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Effect of Fatigue Strength and Crack Growth Rate at Different Stress Ratio on 38mnvs6 Microalloyed Steel used for Forged Crankshafts

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***Abstract*— Effect of fatigue strength and stress ratio R on fatigue crack growth rate on 38MnVS6 micro alloyed steel grade was investigated at ambient temperature. The set of rotating bending fatigue test specimens and compact tension (CT) specimens were prepared from forged, machined crankshaft along different orientation from crankpin and other sections of forged crankshaft. Rotating bending fatigue test at fully reverse loading condition and fatigue crack growth rate test was performed at three different stress ratios namely 0.1, 0.2 and 0.5. The stress ratios for fatigue crack growth were so selected that it covers most of the probable conditions experienced by this material during its actual service life. The tested specimens were investigated under scanning electron microscope (SEM) to see the fractographs. The study shows that the fatigue strength at different critical location varies with orientation and fatigue crack propagation of this steel grade was influenced to an appreciable extent by stress ratio, such that, as stress ratio(R) increases fatigue crack growth rate also increases. Fatigue crack propagation at intermediate crack growth rates followed a power law with value of slope “m” increasing with increase in stress ratio.**

Keywords—crankshaft, Fatigue life, fatigue crack, crack growth, stress ratio R, micro alloyed steel.

I. INTRODUCTION

A crankshaft is supposed to be the heart of any engine. In an internal combustion engine, the reciprocating motion of the piston is linear and it is converted into rotary motion by the crankshaft. However, there are many other applications of a crankshaft which range from small one cylinder lawnmower engines to very large multi cylinder marine crankshafts and everything in between. Generally, two types of steels are used for manufacturing of crankshaft; one is being medium carbon steel and other being micro alloyed steel. Micro alloyed steels have been gaining popularity as an economical alternative to the medium carbon steel. These steels have low or medium carbon content and small additions of alloying elements such as Mn, Nb, Mo, V and Ti. Chemical specification of the material used in this study is as shown in Table I.

The crankshaft is one of the most critically loaded parts inside an engine. It experiences cyclic loads in the form of bending and torsion during its service life. Its failure will cause serious damage to the engine so its reliability verification must be essential for successful design of crankshaft [1]. Engine mechanism and geometry has large impact on the critical locations on the crankshaft which experience large stress cycle during its working. Any small crack initiation at critical location, due to stress concentration, subsequently propagates and led to failure of crankshaft [2]. It is thus important to examine the fatigue and crack growth behavior of this material after it’s forging, at different stress ratios which will cover most of the probable conditions experienced by this material during actual service life.

TABLE I. MATERIAL SPECIFICATION (IN MASS %)

Material 38MnVS6	C	0.38
	Mn	1.37
	Si	0.57
	P	0.01
	S	0.027
	Cr	0.25
	Ni	0.25
	Mo	0.04
	V	0.02
	Ti	0.01
	Nb	0.02
	As	0.012
	Sb	0.01
	Sn	0.02
	Al	0.015
	Su	0.15

The stress ratio (R) is the ratio of minimum stress (σ_{min}) to the maximum stress (σ_{max}). The endurance/fatigue strength of the material is found out using rotating bending fatigue testing equipment at stress ratio R=-1 which is fully reversed condition loading cycle. It is reported that the stress ratio have marked influence on the fatigue crack growth rate (da/dN) of many materials. Raghuvir Kumar and Kamlesh Singh [3] studied the influence of stress ratio on fatigue crack growth in mild steel with different stress ratios (0, 0.2 and 0.4). It was seen that crack growth rate decreases with increasing stress ratio R at a particular K_{max} value. Adel B. El-Shabasy, John J. Lewandowski [4] studied effects of load ratio, R, and test temperature on fatigue crack growth in fully pearlitic eutectoid steel. The fatigue crack growth experiments were performed at load ratio of 0.1, 0.4, and 0.7 at -125°C and comparison were made with results obtained at room temperature. Authors concluded that increase in stress ratio R and/or decrease in test temperature from room temperature to -125 °C produced significant increase in the Paris Law slope. Many researchers have seen different behavior of material under influence of different stress ratios. However, it is very important to see the material behavior of micro alloyed steel after forging it into component like crankshaft. In this paper, 38MnVS6 micro alloyed steel grade material has been considered for investigation. The rotating bending fatigue test is carried out on R.R.Moore fatigue testing machine and fatigue crack growth test is carried out on MTS servo hydraulic machine. Both the rotating bending fatigue test specimen and compact tension (CT) specimens were taken from weakest section of the crankshaft, which is crankpin of forged crankshaft. The fatigue crack growth rate test has been conducted at three different stress ratios 0.1, 0.2 and 0.5 so as to cover most of the probable conditions experienced by this material in its actual service life.

