hz)	Load P(N)	BendingStress (MPa)	No. of Cycles
1	(±)4	1	8130	170	-
2	(±)2	1	7343	155	-
3	(±)1.5	1	6882	145	-
4	(±)1	1	7930	160	-
5	(±)0.5	1	5137	105	-

Table 5
Fatigue experimental results for heat-treated Al 7075-O

S.No.	Amplitude (mm)	Frequency (Hz)	Load P (N)	Bending Stress (MPa)	No. of Cycles
1	(±)4	1	6036	130	-
2	(±)2	1	4435	95	-
3	(±)1.5	1	5790	115	-
4	(±)1	1	5134	105	-
5	(±)0.5	1	2427	50	-

fracture surfaces of both Al 7075 and Al 7075-T6 specimens exhibit primary cracks, which are the initial or main cracks that form in the material. These cracks result from external forces or applied stress. Additionally, secondary cracks are visible, which are smaller cracks that develop as a result of stress redistribution and propagation from the primary cracks.

Voids, or empty spaces, are observed within the microscopic structure of the material. Fractography analysis at high magnification of the Al 7075-T6 specimens revealed the presence of flat facets. These flat facets indicate the planes of separation or crack propagation that failed under high alternating loads. Fig. 6 specifically displays regions with flat facets, indicating failure at the highest maximum alternating stress.

3. Results and Discussion

A. Tensile Test Results

A number of tensile test specimens were also made from the Aluminum 7075 according to ASTEM E8 standard.

- Maximum Load = 21.5KN
- Maximum Stress= 427.52 N/mm²
- Displacement= 5.4mm

B. Fatigue Experimental Results

The tables 2, 3, 4, and 5 shows the experimental results.

