

FATIGUE STRENGTH PROPERTIES OF SS304 AT CRYOGENIC TEMPERATURES

¹D.S. NADIG, ¹Chandan MAHISHI

Centre for Cryogenic Technology, Indian Institute of Science, Bengaluru, India, nadig@iisc.ac.in, chandann2008@gmail.com

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Abstract

Fatigue is a progressive and permanent structural change that occurs in materials subjected to fluctuating stresses, which results in fracture after a certain number of stress cycles. Data of fatigue strength properties of materials for room temperature applications is abundantly available. However, information of this property at cryogenic temperature is very scarce. It is not possible to interpolate the available data to cryogenic temperature zone, since mechanical properties abruptly change at low temperatures. Hence, a rotating beam fatigue testing machine for cryogenic temperature zone has been designed and developed. This machine can be used to obtain the data of fatigue properties of any specified material from room temperature down to cryogenic temperature. The cryogenic temperature environment is produced by circulating controlled quantity of liquid nitrogen (LN₂) around the test specimen. In this experimental work, fatigue properties of stainless steel (SS304) are determined, compared and analysed at both room and cryogenic temperature

Keywords: Cryogenics, Liquid Nitrogen, SN curves, Stress, Strain

1. INTRODUCTION

Sufficient data of mechanical properties of materials is easily available at room temperature [1]. However, data of these properties are not readily available at cryogenic temperatures [2]. At the same time, the available data cannot be interpolated down to cryogenic temperature since the properties suddenly change at low temperatures. Knowledge of fatigue strength is very essential for materials which are subjected to continuous cyclical stresses. Fatigue is a progressive, localised and permanent structural change that occurs in materials subjected to fluctuating stresses and strains that may result in cracks or fracture after sufficient number of stress cycles [3]. Inadequate fatigue strengths can lead to premature failure of mechanical components. In view of this critical background, a rotating beam fatigue testing machine for cryogenic temperature zone has been designed and developed. The cryogenic temperature environment is produced by circulating controlled quantity of liquid nitrogen (LN₂) around the test specimen. In this experimental work, fatigue properties of stainless steel (SS304) are determined at both room and cryogenic temperature. The test results are compared and analysed.

2. FATIGUE STRENGTH

When a material is subjected to repeated loading, the structure gets damaged progressively and after a given number of cyclical stresses, it fails. Ferrous and titanium alloys exhibit a limiting value of stress below which the material will not fail by fatigue for any number of stress cycles [4]. Fatigue properties of materials are usually described by S-N curves, where the limiting stress values (S) are plotted against the number of stress cycles (N). A typical S-N graph is shown in **Figure 1**.

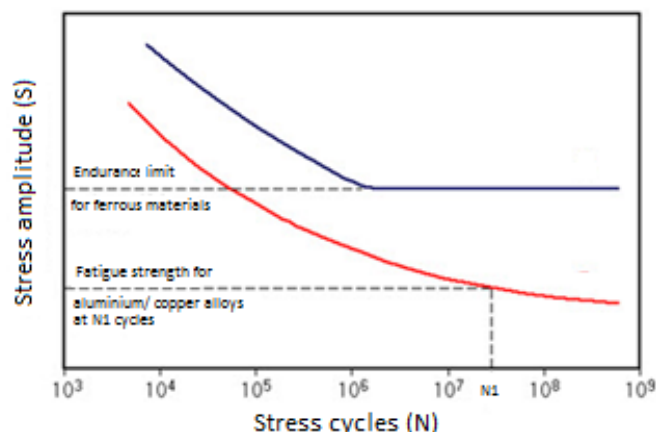


Figure 1 S-N curves

3. ROTATING BEAM FATIGUE TESTING MACHINE

The rotating beam fatigue testing machine has been developed following the guidelines of ASTM-E466. This works on the concept of holding a test specimen firmly at one end and applying cyclical stresses at the other end. This procedure is repeated for series of dead weights and for each applied stress (S). The number of rotations for failure is recorded. With this data, the graph of Stress vs number of cycles to failure is plotted in a S-N curve – see **Figure 1**. This concept is extended to develop the rotating beam fatigue testing machine suitable for cryogenic temperature zone using LN2 to produce low temperature environment.

The specimen is held at one end of its length and made to rotate, while the other end is subjected to loads. The rotational speed of the spindle, the number of rotations (cycles), applied load, etc are displayed on the display unit. The entire specimen is enclosed within a double walled insulated cryochamber. Pressure gauge, pressure relief valve, LN2 inlet/outlet connections and temperature sensor (PT 100) are mounted on the top cover. After starting the machine, the test specimen continuously rotates under applied load. After reaching the endurance limit, the specimen fractures by fatigue. A part catcher in the shape of a cut cylinder is fixed on base plate positioned below the load holder. After the specimen fractures, the sheared specimen falls down along the load holder over the parts catcher.