II. EXPERIMENTAL WORK

A. Rotating Bending fatigue test

The mechanical properties were found using standard metallurgical testing which are summarized in Table II.

TABLE II. MECHANICAL PROPERTIES

Material	Modulus of elasticity (GPa)	Poisson's ratio	Yield strength (MPa)	Ultimate tensile strength (MPa)
38MnVS6	210	0.3	550	880

The fatigue strength of material was found out by rotating bending fatigue test using Instron R.R.Moore fatigue testing setup as per DIN 50113 standard [5] which is shown in Fig 1.

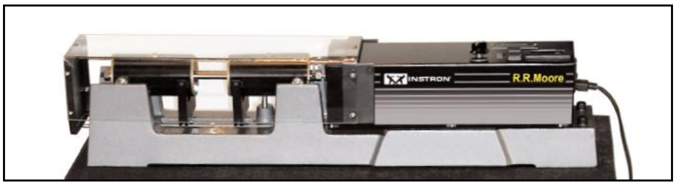


Fig. 1. Rotating bending fatigue test setup

The specimens for this test were taken from pin and bearing section of crankshaft along grain flow direction and transverse to grain flow direction as shown in Fig 2. Dimensions of specimen are designed as per DIN 50113 standard. 12 no. of specimens were tested as per S-N approach. The stress level at which three or more specimens run out 5 x 10^6 million cycles was considered as fatigue strength of that material.

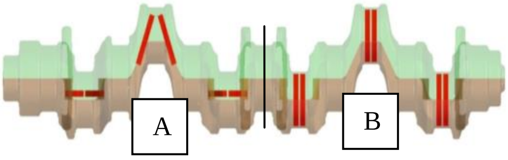


Fig. 2. Rotating bending fatigue test specimens , A] Along grain flow direction B] Tranverse to grain flow direction

B. Fatigue crack growth analysis

An experimental investigation was undertaken to determine effect of stress ratio R on fatigue crack growth rate of crankshaft steel i.e. micro alloyed steel "38MnVS6" grade. The tension-tension fatigue test was conducted on compact tension (CT) specimen using servo hydraulic MTS 880 machine of capacity 100KN. The compact tension specimens were prepared from forged crankshaft. As the crankpin is considered the most critical zone, CT specimens were prepared by cutting crankshaft pin in longitudinal grain flow direction as shown in Fig 3.

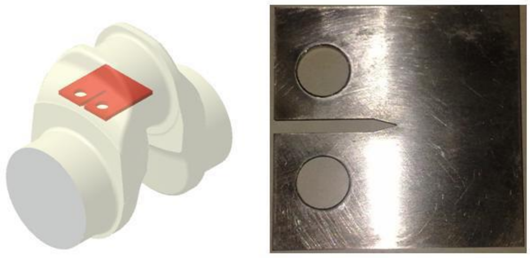


Fig. 3. Location of CT specimen taken from pin area and actual CT specimen

The CT specimens was prepared by machining and wire EDM as shown in Figure1, The dimensions of the CT specimen 61.3 x 61.3 x 4 [mm] were designed as per ASTM 647 [6].

The fatigue crack growth analysis was carried out on servo hydraulic MTS 880 machine of capacity 100KN under load controlled mode. The entire setup for fatigue crack growth analysis is shown in Fig 4. All three stress ratio tests were conducted at constant maximum load of 5000[N] and constant frequency of 6 [Hz]. All the tests were carried out at room temperature. Initially, all the specimens were pre-cracked to approximately 0.45 [mm]. The increase in crack length was carefully monitored using travelling microscope and calibrated after fixed interval of 1[mm]. The increases in crack length (a) after various number of cycles (N) were recorded. Maximum possible readings were taken from each specimen for all three stress ratios.