C. Fatigue Simulation Results

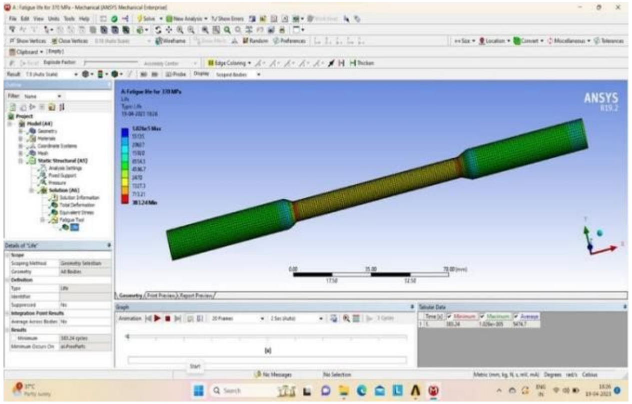

Fig. 7. Fatigue life for Al 7075 at 370 MPa

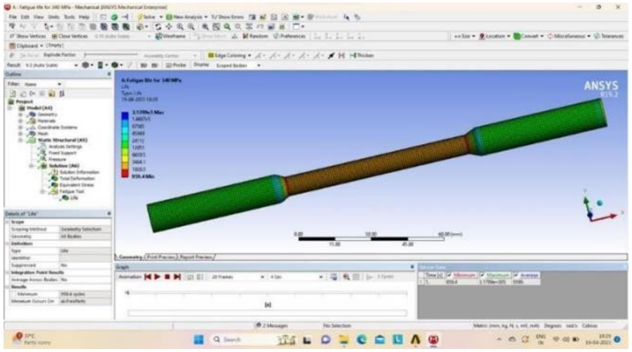

Fig. 8. Fatigue life for Al 7075 at 340 MPa

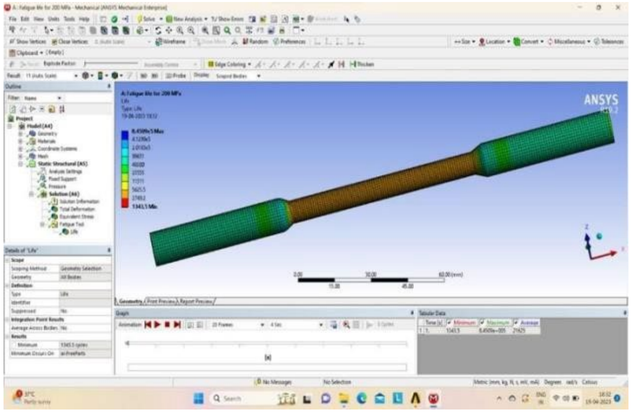

Fig. 9. Fatigue life for Al 7075 at 200 MPa

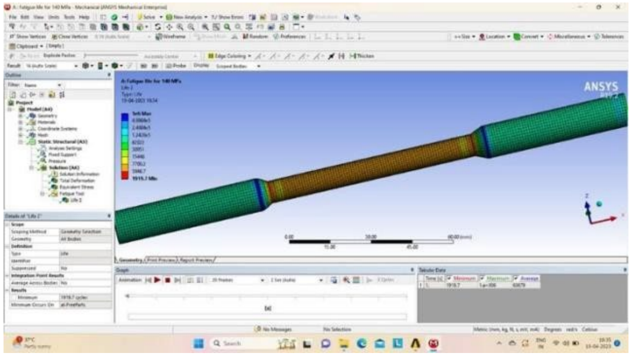

Fig. 10. Fatigue life for Al 7075 at 140 MPa

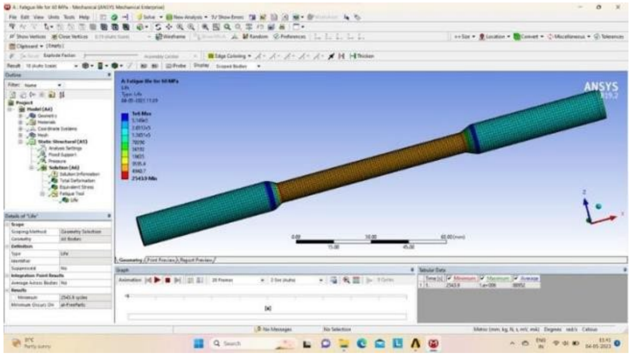

Fig. 11. Fatigue life for Al 7075 at 60 MPa

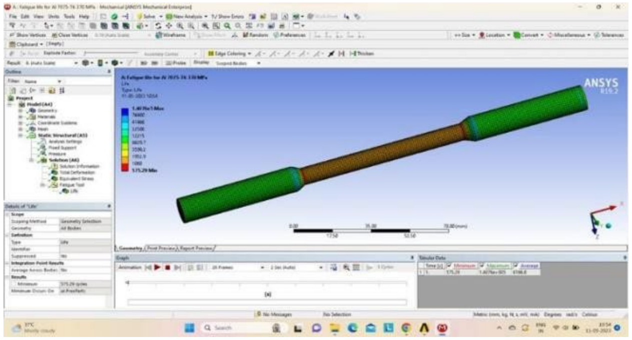

Fig. 12. Fatigue life for Al 7075-T6 at 370 MPa

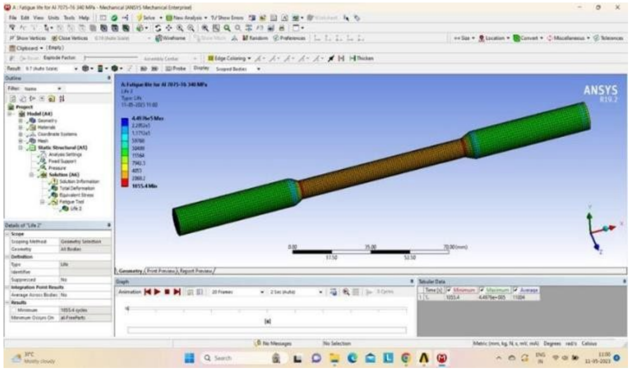

Fig. 13. Fatigue life for Al 7075-T6 at 340 MPa

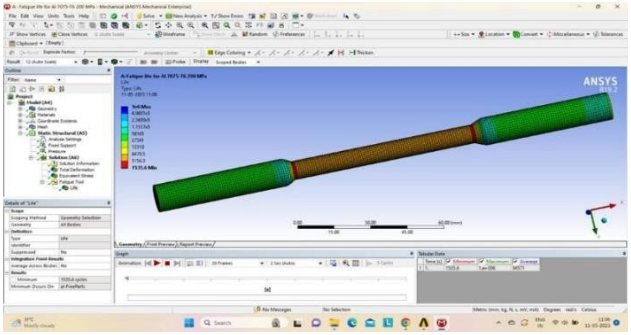

Fig. 14. Fatigue life for Al 7075-T6 at 200 MPa

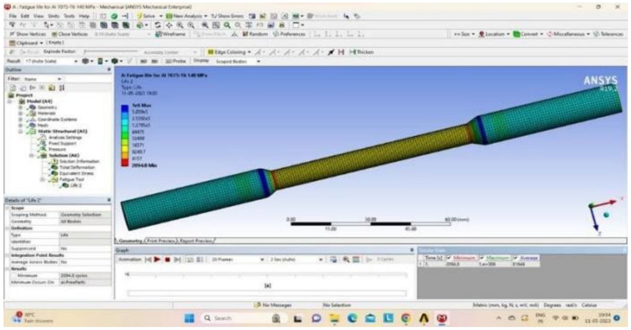

Fig. 15. Fatigue life for Al 7075-T6 at 140 MPa

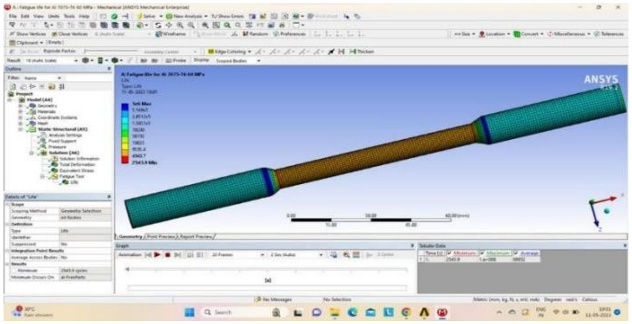

Fig. 16. Fatigue life for Al 7075-T6 at 60 MPa

D. *Experimental vs. Simulation: A Comparative Analysis*

The comparison between experimental and simulation results was conducted using the S-N curve. The S-N curve, also known as the fatigue curve, relates the number of cycles to failure (N) with the applied stress or strain amplitude (S).

The small variations observed in the values between the two curves could be attributed to experimental uncertainties or slight variations in the testing conditions. Factors such as specimen preparation, environmental conditions, or variations in the testing equipment could contribute to these minor discrepancies Overall, the similarity between the SN curves indicates that the material's fatigue behavior is consistent, and the obtained results are reliable. The minor changes in the values between the curves are within an acceptable range of experimental error and do not significantly impact the overall understanding of the material's fatigue characteristics.

