DESIGN AND DEVELOPMENT OF FATIGUE TESTING MACHINE FOR CRYOGENIC TEMPERATURES

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Abstract - Prior knowledge of fatigue strength properties of materials is very crucial in design and development of a mechanical system failing which the entire system can fail prematurely without any indication. Reliable data of strength properties of many engineering materials are not available at cryogenic temperatures. Available room temperature data cannot be extrapolated down to cryogenic temperature zone since many of the mechanical properties change abruptly e.g. ductile to brittle transition of carbon steels. With this background, a rotating beam fatigue testing machine suitable for both room and cryogenic temperatures has been designed and developed to determine fatigue properties of various materials commonly used for cryogenic temperature applications. The test specimens of the selected material are fabricated as per the specifications of DIN 50113. Tests are conducted within an insulated cryogenic chamber. Desired cryogenic temperatures down to 77K are maintained by circulation of pressurised liquid nitrogen with the help a solenoid valve which is activated by a PID controller. In this experimental work, fatigue strength properties of aluminium alloy (Al7075) are determined using the developed machine both at room and cryogenic temperature. The test results are compared and analysed.

Keywords - Cryogenics, Liquid nitrogen, Fatigue strength, cyclical stress and Cryogenic chamber

I. INTRODUCTION

Prior information of physical and mechanical properties of materials is very crucial in design and development of a mechanical system. In the normal course, sufficient data is available at around room temperature. However, data of these properties are not easily available at cryogenic temperatures. At the same time, the available data cannot be extrapolated down to cryogenic temperature since the properties suddenly change at low temperatures like ductile to brittle transition for carbon steels, etc. Wide varieties of materials are used for low temperature applications and obtaining information of the low temperature properties becomes a case to case study.

Knowledge of fatigue strength is very essential for materials which are subjected to continuous cyclical stresses e.g. springs. 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. Cyclic stresses induce micro cracks within the material which tend to grow with time. These cracks initiate and propagate in regions where strain is very severe. Since most of the engineering materials contain internal defects, fatigue cracks mainly initiate and grow from these structural defects. Inadequate fatigue strengths can lead to premature failure of mechanical components resulting in entire collapse of the system

In view of this critical background, 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 aluminium alloy (Al7075) are determined both at room and cryogenic temperature. The test results are compared and analysed.

II. FATIGUE STRENGTH

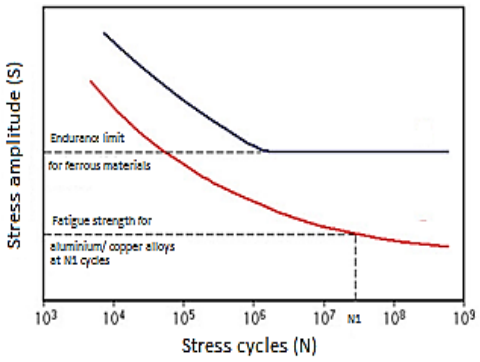

Fig.1 S -NCurves

Fatigue property of a material indicates its resistance to the weakening of a material which is subjected to repeatedly applied loads. When a material is subjected to repeated loading, the structure gets damaged progressively and after a given number of cyclical stresses, it fails. The maximum value of this stress which does not cause failure is the fatigue strength of a material. The fatigue properties of stronger materials like ferrous and titanium alloys have adistinct difference as compared with softer materials like aluminium and copper and their alloys. 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. Softer materials like copper and aluminium will eventually fail even from small stress amplitudes after elapse of large number of stress cycles. In such cases, the number of cycles is chosen to indicate the fatigue life. Normally a limiting value of 107 cycles is taken as a standard reference. 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 is shown in Fig .1

III. DEVELOPMENT OF FATIGUE TESTING MACHINE FOR CRYOGENIC TEMPERATURE

A conventional fatigue testing machine works on the concept of holding a test specimen firmly at both the ends and applying cyclical stresses at the centre as shown in Fig. 2. The test specimen in the shape of a circular rod with reduced diameter at the centre is held firmly in the collets at both the ends. This specimen is axially connected to a motor and rotates with it. The rod is subjected to uniform loading at the centre with the help of dead weights. As the motor rotates, the rod is subjected to alternate stresses of compression and tension due to the stresses induced (S) by the dead weights.

