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Research Article

Assessment of fatigue life of square threads using SN curve analysis

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Abstract - When coil tubing is used, thread failure in Bottom Hole Assemblies (BHA) at high depths is a worry due to tough well paths. Square threads made from medium carbon steel (AISI 1045) are investigated to find out if they can enhance the fatigue resistance in extreme drilling environments. The study investigates if square threads, with their flat geometry, may permit steady and balanced loading of BHA parts, in contrast to traditional thread forms. A four-point rotating bending fatigue machine was used to test samples at different stress levels. To determine the performance of square threads, fatigue life and endurance limits were calculated by analyzing the data with the S-N methodology. The minimum load we used is 130N and we get maximum number of cycles i.e. 773250, whereas, maximum load is 450N at which we got 4037 number of cycles. Stress Concentration factor K_t is 1.72. Analysis concluded that, even if their fatigue life is just below that of rounded threads, square threads are still a better alternative than traditional thread designs for BHA components working in tough conditions.

Keywords-component; Bottom Hole Assemblies (BHA); Coil tubing; Square threads; Fatigue resistance; AISI 1045; Bending stresses; Rotating bending fatigue; S-N curve; Stress concentration; Endurance limit

I. INTRODUCTION

Efficient and reliable oil extraction in deep well environments relies heavily on the integrity of oil well tubing and the attached components known as Bottom Hole Assemblies (BHA). BHAs are critical mechanical systems installed at the lowermost part of the tubing and are essential for various downhole operations, including drilling, coil tubing services, pumping, and milling. Given the harsh conditions and complex trajectories encountered at depths up to 20,000 feet, these assemblies are exposed to extreme loads, including bending, torsion, and axial stresses. These loading conditions often lead to fatigue-related failures in threaded connections, which include cracking at thread roots, abrasion, thread rupture, and geometric distortions [1].

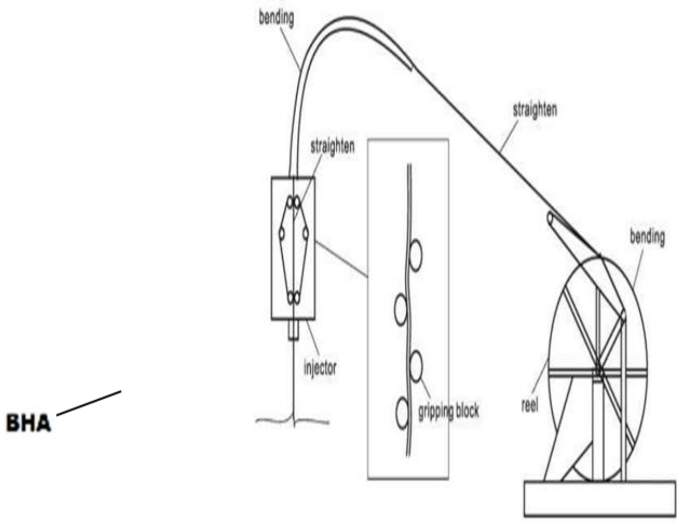

Figure 1: Bending in BHA and string

To mitigate such failures, industry practices typically employ BHA connectors—intermediate components made from relatively weaker materials, such as AISI 1045 medium carbon steel—to absorb damage and prevent it from propagating into the tubing or operational BHAs. These connectors utilize various thread types, including square, screw, and knuckle threads, each influencing the system's overall durability and performance[2]. All the failures in threads occur due to Wash-out or Twist-off [3].

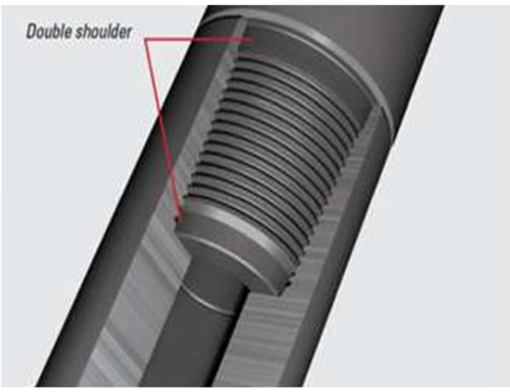

Figure 2: BHA and Connector Assembly[4]

Despite regular inspections through techniques like Magnetic Particle Inspection (MPI) and Magnetic Flux Leakage (MFL)[5], these methods merely detect existing flaws rather than predict fatigue life, often leading to the premature rejection of components to avoid catastrophic failure.

