Predicting Fatigue Behavior in Friction Stir Welded Joints: A Simulation-Driven Approach for Critical Industrial Applications

Naveen Khatak* [1]
[1] Research Scholar, Department of Mechanical Engineering, U.I.E.T, Maharshi Dayanand University, Rohtak, 124001
[1]naveenkhatak.uiet@mdurohtak.ac.in

Prabhakar Kaushik [2]
[2] Professor, Department of Mechanical Engineering, U.I.E.T, Maharshi Dayanand University, Rohtak

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Abstract
The pervasive use of welded components in critical industrial equipment, ranging from heavy machinery to high-pressure vessels, presents a significant vulnerability. Inadequate analysis and subsequent fatigue failures not only trigger costly production disruptions and severe workplace accidents but also pose a substantial impediment to achieving global net-zero targets, sustainable economic growth, and the broader objectives of the Sustainable Development Goals (SDGs). Understanding the fatigue behavior of welded materials, especially in the critical heat-affected zone (HAZ), is paramount for ensuring structural reliability. This research introduces a novel approach utilizing numerical simulation to accurately predict fatigue life in both base metal (BM) and friction stir welded (FSWed) configurations. Through meticulous validation against experimental results, the research demonstrate the predictive fidelity of proposed model. The study concluded that a consistent trend of maximum stress concentration within the HAZ, directly linking simulated stress patterns to observed failure mechanisms. Furthermore, this study provides critical insights into the material behavior of welded joints under cyclic loading, paving the way for improved design and performance in demanding applications

Keywords: friction stir welding, numerical simulation, heat treatment, mechanical testing, surface morphology.

1.Introduction
To understand the modelling process, we need to first understand the meaning of a model. A model is nothing but a replication of something which is happening in real. So, a model is a miniature (abstract) representation of something. Why it is called miniature? Because most of the time the model is drawn on a small scale as compared to the real objects. How the real object or real phenomena is happening, we try to replicate through modelling and it is a representation used to visualize something.

2.Need of numerical methods & simulation techniques
We know that all of us have been performing mathematical modelling knowingly or unknowingly since our school days. So, whatever school-level of mathematical formulae we have studied, ultimately, they were nothing but all mathematical models. Many laws of nature are captured and explained with the help of mathematical modelling.
Most physical problems do not have an analytical solution. Thus to gather an understanding of the system we need computational techniques to arrive at the solution. These solutions when analysed, render an understanding of the key concepts that were embedded into the equations. There are approximation techniques which we have seen in course of quantum mechanics or sometimes even in classical mechanics. They only give an approximate solution, so to gather an understanding of those

systems where exact numerical methods or rather exact analytical solutions are not available. Computational techniques are the only solution to those problems and we need to arrive at the solution and these solutions when we analyse them they give you an understanding of the key concepts that are imbibed in the equations. The equations do not make any sense to us unless they are solved and they are put in perspective and they are made physically meaningful for us to gather information about the system its property its character. Simulation techniques are powerful methods to handle large systems of equations with several unknowns, large matrices, complicated non-linearities etc. We cannot physically solve maybe more than one particle or two-particle or maybe a few particles but these computers these computational techniques can solve a large number of simultaneous equations with several complications such as they can have a large number of unknowns. Usually, non-linear equations cannot be sold by hand you need to have computational methods for numerical methods to solve the non-linear equations. So, these are some of the very basic things that numerical methods come to have and they are heavily used in most the situations. Previous studies have shown that the incorporation of reinforcements such as SiC whiskers, nickel-coated carbon fibers, and garnet particles significantly enhances the wear resistance of aluminum and zinc-based metal matrix composites under various wear conditions, including oscillating, abrasive, and dry sliding wear [1-4].

Different computational techniques provide efficient usage of the computer by learning computer languages, such as C, Python, Fortran etc. many of the software packages which we use daily for our computing/plotting/documentation need to employ numerical techniques. And importantly last and not least, the numerical techniques and idea of how the errors propagate and especially in high-accuracy computation. So, when need results which are you know you need the accuracy of 10 to the power – 6, then, of course, you have difficulty getting anything up to the five decimal places.

The FEM practices have advanced to the point where they can be used to study complicated structures while they are being designed. Furthermore, direct load, response, and strength evaluations might yield useful data when design advances are explored. In those kinds of circumstances, it is crucial to accurately determine the correlation between the limit values and the corresponding loading conditions. These cutting-edge technologies provide a platform for an investigation into the principles of fracture mechanics, which control complicated structures. Numerical solutions serve as a unique tool for engineers.