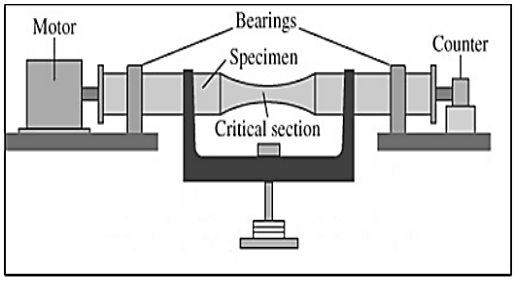

Fig.2. Concept of fatigue testing machine

Every rotation corresponds to one stress cycle. As the rod continues to rotate, fatigue stresses are continuously induced within and a small micro crack initiates at the weakest location of the test specimen, normally at the central portion. As the specimen rotates further, this micro crack starts growing and after certain number of rotations, it fails. The number of rotations (N) completed by the motor is noted. This procedure is repeated for series of dead weights and for each applied stress (S) and the number of rotations for failure are recorded. With this data, the graph of Stress Vs number of cycles to failure is plotted viz. the S-N curve.

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 schematic diagram of the machine is shown in Fig. 3. The machine is firmly mounted on the floor with strong supports to bear the entire load and absorb vibrations while running. It has an independent dedicated controller which also functions as an output display unit. The entire unit is controlled by switches and knobs mounted on the front panel with their display.

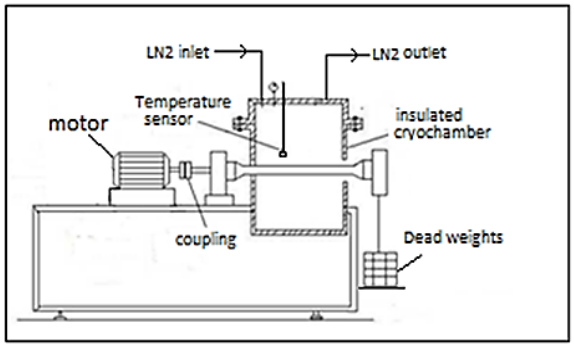

Fig.3. Schematic of rotating beam fatigue testing machine for cryogenic temperatures

The main principle of the machine is to clamp the specimen at one end of its length and rotate, while the other end is subjected to loads. The spindle is supported on bearings inside a housing mounted on a pedestal which is coupled with an A C motor of 5.7 kW capacities. The other end of the spindle is clamped with the test specimen in a collet. The rotational speed of the spindle and the number of rotations (cycles) are measured by a proximity sensor. Both these readings are displayed on the display unit. Load is applied on the free end of the specimen. The specimen is clamped in a rotating collet and this sub-assembly which is housed within a load holder. This load holder is pulled downward by a chain which is connected to the loading lever arm. The lever arm is pivoted at one end and the other end has a suspended loading pan on which dead weights are placed. The long lever arm provides mechanical advantage of 5:1. Thus, the applied dead weight magnifies five times and pulls down the free end of the specimen downwards. A load cell is fastened between chain and loading lever arm and senses the resulting downward load. This value is indicated on the display monitor.

The entire specimen is enclosed within a double walled insulated cryochamber. The chamber is mounted on the base plate and the top is covered with a circular disc. Pressure gauge, pressure relief valve, LN2 inlet/outlet connections and temperature sensor (PT 100) are mounted on the top cover. The temperature sensed by the PT 100 is continuously displayed by PID controller.

After starting the machine, the test specimen continuously rotates under applied load. After reaching the endurance limit, the specimen fractures by fatigue. This fracture takes place in the critical region around the centre. 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 with load holder over the parts catcher. This sudden action in turn results in lowering of the loading lever from horizontal position and activates a limit switch to trip motor immediately. At this juncture, the number of rotations for the fatigue failure can be observed on the display unit which indicates upper limit of stress cycles cause failure. The photograph of the developed machine is shown in Fig. 4.