Figure 3: Damaged Screw Thread [3]

Fatigue is a primary concern in threaded components subjected to cyclic loading. Even when applied stresses are below the material's yield strength, repetitive stress cycles can lead to crack initiation and eventual failure [6]. Several studies have investigated the fatigue behavior of conventional thread designs under such conditions. Peterson (1959) provided foundational models to understand stress concentration at thread roots [7]. Dixon and Nevill (2006) conducted fatigue testing on standard threads and emphasized the importance of geometry on fatigue life, with sharper roots accelerating crack initiation[8]. Frost et al. (2011) further highlighted how thread root radius and pitch affect resistance to fatigue failure, showing that larger root radii lead to reduced stress concentrations and improved fatigue resistance [9].

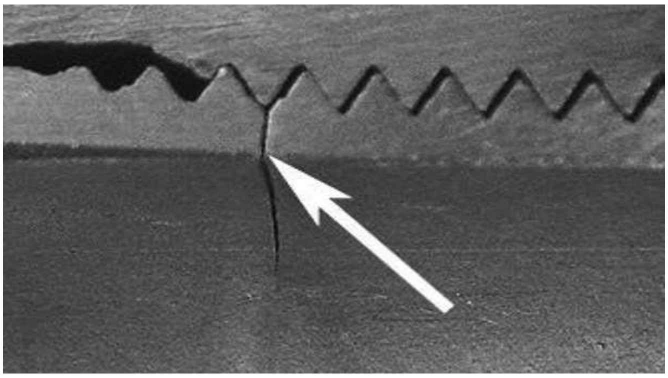

Figure 4: Crack development due to bending fatigue

Recently, square threads have gained attention for their potential to improve fatigue performance in high-stress environments. Characterized by their flat profiles, square threads are believed to reduce stress concentration and delay fatigue crack initiation. Studies suggest that square threads offer better stress distribution and fatigue resistance compared to traditional thread forms. However, most of these works focus on qualitative assessments or comparative studies, and few provide a comprehensive fatigue life analysis based on S-N (stress-number of cycles) curve methodology. An S-N curve of aluminum [10] is given below