The maximum load (P_{max}) and minimum load (P_{min}) for fatigue test were decided From the applied load range ΔP and the obtained value of crack length (a) from the experiment, the stress intensity factor range (ΔK) was determined using Equation 1 [6].

$$\Delta K = \Delta P/(B\sqrt{w})\ f(a/w) \qquad (1)$$

Where,

$$f(\propto)=(2+\propto)/[(1-\propto)^{(3/2)}(0.886+4.64\propto 13.32\propto^2+14.72\propto^3-5.6\propto^4)] \qquad (2)$$

Here $\propto = a/w$

Where,

B = Thickness of specimen

W= Width of specimen

Fig. 4. Fatigue crack growth analysis setup

The crack growth rate (da/dN) was determined from the CT specimen based on number of cycles reading taken after every 1[mm] intervals. Fig 5 shows some failed specimens during fatigue crack growth analysis.

Fig. 5. Specimens after fatigue crack growth analysis

The failed specimens were analyzed at three different locations as shown in Fig 6 under stereo microscope scanning electron microscopy (SEM) to study the fractography of crack propagation. The SEM fractographs were taken at three regions on cracked surface. The three regions were taken in the direction of fatigue crack growth as shown in Fig 6. The fractographs were taken at 2000X magnification.

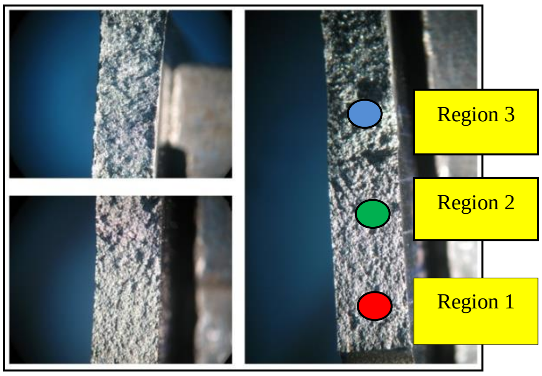


Fig. 6. Stereographic image of CT specimen

III. RESULTS AND DISCUSSION

A. *Rotating Bending fatigue test*

The results of the rotating bending fatigue test, carried out at fully reversed condition, are plotted with duplex S-N curves as shown in Fig 7.

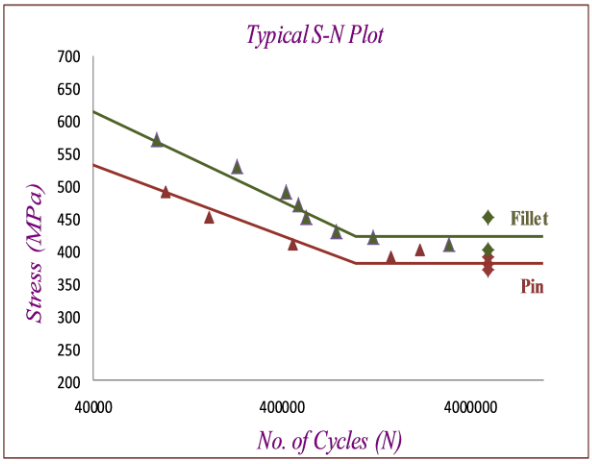


Fig. 7. Duplex S-N Plot

The graph shows that, the specimens taken along grain flow direction (i.e. fillet) shows fatigue strength 420Mpa and the specimen taken transverse to grain flow direction (i.e. pin, main bearings) shows endurance strength 380Mpa.

B. *Fatigue crack growth analysis*

The results of the fatigue test, carried out at three different stress ratios, are plotted as shown in Fig 8. The graph shows that, the fatigue crack growth rate increases with increase in stress ratio (R). All curves in the plot follow Paris law in their region II. Paris-Erdogan law as per equation (3) relates the stress intensity factor range to sub-critical crack growth rate under a fatigue stress regime [7].

$$da/dN=C(\Delta K)^m \qquad (3)$$

Where, C and m are material constant. The log-log plot of region II points were plotted for each stress ratio R and by taking slopes of the curves, values of material constants were determined. The values of material constants are summarized in Table III.

TABLE III. VALUES OF C AND M AT THREE DIFFERENT STRESS RATIOS R

R	**R=0.1**	**R=0.2**	**R=0.5**
m	2.531	2.577	3.86
C	2.259E-8	2.654E-8	5.79E-10

The determined values of material constants C and m are plotted with respect to stress ratios as shown in Figure 10.The plots show that, as stress ratio R increases the value of m increase and value of C decreases. This proves that, as the stress ratio R increase fatigue crack growth increases.