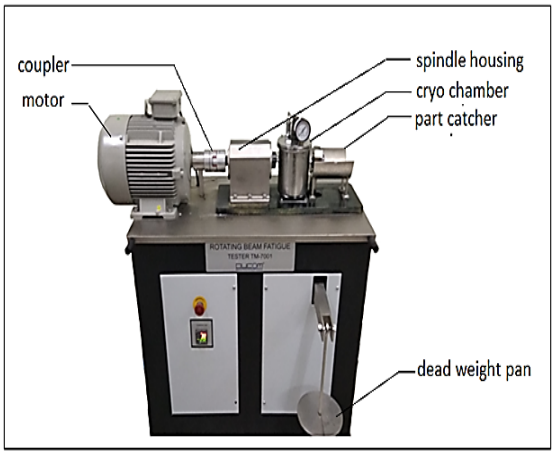

Fig.4. Rotating beam fatigue testing machine

This machine was modified to conduct fatigue tests at cryogenic temperature using liquid nitrogen. Similar to the procedure followed in conventional machine, the test specimen is firmly held between the collets ensuring its entire length being maintained at cryogenic temperature within the cryochamber using LN2. The cryochamber made out of SS304 is a double walled insulated enclosure with the annular space filled with polyurethane foam (PUF). On the hinged top cover various attachments like LN2 inlet valve, pressure relief valve, pressure gauge, feed through for mounting temperature sensor, etc. are mounted. Liquid nitrogen from a pressurised container is supplied to the cryochamber through a cryogenic solenoid valve which is activated by a PID controller.

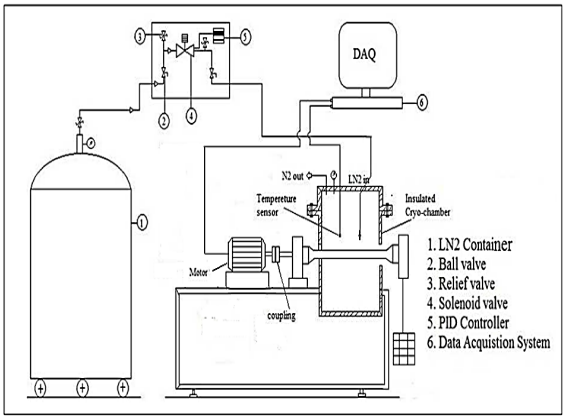

Fig.5.Schematic of the experimental system for cryogenic temperatures

The temperature sensor located in the vicinity of the test region within the cryochamber senses the temperature and sends signals to the PID controller. Based on the difference between the actual temperature and the set temperature, the PID controller regulates the LN2 flow by turning the solenoid valve to either on or of position. The Data Acquisition System (DAQ) continuously monitors and records the experimental parameters like temperature, speed of the motor and elapsed number of stress cycles. After repeated stress cycles, the test specimen fails by fracture and the corresponding number of cycles is recorded. The schematic of the experimental system is shown in the Fig.5.

IV. EXPERIMENTS

4.1 Approach

Aluminium alloys find many applications in cryogenic engineering due to their high thermal conductivity properties, high strength to density ratio, low cost, absence of ductile to brittle transition at low temperatures and ease of machining. Due to these reasons, it was planned to carry out fatigue tests on Al7075 which is a stronger grade of aluminium alloy. Al7075 contains around 5.6-6.1% of Zinc, 2.1-2.5% of magnesium, 1.2–1.6% copper and traces of silicon, iron, manganese, titanium and chromium. After identifying the material and preparing the test specimens, it was planned to conduct the fatigue tests both at room and cryogenic temperature and obtain the test results. These test results would enable to study and analyse the effects of cryogenic temperature on the fatigue properties of the specimen. The plan of action to carry out the experimental study is shown in Fig. 6.

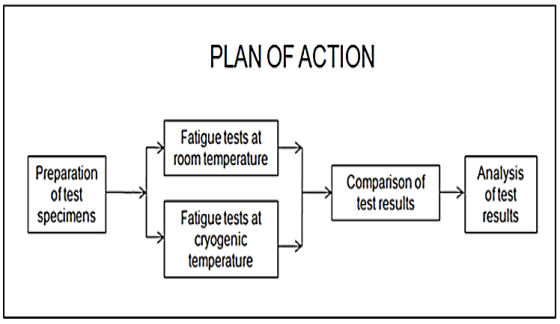

Fig. 6.Plan of action

4.2 Test specimens

In order to arrive at convincing and repetitive results, large number of fatigue tests have to be carried for each applied load. To support this objective, it was planned to conduct a minimum of six trials for each load. Specimens were fabricated as per the specifications of DIN 50113 standard. The technical drawing of the specimen is shown in Fig.7.