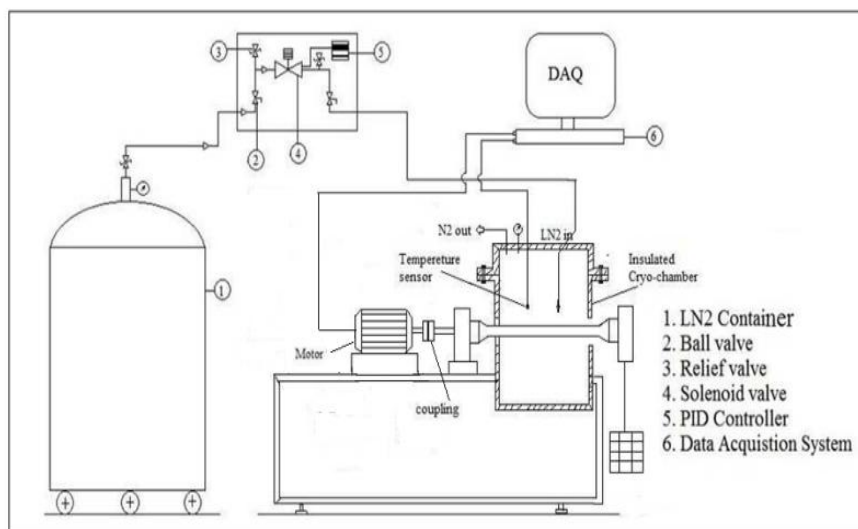


Figure 2 Schematic of the experimental system for cryogenic temperatures

Fatigue tests are conducted at cryogenic temperature using liquid nitrogen. The entire length of the test specimen is maintained at cryogenic temperature within the cryochamber. The cryochamber made from SS304 is a double walled insulated enclosure with the annular space filled with polyurethane foam (PUF). Liquid nitrogen from a pressurised container is supplied to the cryochamber through a cryogenic solenoid valve, which is activated by a PID controller. The temperature sensor located in the vicinity of the test region within the cryochamber senses the temperature and sends signals to the PID controller. The Data Acquisition System (DAQ) continuously monitors and records the experimental parameters like temperature, speed of the motor and elapsed number of stress cycles. The schematic of the experimental system is shown in the **Figure 2**.

4. EXPERIMENTS

4.1 Approach

In this study, experiments were carried on stainless steel (SS304) which finds many applications in cryogenic engineering like manufacture of cryogenic containers, cryogenic valves, cryogenic liquid transport lines, etc. The plan of action to carry out the experimental study is shown in **Figure 3**.

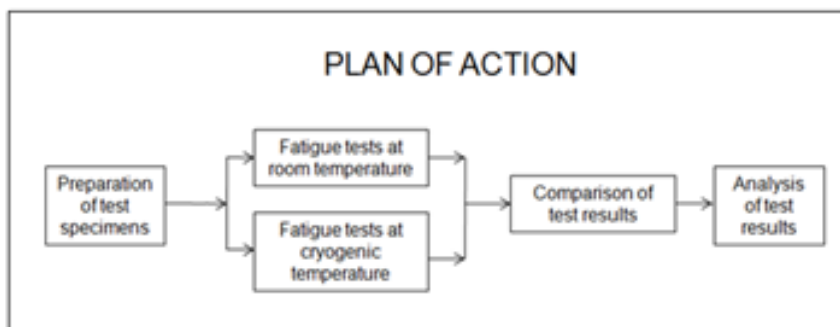


Figure 3 Plan of action

4.2 Test specimens

To arrive at convincing and repetitive results, large number of fatigue tests must be carried for each applied load. To support this objective, it was planned to conduct a minimum of six trials for each load [5]. The technical drawing of the specimen is shown in **Figure 4**.

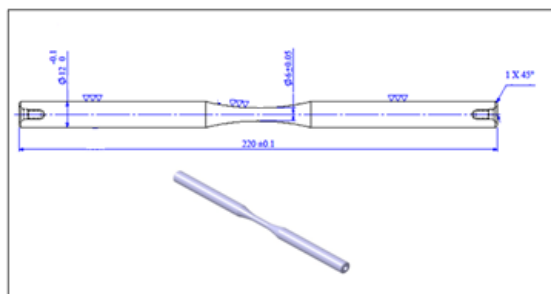


Figure 4 Technical drawing of the test specimen in accordance with DIN 50113

4.3 Load calculations

The specimen is held as a cantilever, and dead weight loads are applied at the free end. The configuration of the load acting on the free end of the cantilever is shown in the **Figure 5**.