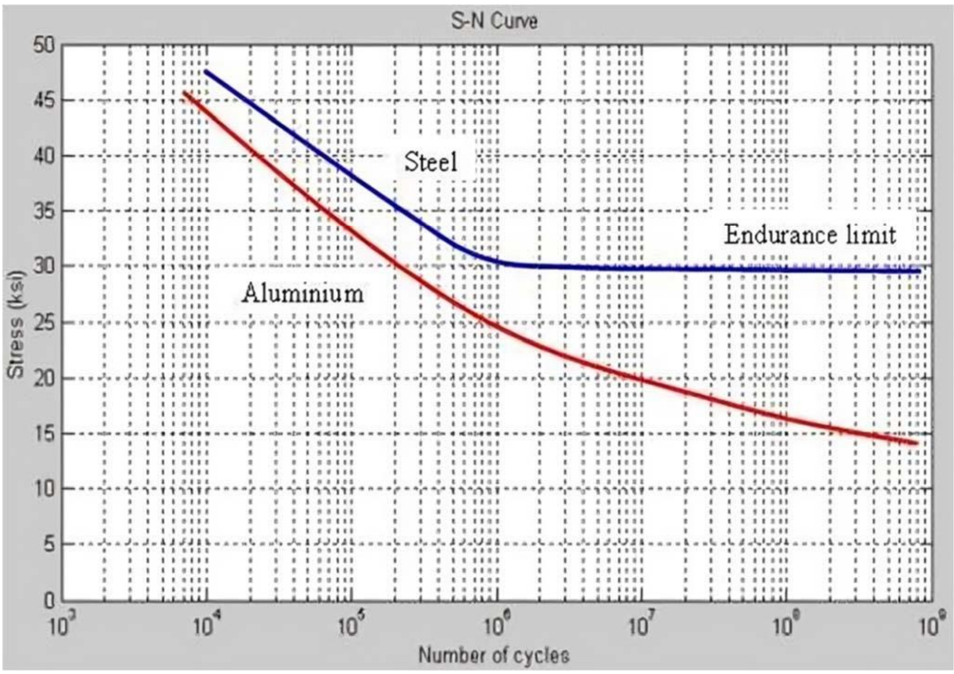

Figure 5: SN Curve explained

Our study aims to address these gaps by evaluating the fatigue life of square threads through experimental S-N curve analysis. The research focuses on square threads manufactured from AISI 1045 steel and subjected to various cyclic loading conditions using a 4-point rotating bending fatigue machine. The objective is to generate reliable fatigue life data that can inform the design and selection of thread profiles for critical oil and gas applications. By doing so, this study contributes to the enhancement of thread reliability in BHAs and supports the development of more robust components for high-stress, fatigue-prone environments [11].

II. METHODOLOGY

2.1 Stresses in Specimen

Load which is being applied on the specimen at the bottom of machine must be converted into some stress value according to its thread type stress concentration value. The notch (Threads) stress concentration factors Kt are found by mathematical equations [12]. Following equation of fundamental beam theory was used to calculate the magnitude of the alternating stress when it is been subjected to load using un-notched specimen.

$$\frac{\sigma}{C} = \frac{M}{I} \quad (1)$$

Adding nano Mo to the dielectric fluid improved the thickness of the white layer due to its effect on enlarging the machining gap distance, Where, σ = Applied Stress (MPa), Q = Applied Load (mm), M = Bending Moment = Q*(a/2) (N-mm), a = Central Axial Distance between Two Bearings (Bending Arm) which is 100mm for this machine (mm), C = Half of the Core Diameter of specimen = d/2 (mm), I = Moment of inertia = Second Moment of Area =

$$\text{Moment of Area} = \frac{\pi d^4}{64} \quad (2)$$

$$\frac{\sigma}{\frac{D}{2}} = \frac{Q*\frac{l}{2}}{\frac{\pi}{64}*D^4} \quad (3)$$

$$\sigma = \frac{Q(N)*50(\text{ mm})*32}{\pi D^3(\text{ mm}^3)}$$

$$\sigma = \frac{509.55Q}{D^3}\left(\frac{N}{m^2}\right) \quad (4)$$

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The units of the stress are Nmm^{-2}

For un-notched specimens maximum bending Stresses (σ) are obtained through following equation,

$$\sigma_b = \frac{32M}{\pi d^3} \quad (5)$$

The 'K_t' stress concentration factor is defined as,

$$K_t = \frac{\text{Max.Stress with notch}}{\text{Max.Stress without notch}} \quad (6)$$

The alternating stress for the notched specimen

$$\sigma_{\text{Notched}} = K_t \times \sigma_{un-notched} \quad 7$$

Stress concentration factor for this type of thread in bending is obtained. We found the value of $K_t \sim 1.72$.

2.3 EXPERIMENTAL WORK

Materials

Medium carbon steel AISI 1045 which has 0.43%-0.5% carbon is used for testing as it is widely used in Oil and gas sector for the preparation of assemblies. Rods of 19mm diameter were purchased from local market. Material offers good machinability, high strength, impact properties and good surface finish. Mechanical properties of the material are given below

Figure 11: Rods of Medium carbon Steel AISI 1045

2.3.1 Chemical Composition of Material

The specimen which is being used is AISI 1045 steel as mentioned above has following chemical composition. [13]

Table 1: Chemical Composition of Material

Element	Content
Iron, Fe	98.51 - 98.98 %
Manganese, Mn	0.52 - 0.80 %
Carbon, C	0.430 - 0.50 %
Silicon, Si	0.11 – 0.20 %
Phosphorus, P	≤ 0.020 %
Sulfur, S	≤ 0.010 %

2.3.2 Mechanical Properties of Material

Hardness testing and tensile testing is being used to get the mechanical properties. The specimens for tensile tests were prepared separately with different geometry just to conduct the test. Total three specimens were tested for tensile strength on universal testing machine and mean value was taken and used for further study. Tensile testing picture is shown in Figure.