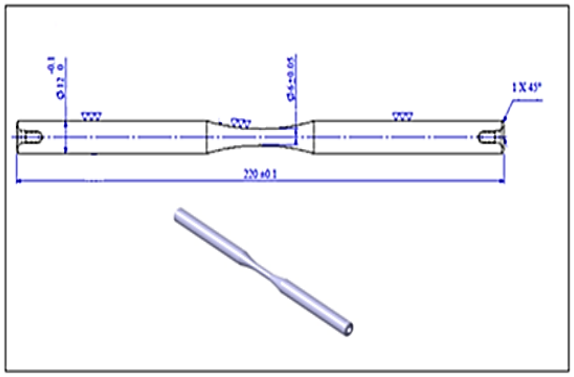

Fig. 7. Technical drawing of the test specimen in accordance with DIN 50113

4.3 Load calculations

The specimen is held as a cantilever and dead weight loads are applied at the free end as shown in figure 3.The ultimate strength of the specimen was found to be 630 MPa which was determined with the help of an universal test machine (TUE-C-1000).The 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).

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

Where,

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

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

σ = ultimate tensile strength = 630 MPa

y = $\frac{d}{2}$

For critical diameter (d) of 6 mm and length (L) 220 mm, the maximum load (F) of 121N was calculated using the equation (1).The configuration is shown in the Fig 8.

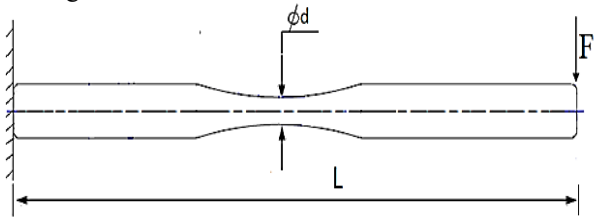

Fig.8. Cantilever configuration of the test specimen

It was planned to conduct fatigue tests with gradually decreasing applied loads in the range from 90 to 40 % of the maximum load (F).

4.4 Procedure

The main objective of conducting the fatigue strength test is to determine the stress level below which the material does not fail and can endure stress cycles infinitely. As mentioned earlier, the load in the form of fixed bending moment is applied to the circular test specimen which is synchronised with a rotating motor. After preparation of the test specimens, fatigue tests were conducted both at room and cryogenic temperature as follows.

4.4.1 Room temperature tests

The surface of the test specimen was thoroughly cleaned with solvent to remove grease and any other oily matter. One end of the specimen was clamped to the spindle assembly by tightening the collet with a spanner. The other free end of the specimen was passed through the cryogenic chamber and inserted into the load holder assembly and firmly clamped by tightening the collet with the spanner. After clamping both the ends, the specimen was turned slowly by hand to ensure true co axial rotation. Calculated dead weight was placed on the loading pan and the leveraged load was noted as displayed on the monitor. The push button was pressed to start the rotation of the specimen and speed was increased till the required speed was indicated on the monitor. The machine was allowed to run in this condition smoothly. After elapse of large number of rotations, the specimen fractures due to fatigue which is indicated simultaneously by sudden stoppage of the motor and fall of the load holder within the part catcher. At this juncture, the number of elapsed cycles was noted. This procedure was repeated for each load in the descending order.

4.4.2 Tests at cryogenic temperature

The same procedure for room temperature tests is followed for tests at cryogenic temperature, except the rotating specimen being maintained at cryogenic temperature within the cryochamber. Similar to the procedure followed earlier, the specimen was firmly clamped within the collets at both the ends ensuring the specimen rotated coaxially synchronized with the motor. After ensuring the temperature sensor hanging very close to the critical section of the specimen, the cover plate of the cryochamber was tightly closed. As in the case of room temperature tests, motor was switched on to reach desired rpm. Pressurised LN2 container was connected to the supply manifold and the PID controller was set to the desired temperature. LN2 was allowed to flow into the cryochamber till it reached steady cryogenic temperature as indicated by the temperature sensor. Ensuring this smooth running at cryogenic temperature, dead weights were placed on the loading pan. The machine was allowed to run till the specimen fractured and the number of cycles was to cause fracture was noted. Tests were repeated for various loads at the same cryogenic temperature. The photograph of the experimental system is shown in Fig. 9.



Fig. 9. Experimental system

RESULTS

In the present experimental study, fatigue tests were conducted on the identified aluminium alloy (Al 7075) both at room and cryogenic temperature of 77K. Dead weights of 109N, 97N, 85N, 73N, 61N and 55N were applied to induce cyclical stresses corresponding to 90,80,70,60, 50 and 45 % of the ultimate strength of the material (630 MPa) respectively. The obtained results are shown in the table 1 and Fig.10.