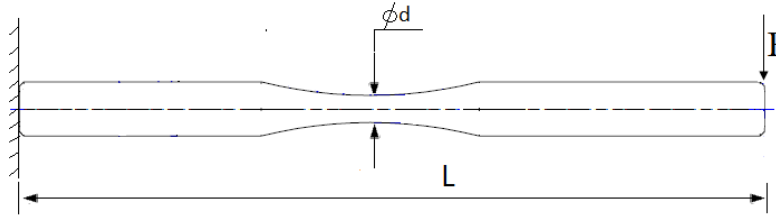


Figure 5 Cantilever configuration of the test specimen

The specimen is held as a cantilever, and dead weight loads are applied at the free end. The ultimate strength of the specimen was found to be 755 MPa, which was determined with the help of universal test machine (TUE-C-1000). Tests were carried out following the guidelines ASTM E8 standard. With the data of ultimate strength, the maximum load (F) to cause failure at the critical section of the specimen under static condition is calculated using the following pure bending equation (1).

$$M/I = \sigma/y \quad (1)$$

where,

$$M = \text{Bending moment due to applied load} = \frac{FL}{2}$$

$$I = \text{Moment of inertia} = \frac{\pi d^4}{64}$$

$$\sigma = \text{Ultimate Tensile Strength} = 755 \text{ MPa}$$

$$y = d/2$$

For critical diameter (d) of 6 mm and length (L) 220 mm, the maximum load (F) of 145N was calculated using the equation (1). It was planned to conduct fatigue tests with gradually decreasing applied loads in the range from 90 to 40 % of the maximum load (F).

5. RESULTS

Fatigue tests were conducted on SS304 at both room and 77K. The test results are shown in **Figure 6**.

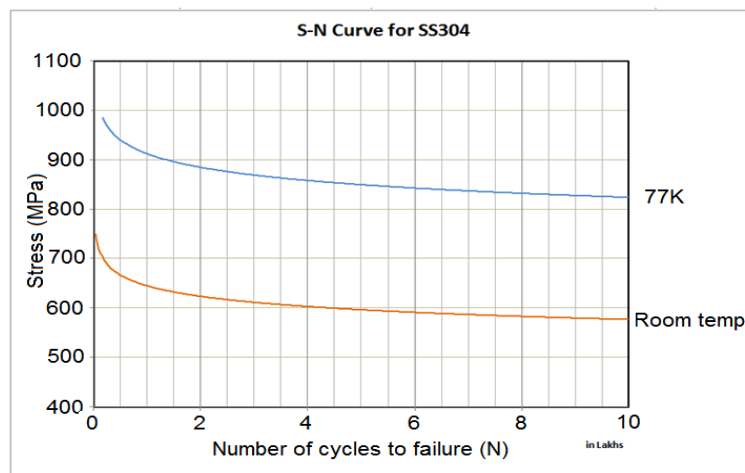


Figure 7 Graph of Stress Vs Number of cycles for failure

Test results at room temperature show increase in number of stress cycles (N) for failure with decrease in stress values (S). For the applied stress of 602 MPa and below, the specimen did not fail and could sustain stress up to 10^6 cycles. This indicated the fatigue stress of 602 MPa, which amounted to nearly 80 % of the ultimate tensile strength.

Tests conducted at cryogenic temperature also showed similar tendency of increased number of cycles for fracture with decrease in stress values. As compared with the room temperature tests, the specimen offered higher resistance to fatigue. For the applied stress of 742 MPa the specimen could withstand more than 10^6 stress cycles which amounted to nearly 98 % of the ultimate strength of 755 MPa. The material could withstand further loading up to 835 MPa without any indication of fracture. The specimen started yielding for stresses beyond 908 MPa and started fracturing faster. Induced stresses below 835 MPa did not indicate any signs of fracture. This upper limit of the induced stress of 835MPa indicated the fatigue strength of SS304 at 77K. The experiments indicated increase of fatigue strength from 602 MPa to 835 MPa at cryogenic temperature by nearly 140 %.

6. DISCUSSIONS

SS304 contains many alloying elements like carbon, nickel, chromium, etc. These elements have different atomic sizes as compared with the basic metal. The alloying atoms tend to migrate to regions towards dislocations within the metal matrix and tend to pin the dislocation or make its movement very difficult [6]. The metal yields only when the stress value large enough to pull these dislocations away from their cluster. As the temperature is lowered, the atoms within the metal matrix vibrate less vigorously causing reduced thermal agitation. In this condition, larger stress has to be applied to tear the dislocations from the cluster of alloying elements. Due to this reason, resistance for fracture increases indicating higher fatigue strength. Decrease in temperature results in refinement and reduction of grain size of the alloying elements which turn the atomic structure more compact, dense and strong [7]. Hence, larger stress is required to cause fracture. Steel contains soft and tough ductile retained austenite within the metal matrix. As the temperature is lowered, this soft austenite gets converted to strong and hard martensite and hard micro sized carbide particles are precipitated within the metal which fill up the voids within the atomic structure [8,9]. These combined effects add to the hardness and strength of the material and hence larger stress is required to cause failure by fatigue.

CONCLUSION

A functional rotating beam fatigue testing machine suitable for both room and cryogenic temperatures has been designed developed. Tests conducted on SS304 indicated increase in the fatigue strength increased from 602 MPa to 835 MPa as the temperature was reduced from room temperature to 77K.

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