Figure 12: Tensile Testing of the Material

Tensile testing was conducted using a Universal Testing Machine (UTM) to evaluate the mechanical properties of AISI 1045 medium carbon steel specimens. The UTM applied a controlled uniaxial tensile load while continuously recording force and elongation until specimen fracture. This setup enables precise determination of yield strength, ultimate tensile strength, and elongation, providing insight into the material’s deformation behavior. The dog-bone shaped specimens featured a square thread notch at the center to introduce stress concentration, allowing assessment of the material's performance under realistic service conditions.

Figure 13: Hardness Testing of the Material

The hardness of AISI 1045 medium carbon steel specimens was evaluated using a Universal Hardness Testing Machine, capable of performing multiple standardized hardness tests, including Brinell, Rockwell, and Vickers. For this study, the machine was configured to apply controlled loads via a specified indenter, and the resulting indentation was measured to determine the material's hardness value. The Universal Hardness Tester ensures precision, versatility, and repeatability, providing an essential measure of the material's resistance to deformation before proceeding with fatigue and mechanical testing. Number of hardness test were performed.

Total three test each were performed for finding the exact material properties; average of these tests for hardness and tensile tests are provided in Table 3-3, and stress-strain curve taken from ASM standards book [13] to find the exact yield strength value of the material diagram is shown in Figure 14.

Table 2: Tested Mechanical Properties

Mechanical Property	Hardness Testing	UTS
Hardness, Rockwell HRC	24.5	
Tensile Strength, Ultimate	840 MPa	798 MPa
Yield Strength	415 MPa	403 MPa

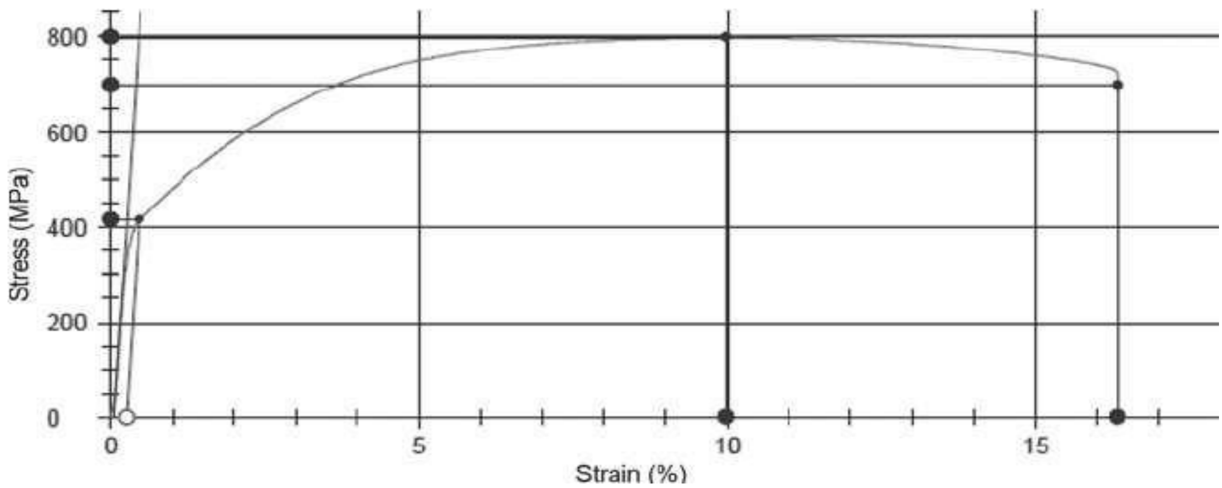

Figure 14: Stress Strain Diagram [14]

So, after the above-mentioned experimentation the value of Yield strength and Tensile strength that is being used during the research are in Table 3-3

Table 3: Used Mechanical Properties

Mechanical Property	Value
Tensile Strength, Ultimate	840 MPa
Yield Strength	410 MPa

2.3.3 Experimental Setup

For investigation of the fatigue strength of the material with thread at the center, 4-Point rotating bending machine is used. Machine designed seeing the exact design suggested by R.R. Moore for conducting rotating beam testing system [15]. This machine allows two set of sizes to be fir in it for conducting the testing. Technical specification of the machine is given in Table 3-4, During this research all the specimen were made with 17 mm diameter and due to faulty counter assembly, simple watch was used to calculate the time and then multiplying the time (minutes) with RPM value of the motor to calculate the cycles of the desired specimen.