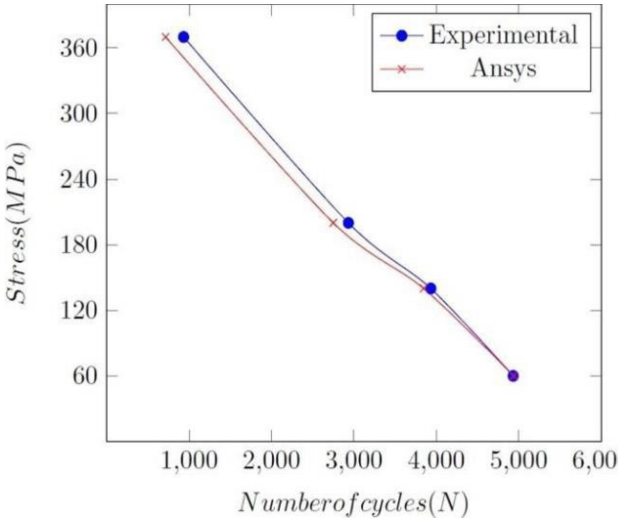

Fig. 17. Stress versus life (S-N) curves for Al 7075

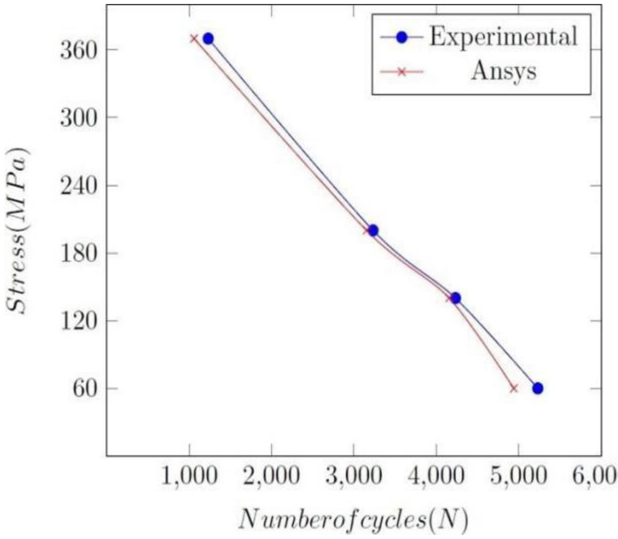

Fig. 18. Stress versus life (S-N) curves for Al 7075-T6

E. *Fractographic Analysis Results*

In the microstructure analysis of two fatigue-tested aluminum 7075 samples using SEM, several observations were made. The first sample, which was not heat treated (T6), exhibited one primary crack, two secondary cracks, one cracked particle, and two voids. These findings suggest that the material experienced localized stress concentrations and the presence of impurities or inclusions, leading to crack initiation and growth. The primary crack signifies the initiation point, while the secondary cracks indicate multiple crack paths, which can result from stress concentration factors, material heterogeneity, or complex loading conditions during fatigue. The presence of a cracked particle suggests the presence of impurities or inclusions acting as stress concentrators, causing localized failure. Additionally, the presence of voids within the microstructure can contribute to reduced structural integrity, promoting crack initiation and growth under cyclic loading conditions.

The second sample, which was T6 heat treated, displayed one primary crack, two secondary cracks, three flat facets, two voids, and two micro voids. The occurrence of flat facets indicates the presence of brittle fracture, possibly due to the heat treatment process. It suggests that the heat treatment might have altered the material's microstructure, resulting in more brittle behavior during fatigue loading. The presence of micro voids indicates the presence of internal defects, which could have been influenced by the heat treatment. These defects may act as stress concentrators, contributing to crack initiation and propagation.

Overall, the microstructure analysis reveals that both samples of aluminum 7075 exhibited fatigue damage, but the T6 heat-treated sample displayed additional features related to the heat treatment process. These findings emphasize the importance of understanding the microstructural changes induced by heat treatment and their impact on the material's fatigue performance. Further investigations and optimization of the heat treatment process may be necessary to enhance the fatigue resistance of aluminum 7075, ensuring its suitability for applications requiring high-strength and fatigue resistance. Careful consideration of heat treatment parameters and quality control measures can help minimize the formation of defects and brittle fracture facets, thereby improving the overall mechanical properties and fatigue life of aluminum 7075.

4. Conclusion

Experimental tests were conducted on Al 7075 specimens using an advanced fatigue testing machine (AFUTM), providing valuable insights into the material's fatigue behavior. To validate the accuracy of the simulation model, a comparison was made between the test results and finite element analysis (FEA) simulations carried out in ANSYS. The agreement between the experimental and simulated fatigue behavior confirmed the reliability of the simulation model in predicting the material's response under cyclic loading conditions.

Among the different heat treatments applied to Al 7075 specimens, the T6 treatment demonstrated superior fatigue resistance compared to the untreated sample. The T6 specimens exhibited a significantly higher number of cycles to failure, indicating an enhanced ability to withstand fatigue loads. In contrast, the specimens subjected to the HTPP and O treatments displayed reduced load-bearing capacity due to the resulting softer material characteristics.

The fatigue behavior analysis was further complemented by microstructural analysis using scanning electron microscopy (SEM). This combined approach, integrating experimental tests, FEA simulations, and microstructural analysis, provided a comprehensive understanding of the material's fatigue behavior and mechanical properties. The microstructural analysis enabled the identification of crack initiation sites, crack propagation paths, and other fatigue-related features, shedding light on the underlying mechanisms influencing the material's performance.

The comprehensive investigation revealed that Al 7075-T6 offers an extended fatigue life compared to Al 7075. The T6 heat treatment not only enhances mechanical properties but also improves the material's resistance to cyclic loading, making Al 7075-T6 a favorable choice for applications requiring durability and the ability to withstand repeated stress. The combination of experimental tests, FEA simulations, and microstructural analysis contributes to a thorough understanding of Al 7075's fatigue behavior, facilitating informed decision-making in material selection and design optimization for fatigue-prone components.

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