FEM has become an essential part of the design and development of numerous engineering systems, including those in the aerospace, automotive, electrical, electronics, and healthcare industries. Surprisingly, it is also used in the chocolate industry to keep it from breaking during packaging. So, learning FEM is essential in design and development.

Differential equations mathematically represent the majority of systems. These equations in engineering problems are accompanied by additional constraints known as boundary conditions. The differential equations together with boundary conditions are referred to as boundary value problems (defined for a specific domain or geometry). There is no other option to design efficient engineering systems but to solve these boundary value problems. When solving boundary value problems, analytical methods (direct integration, Laplace transform, etc.) are only applicable to simple geometry. The question now is how to deal with complex geometries in real-world applications. The solutions are numerical methods. The FEM is a numerical method for obtaining an approximate solution to a boundary problem. It converts the boundary value problems into linear equations, and the computers are used to solve them. The basic geometry is split into smaller units in the first step. This is known as meshing, one of the most critical steps in FEM. Each unit is called an element, and all the intersection corner points are known as nodes. After meshing, one element at a time is considered and computed for that. Likewise, all elements are calculated separately. Once the input is given to the software, it creates a mathematical model for a given physical problem. The software provides results at some selected points. It is always advisable to do some hand calculations or, if possible, have some experimental data so that whatever results we get here are not totally out of context. Next, all the information is gathered and obtained the solution at all the domain nodes. Finally, further calculations are performed to obtain the field solution for the entire domain. Extensive research highlights that the wear behavior of aluminum-based composites is significantly influenced by reinforcement type, heat treatment, and testing conditions, with studies on Al7075-glass fiber, SiC, and garnet reinforcements revealing improvements in dry sliding, abrasive, slurry, and corrosive wear resistance, while tool design also plays a key role in optimizing composite fabrication through friction stir welding[5-10].

Materials and Methods:

Numerical software can reveal the model's advantages and shortcomings before the final design. The ANSYS Workbench can be considered a general-purpose FEM software tool. It can offer a practical means of investigating how well products operate in a virtual setting. The general steps to solve any problem in ANSYS Workbench are as follows:

Pre-processing phase:

- Identify the type of analysis
- Enter material characteristics
- Import or create geometry
- Mesh/discretise the geometry
- Give appropriate boundary conditions

Post-processing phase: Obtain the other important information. Like in static structural analysis, obtain total deformation, stresses etc.

3. Experimental procedure

Numerical simulation methodology

The problem's answer is already in the workbench file that was supplied. After the archive has been restored, double-click Engineering Data. Click on Structural Steel under Engineering Data, then Alternating Stress Mean Stress. Before defining a new material's isotropic properties, you must enter its alternating stresses at cycles if you want to use it for fatigue analysis. The majority of strength of materials textbooks contain information on alternating stresses for different materials. Problem solutions are approximated using numerical software. Once the experimental results are accessible, any numerical results can be verified. The dog-bone-shaped 3D model of the fatigue specimens for the simulation study was created using AutoCAD 2019. Four distinct microstructure zones—SZ, TMAZ, HAZ, and BM—are identified in the FSWed model. Various welding zones were represented in the model using various materials with various properties. In other words, as indicated in Table 1, FSWed zones were introduced to the model by giving the mesh components in the ANSYS Workbench tool the zone material properties. For every zone, the Young's modulus of elasticity and poisson's ratio have the same magnitude. Recent studies emphasize the critical influence of tool design, process parameters, and reinforcement materials on the mechanical, tribological, and microstructural properties of friction stir welded and stir-cast aluminum composites, with optimization techniques such as Taguchi-Grey Relational Analysis further enhancing performance; additional investigations also explore hybrid reinforcements, fatigue life, and advanced applications in additive manufacturing and thermal systems[11-28]. Fig. 1 displays the full 3D models for the BM and FSWed specimens.