Table 4: Specifications of four point rotating bending machine

Overall dimensions	1170 x 500 x 1220
Motor power	3 phases, 0.75 KW, 50Hz, 380V
Maximum bending moment	60 N.m
Speed of motor	3000 rev/min
Specimen Dia	12mm and 17 mm
Maximum length of specimen	226 mm
Temperature in spindle box	≤ 30°C
Counting limit	1 x 107

Working of this apparatus is shown in Figure. In each revolution of the specimen; tensile and compressive stresses of equal amplitude are produced. Specimen are prepared with 17 mm diameter with standard dimensions mentioned above. To investigate the fatigue strength, set of specimens having different threads are tested at different load levels.

Figure 15: 4-Point rotating bending fatigue testing machine

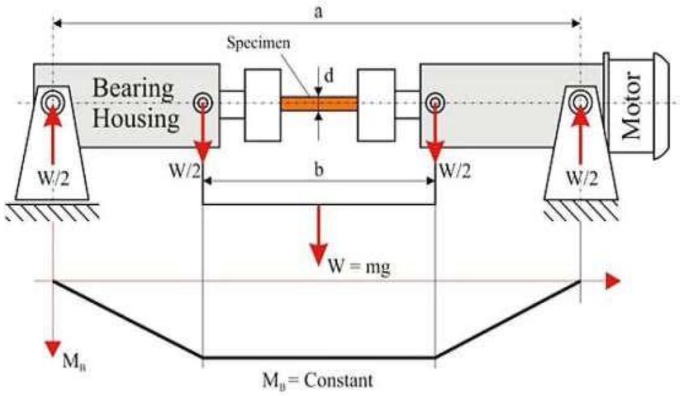

Figure 16: Schematic of 4-point rotating bending fatigue testing machine [16]

During experimentation it is been observed that after the fracture of the material both the fractured corners concedes with each other resulting in the loss of fractographic data. Therefore, to protect the fractured surface, wedge-column mechanism was designed [17], shown in Figure 17 (a), and was attached with machine. Mechanism was designed with so care that specimen's rotation and its working was not affected by it. Both scenarios are shown in Figure 17.

Figure 17: Wedge and column attachment; (a) before fracture, (b) after fracture

As mentioned above in Table 3.4 only 17 mm and 12 mm diameter of specimen is allowed in 4-Point rotating bending machine with 226 mm length. So, following points/instructions must be kept in mind while doing experimentation on that machine. Standing in front of the machine, first the right side of the specimen is inserted in elastic clamps chucks and then left side. Elastic clamps or collets are shown in Figure 3.8. While mounting the specimen load should be removed. Specimens both sides have to be equally tight. One side should coincide with the other side i.e. dimension and geometry of the specimen has to be completely aligned. As counter assembly is out of order; there should be proper stop watch in place to count the time to failure

Figure 18: Elastic Clamps or Collets

Now we discuss the parameters of 4- Points Rotating Bending Machine used for finding Fatigue failure of specimen due to cyclic bending stresse. Here is the table given;

Table 5: Machine Parameters

Parameters	Level one
Overall dimensions	1170 x 500 x 1220
Motor power	3 phases, 0.75 KW, 50Hz, 380V
Maximum bending moment	60 N.m
Speed of motor	3000 rev/min
Specimen Dia	12mm and 17 mm
Maximum length of specimen	226 mm
Temperature in spindle box	≤ 30°C
Counting limit	x 107

2.4. PREPARATION OF SPECIMEN

The size and dimensions of the specimen were determined based on the specifications and limitations of the fatigue testing machine, as different machines require specific standards for proper specimen mounting [18]. In bending fatigue testing, two dimensions are particularly critical: the diameter and the length of the specimen. For this research, the standard specimen used had a main diameter of 17 mm, which aligns with the machine's compatibility for either 12 mm or 17 mm diameters. The total length of each specimen was 226 mm, with a reduced section diameter of 12 mm specifically designed for fatigue loading, while the core diameter varied depending on the thread type being tested. Additionally, the gauge length — the effective length over which fatigue failure was expected to occur — was maintained at 96 mm. Figure Rods of Medium carbon Steel AISI 1045