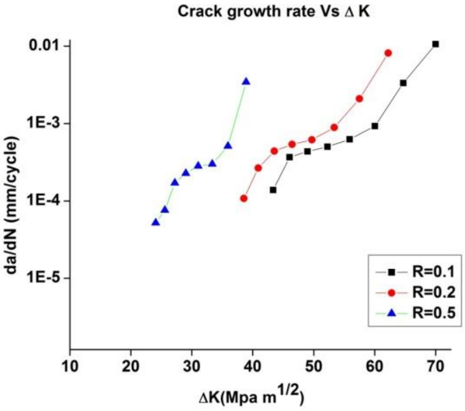
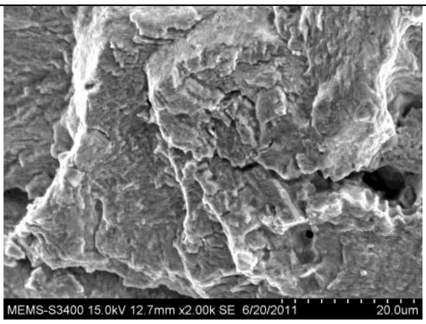
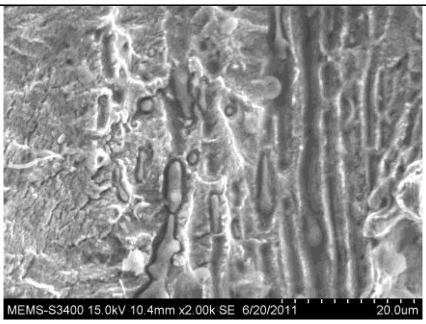


Fig. 8. Plot of crack growth rate (da/dN) vs. ΔK at three different stress ratios

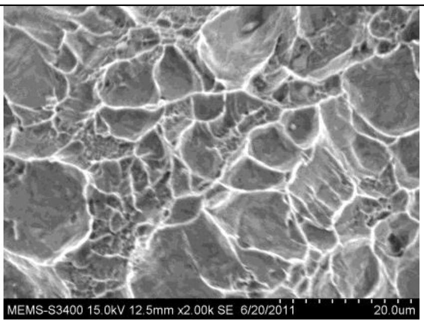
The SEM fractographs as shown in Fig 9 were taken at 2000X magnification. At region 1 [A] typical striations at fatigue pre-crack zone observed.



[A] Region 1 [2000X]



[B] Region 2 [2000X]



[C] Region 3 [2000X]

Fig. 9. SEM fractographs of tested CT specimen at three different regions

As the crack grows beyond pre-cracked region some void nucleation are observed at region 2 [B]. Void nucleation occurs more readily at larger inclusion sites.

As stress ratio R increases and void growth also proceeds more rapidly from larger inclusions. Ductile striations are the most commonly observed fatigue features that occur in the micro-structurally insensitive intermediate ΔK regime. The region 3 [C] shows dimple rupture which is sign of ductile fracture that occurs through the formation and coalescence of micro-voids along the fracture path [7].

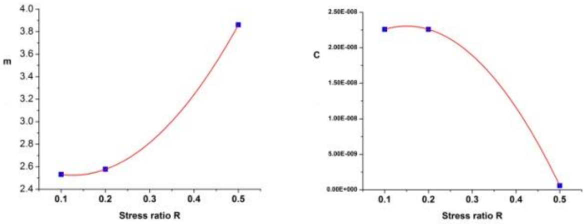


Fig. 10. Plots of material constants C and m vs. stress ratios R

IV. CONCLUSIONS

The following conclusions were arrived at from this investigation.

1. The endurance strength obtained from rotating bending fatigue strength of the specimens taken along grain flow direction i.e. from fillet area shows 9-10% more endurance strength than the specimens taken from transverse grain flow direction i.e. from pin and main bearing area.
2. The crack growth rate for 38MnVS6 micro alloyed steel grade material taken from forged and machined crankshaft shows that, as stress ratio R increases, fatigue crack growth rate also increases.
3. Fatigue crack propagation at intermediate crack growth rates follows a power law as per equation (3) in which value of the slope m increases with increase in stress ratio R and value of C decreases.
4. The SEM analysis shows different fractographs consist of striations, voids and dimple rupture at three different regions in the direction of crack growth on fracture surface of CT specimen.

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