Table 1. FSWedaluminum 6061-T6material properties

FSW zones	SZ	TMAZ	HAZ	BM
Young's modulus of elasticity (MPa)	68900	68900	68900	68900
Poisson's ratio	0.33	0.33	0.33	0.33
YS (MPa)	276.2	263.65	311.67	287
UTS (MPa)	309.87	299.69	350	328.9
Micro-Hardness	89.3	80.4	95.6	88.7

The ANSYS Workbench software tool has two different kinds of meshing. There are two mesh settings: the global mesh setting and the local mesh setting. While local meshing enables the selection of one or more specific surfaces, global meshing enables the selection of the entire geometry. After that, the software application will create meshing using the data from the default option. Fig. 2 shows the whole collection of items needed to set up the static fatigue assessment.Every zone with mechanical properties was subjected to the Von-Mises criterion. Additionally, the identical stress values used in fatigue experimental testing were used in the simulation investigation. The fatigue life experimental testing was validated using the simulation model's results.You have a number of options from the fatigue tool to incorporate into the analysis; select the appropriate ones. Only life, safety factor, and alternating stress will be assessed for demonstration. Insert Life, Safety Factor, and Equivalent Alternating Stress by performing a right-click on the Fatigue tool[22].

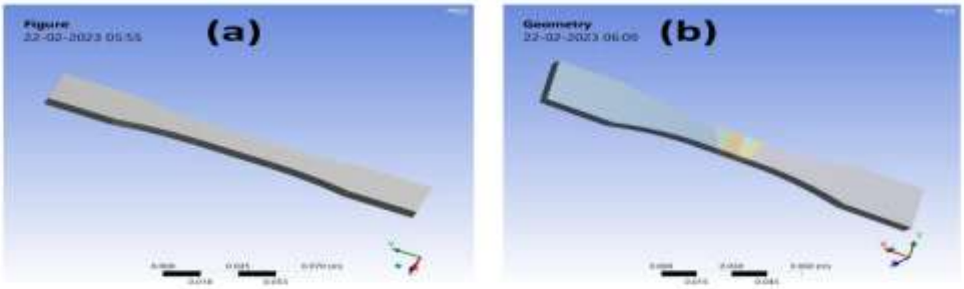

Figure 1 The 3D fatigue model of BM (a) and FSWed specimens (b)

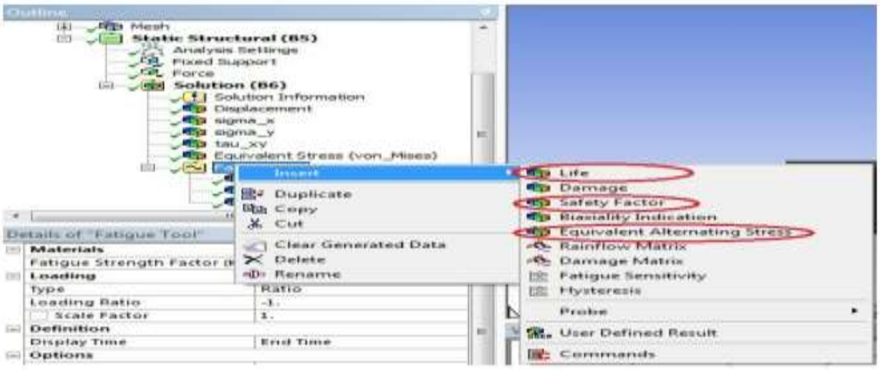

Figure 2 Different options in the Fatigue Tool

4.Results and discussion

Fatigue life determination

The material properties of the aluminium 6061-T6 alloy derived from experimental testing were given engineering data, including YS, UTS, mean stress, alternating stress, and fatigue life. A fine mesh was also selected in order to predict results that were more in line with the experiments. In contrast to the FSWed specimen, which had 6725 nodes and 1052 elements, the BM specimen's mesh model was built with 7873 nodes and 1320 elements. Fig. 3 displays the mesh model for both kinds of specimens[22].