Table 6: Square Thread Specification

Thread Type	Depth	Angle
Square thread	0.500p	0

Above mentioned thread on specimen is shown in below pictures Figure

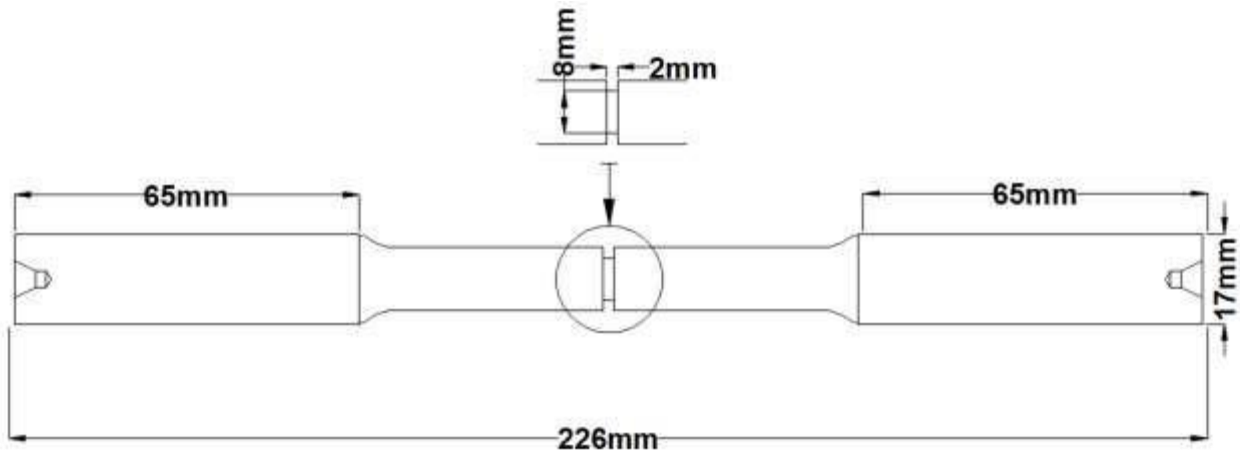

Figure 19: Specimen with Square Thread

III. RESULTS AND DISCUSSIONS

Now we discuss about the load that were applied on all specimens. There was a selected same load which was applied on square threads. Then experimentation results for all specimen of square threads will be discussed, their SN curves will be drawn accordingly [19]. At the end better thread type will be suggested and will be recommended for future.

3.1 Load and Specimen Tested

Following Table 6 Shows the list of loads applied on specimen and their tested specimen quantity. Specimens those were tested 0 in the above table is because whether they have already reached their endurance limits or they were tested by nearby loads or data is sufficient enough to draw the SN curve properly.

Table 6: Loads Applied on Square Thread Specimen

Serial No.	Load (N)	Square Thread No. Of Specimen Tested
1	130	3
2	175	3
3	220	3
4	250	3
5	285	0

6	300	3
7	315	3
8	350	3
9	400	0
10	450	3

3.3 Results of Square Thread

Around 23 specimen (03 each on every load) with square thread were tested and their data is shown in Table 7.

Table 7: Square thread Tested Specimen results

Sr. No.	*Load 'N' (Q)*	*σ = 509.3Q/(d^3 'N/mm2'*	*Alternating Stress Sa= σxKt= 1.72xσ*	*Fatigue Life (No of cycles)*			
				Trial#01	*Trial#02*	*Trial#03*	*Mean*
1.	130	128	220	786457	625147	908147	773250
2.	175	173	297	184233	256681	158763	199892
3.	220	223	383	71627	55185	63109	63307
4.	300	297	510	39054	26885	41318	35752
5.	315	312	536	85183	34243	30281	49902
6.	350	347	596	14574	13442	14178	14064
7.	400	396	681	7244	6509	7075	6942
8.	450	447	768	3565	4952	3594	4037