Table 1: Fatigue strength test results

S.No	Percentage of Ultimate strength	Applied load	Stress in MPa (S)	Number of stress cycles for failure (N)	
				Room temperature (N1)	77K (N2)
1	90	109N	567	12465	69562
2	80	97N	504	18460	119960
3	70	85N	441	26092	185253
4	60	73N	378	47097	357937
5	50	61N	315	63552	No fracture
6	45	55N	284	No fracture	No fracture

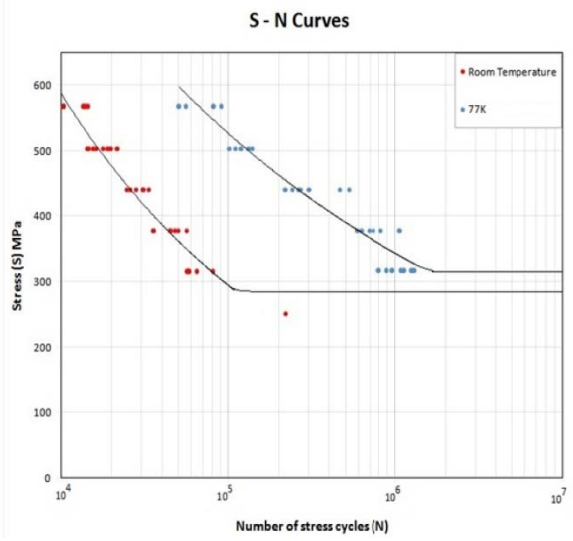

Fig.10. S-N curves

The 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 284 MPa and below, the specimen did not show any signs of fracture. This situation indicated the upper limit of the stress value below which the specimen could to be subjected to any number of cycles without causing failure. Hence, the fatigue stress of Al7075 was arrived at 284 MPa at room temperature which amounts to 45% of the ultimate 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 prior tests, the specimen offered higher resistance to fracture for each applied stress. For the applied stress of 567 MPa the specimen could withstand 69562 cycles with an increase of 5.58 times as compared with room temperature tests. This incremental change increased exponentially with decrease in stress values. For the applied stress of 315 MPa, the specimen did not show any signs of fracture. The specimen continued to exhibit the same fracture resistance for stresses below 315 MPa and hence the fatigue strength value was arrived at 315 MPa at 77K. The fatigue strength increased from 284MPa at room temperature to 315 MPa at 77K, an increase by nearly 10%.

DISCUSSIONS

The conducted experimental tests on Al7075 have shown significant increase in fatigue strength at cryogenic temperature of 77K. This incremental change is mainly due to increase in mechanical properties like strength and hardness of aluminium and its alloys which increase as the working temperature is lowered. Al7075 has alloying elements such as zinc, magnesium and copper and traces of silicon, iron, manganese, titanium and chromium which contribute to its strength properties. The strength properties of Al7075 are higher when compared with other grades.

Alloying elements have different atomic sizes as compared with the basic metal. These 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. The metal yields only when the stress value large enough to pull these dislocations away from their cluster of alloying elements is applied. As the temperature is lowered, the atoms within the metal matrix vibrate 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 value of yield and ultimate strength. Decrease in temperature also results in refinement and reduction of grain size of

the alloying elements which turn the atomic structure to be much more compact, dense and strong. Obviously larger stress has to be applied to cause fracture which indicates increased strength values.

Fatigue failure occurs in three stages viz. microcrack initiation, gradual microcrack growth till critical size and final rapid failure by ductile rupture or by cleavage. Microcrack initiation happens around the critical section of the specimen where stress intensity is maximum. This crack continues to grow around the tip of the crack. As the temperature is reduced larger stress is required for growth of the crack and hence the fatigue strength increases with gradual reduction in temperature down to cryogenic temperature zone.

For aluminium alloys, the ratio of fatigue strength to ultimate strength remains fairly constant throughout the temperature range from ambient to cryogenic zone. In accordance with this analogy also, the fatigue strength of Al7075 is expected to increase as temperature is reduced gradually. This was experimentally verified in the conducted experiments.

CONCLUSION

A rotating beam fatigue testing machine has been successfully designed and developed which is suitable for both room and cryogenic temperatures. Tests were conducted on an aluminium alloy Al7075. The test results clearly indicated increase in fatigue strength properties of aluminium alloys from room to cryogenic temperature. In the present experimental study, the fatigue strength increased from 284 MPa to 315 MPa as the temperature was reduced room temperature to 77K.

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