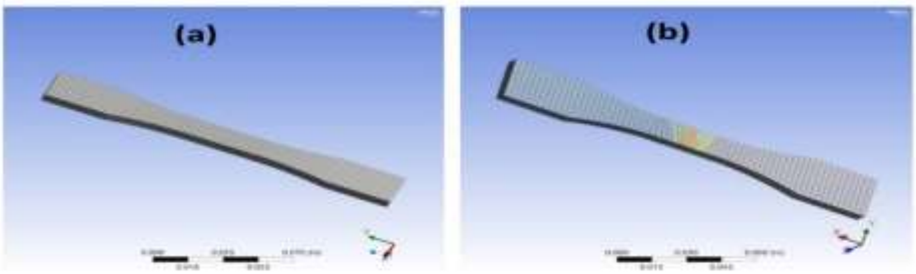

Figure 3. Meshing of BM and FSWed specimens

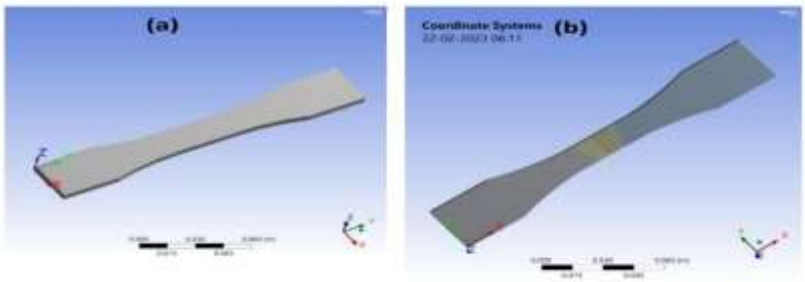

Figure 4. Co-ordinate system applied to BM and FSWed specimens

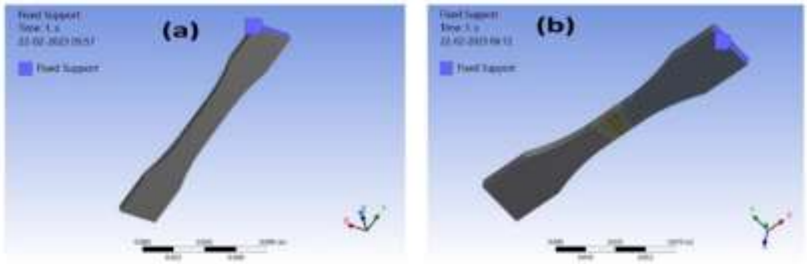

Figure 5. Fixed support applied to BM and FSWed specimens for fatigue simulation analysis

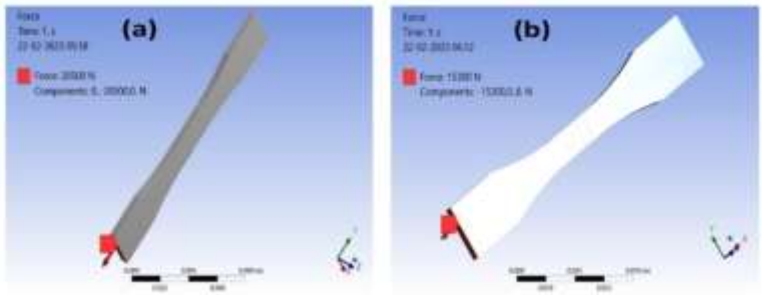

Figure 6. Load applied to BM and FSWed specimens for fatigue simulation analysis

The specimen end was secured with all degrees of freedom set at position A, and the load was applied at point B. In the fatigue tool setting, stress life was chosen with a load ratio of 0.1 and stress component corresponding to Von–Mises criteria. Table 2 gives the simulated results of fatigue lives at different stress levels for both BM and FSWed configurations[22]. Figs. 7(a) and 7(b) illustrate fatigue life results at amplitude stress of 85.5 MPa for both BM and FSWed models.

Table 2. Results of fatigue tests from simulation analysis

S No.	Amplitude stress (MPa)	Estimation of fatigue lives for BM model	Estimation of fatigue lives for FSWed model
1	49.5	7456710	6474200
2	54	6576550	4372600
3	58.5	4781760	3668000
4	63	2769800	2675100
5	67.5	1856600	1460400
6	72	603090	354730
7	76.5	385940	411960

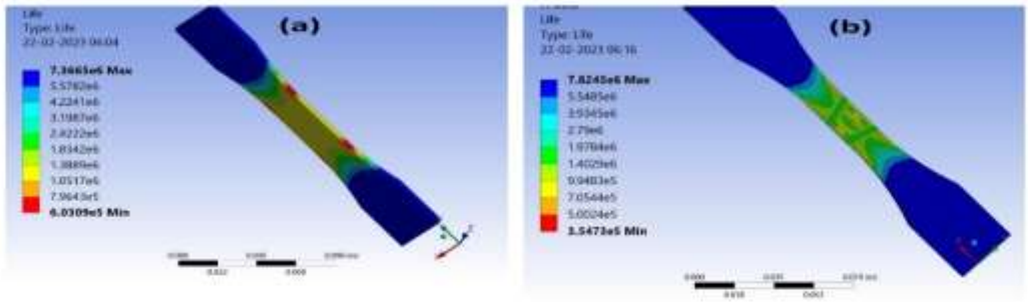

Figure 7. Results of fatigue lives at amplitude stress of 72 MPa for BM model (a) and (b)FSWed model