3.4 S-N Curve of Square Threads

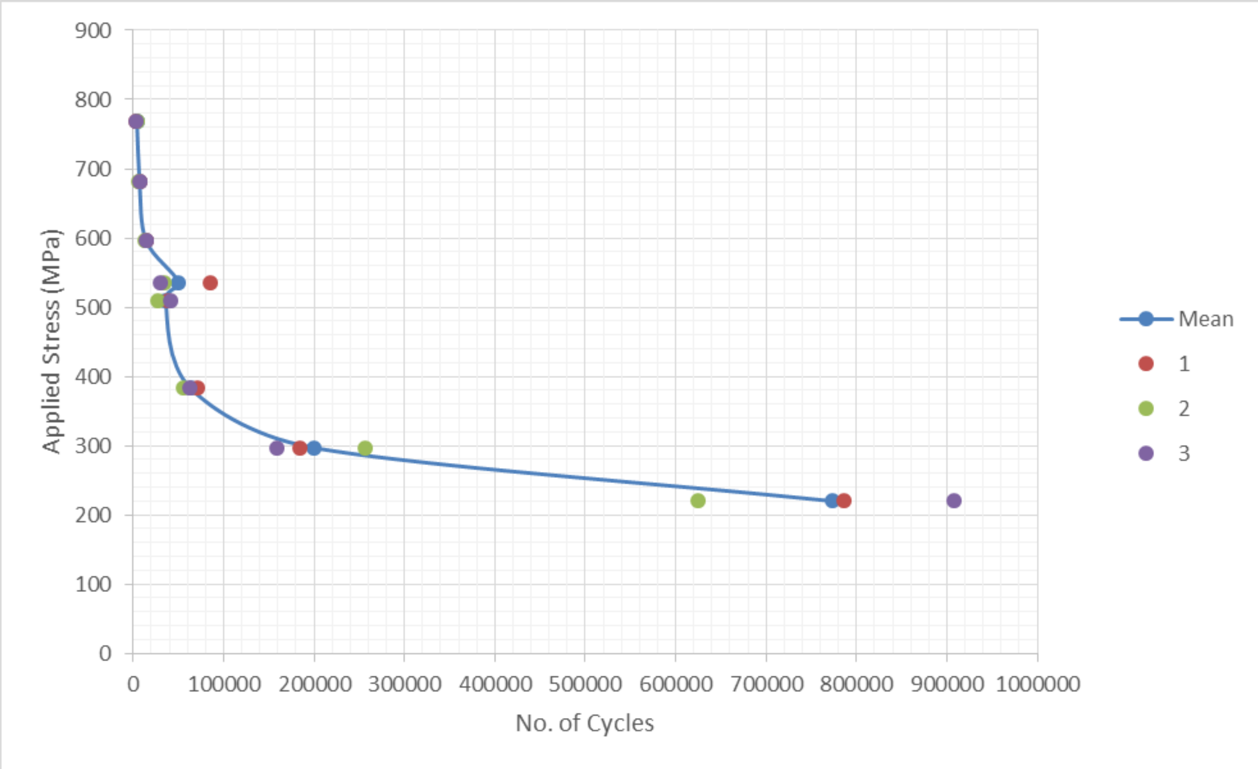

Figure 20: SN curve for Square Thread

We tested 23 specimens with square threads from AISI 1045 steel in order to examine their performance under cyclic loading. As the stress on the specimens increased, the fatigue life went down and the wetting was shorter. Specimens with square threads that could support 552 MPa stress in cycles lasted the longest and behaved identically to HCF. Studies indicated that square threads have sufficient stamina for being used in repeated loading. Kt was used to improve fatigue life calculations, because otherwise, the estimate of stress at the thread's roots could create problems in analysis. Consequently, the stress concentration in square threads is higher than in knuckle and lesser than screw. With this, they are not as resistant to fatigue as knuckle threads, but they are still popular due to their easy and quick assembly. You can use square threads in tough jobs, for example, in oil and gas drilling, Bottom Hole Assemblies, and heavy machinery parts. For engineering work, square threads are satisfactory and offer an easy-to-make solution that lasts after repeated loading. For fatigue-critical tasks, square threads are predictable because they have a stress concentration factor of 1.72. Because of their moderate fatigue life and simple construction, square threads fit in the field of engineering[20].

IV. CONCLUSIONS

This study looked into the fatigue performance of square threads from AISI 1045 medium carbon steel by testing them in a 4-point rotating bending machine. The study found that square threads, despite being moderate fatigue resistant, end up with higher stress due to their flat top and bottom, which makes them more likely to fail before. The graph showed that as the stress increased, the number of cycles before failure was reduced. Since there wasn't any direct testing against other thread types and real-field conditions were overlooked, the findings might not be very generalizable. It would be useful for further studies to work on these issues, as it will fully highlight the usefulness of square threads in demanding areas.

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