Comparison of the experimental and simulation results

The actual and simulated fatigue responses for the BM and FSWed models are shown in Figures 7(a) and 7(b), respectively. Results from simulations and experiments supported the fatigue life. A higher level of stress reduces fatigue life. Within the range, a correlation between the curves representing the experimental and simulated findings was seen. Under identical amplitude loads, the simulation results show that both BM and FSWed material configurations perform better in terms of fatigue. As amplitude stresses increase, the difference between the simulated and experimental data widens. At an amplitude stress of 49.5 MPa, the BM configuration shows a minimum fatigue life difference of 4.2%, and at 76.5 MPa, a maximum difference of 14%. Figure 8 illustrates how the FSWed setup's outcomes are more variable than the BM configuration. At an amplitude stress of 49.5 MPa, the experimental results for the FSWed specimens show noticeably better fatigue performance than the modelling results. At a stress amplitude of 54 MPa, the linear fitting curve shows where the simulation and experimental data connect. When the amplitude stress was 76.5 MPa, the fatigue cycle discrepancy increased to 22.5%. The discrepancy between simulation and experimental results is explained by scratches, abrasive surfaces, and microstructural phenomena. The information shows a favourable trend line comparison with a high level of agreement. According to the modelling results, the HAZ region of both the BM and FSWed specimens had the maximum stress. Because of the short fatigue life, failure occurs in this area[22].

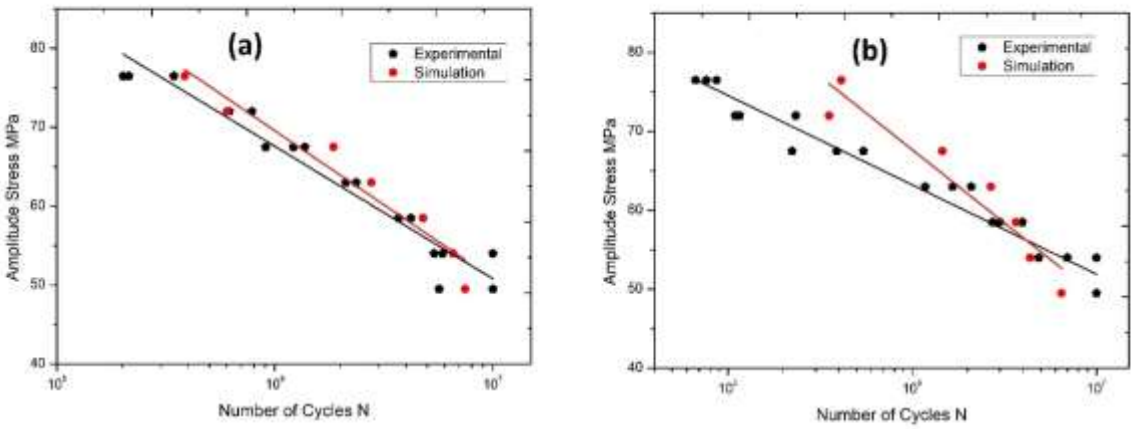

Figure 8. Comparison of the experimental and simulation results for BM and FSWed

Conclusion:

This research has successfully demonstrated the efficacy of numerical simulation in accurately predicting fatigue life within both base metal and friction stir welded configurations, validated through rigorous comparison with experimental data. The consistent identification of maximum stress concentration within the heat-affected zone (HAZ) provides a crucial link between simulated stress patterns and observed failure mechanisms, substantiating the model's predictive fidelity. These findings offer critical insights into the material behavior of welded joints under cyclic loading, particularly in the critical HAZ, and highlight the significant impact of stress concentration on fatigue performance. By providing a robust simulation-based approach, this study paves the way for improved design methodologies, enhanced structural reliability, and optimized performance in demanding industrial applications.

Furthermore, the implications of this research extend beyond immediate industrial applications. Accurate fatigue life prediction in welded components is instrumental in mitigating costly production disruptions and preventing severe workplace accidents. More significantly, it directly contributes to achieving global net-zero targets and advancing the broader objectives of the Sustainable Development Goals (SDGs) by enhancing the durability and longevity of critical infrastructure. By fostering the development of more reliable and sustainable welded structures, this research plays a pivotal role in promoting sustainable economic growth and ensuring the safety and efficiency of critical industrial equipment, ultimately fostering a more resilient and sustainable industrial landscape.

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