FATIGUE AND FRACTURE BEHAVIOUR OF FORGED AND CAST RAILWAY WHEELS

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ABSTRACT

Rail wheels for passenger traffic are conventionally produced through the forging route. The state of the art technology available nowadays for producing a cheap cast wheel has prompted the use of cast wheels in passenger service. Since passenger transport entails the adoption of considerably higher levels of safety and minimisation of failure risks, it is imperative that forged and cast wheels be critically compared with respect to their properties and performance before such a substitution is made. From the point of view of safety therefore, the resistance of the wheel material to fatigue and fracture is of paramount importance. This paper presents a comparative evaluation of suitability of cast wheel produced in Indian industry over forged wheels for passenger train services with respect to their fatigue and fracture behaviour.

1 INTRODUCTION

Railway wheel and track failures leading to train accidents incur huge loss to the railway department both directly and indirectly. In majority of such accidents, the failure is either due to inferior material quality or poor maintenance. In a recent failure investigation of railway wheels, it is noted that thermal fatigue cracks initiated due to excessive hard breaking in the wheel tread region leading to derailment of three express trains. In Indian scenario, the rail wheels for passenger traffic are conventionally produced through the forging route. The state of the art technology available nowadays for producing a cheap cast wheel has prompted the use of cast wheels in passenger service. Since passenger transport entails the adoption of considerably higher levels of safety and minimisation of failure risks, it is imperative that forged and cast wheels be critically compared with respect to their properties and performance before such a substitution is made. From the point of view of safety therefore, the resistance of the wheel material to fatigue and fracture is of paramount importance.

This paper presents a comparative evaluation of suitability of cast wheel produced in Indian industry over forged wheels for passenger train services with respect to their fatigue and fracture behaviour.

2 EXPERIMENTAL METHOD

The railway wheels used in the investigation were commercially produced cast wheel and forged wheel being used in railway industry.

Tensile specimens were fabricated in radial and circumferential directions from each region of the railway wheels. Tensile specimens were tested as per ASTM standard E-8M [1] in a servohydraulic testing system under computer control. A 25 mm gauge length extensometer was employed for measurement of strain. Actuator displacement rates of 0.2 mm/min were used.

The compact tension (CT) specimen in various orientations was used for evaluating the fatigue and fracture properties of the wheel materials as per relevant ASTM standards [2]. The width of specimens used was 50 mm and the l thickness was 25 mm for specimens machined from the rim region and 20 mm for specimens from the web region. This deviation in specimen thickness was required to be made due to the lower net thickness available at the web.

Fatigue crack growth rate (FCGR) tests were conducted using CT specimens as per the methodology laid down in ASTM standard E-647 [2]. Tests were carried out in digital servohydraulic testing systems under software control. Crack lengths were measured on-line by the compliance technique using COD gauges. Crack closure was also monitored on-line following the method recommended in Appendix X2 of the ASTM standard.

Fracture toughness tests were carried out with CT specimens as per the methodology laid down in ASTM standard E-1820 [3]. This standard contains the methods for obtaining both the plane strain linear elastic fracture mechanics (LEFM) parameter K_{Ic} and the elastic-plastic fracture mechanics (EPFM) ductile fracture parameter J_{Ic}. As is apparent later, both the techniques had to be used in this investigation due to the difference in the fracture response of the cast and forged materials. It may be pointed out that the E-1820 standard contains the methods contained in the well-known ASTM standard E-399 [4] for determination of K_{Ic}, and also those contained in the ductile fracture toughness test standards E-813 [5] and E-1737 [6], both of which have now been withdrawn by ASTM. For determination of LEFM fracture toughness, specimens were ramp-loaded in displacement control until fracture instability, often accompanied by a "pop-in", was manifested. For determination of EPFM fracture toughness, necessitated for cases where the toughness is of a higher level, the single specimen test procedure was adopted. In this, a number of periodic partial unloading was implemented while a specimen was ramp-loaded to cause substantial amount of crack extension through ductile tearing. From the compliance exhibited by the specimen at each unloading step, the instantaneous crack length in the specimen was calculated. The *J*-integral at each of these instances was calculated from the load-displacement curve in an incremental fashion, and, when coupled with the crack extension data, provided the *J*-resistance (or *J-R*) curve. The critical *J*-integral at which ductile crack extension was initiated was designated as the ductile fracture toughness of the material. The procedure for evaluation of LEFM fracture toughness is quite straightforward, being possible to be implemented graphically. On the other hand, for EPFM fracture toughness, data analysis is involved, requiring extensive computations. A software developed in-house was employed for EPFM fracture toughness determination from digitally acquired test data.

3 RESULTS AND DISCUSSION

3.1 Tensile Properties

The results obtained from the tensile tests conducted on railway wheel materials are summarised in Table 1. The results shown are the average of multiple tests.

Table 1: Tensile properties of cast and forged railway wheels.

Wheel/Region-Orientation	YS (MPa)	UTS (MPa)	% El.	% R.A.
Cast				
Rim-Circumferential	517	935	11.3	16.2
Rim-Radial	486	809	9.3	9.1
Web-Circumferential	420	806	10.3	16.1
Web-Radial	413	784	10.8	10.9
Forged				
Rim-Circumferential	536	900	18.7	39.4
Rim-Radial	507	857	14.8	19.5
Web-Circumferential	368	747	19.8	42.8
Web-Radial	383	757	23.4	39.5

It can be seen from Table 1 that in both cast and forged wheels, the yield strength (YS) and ultimate tensile strength (UTS) were higher in the rim region as compared to the web region. It is also apparent that in general the cast material shows higher strength properties and concomitantly lower ductility properties in comparison to the forged material. This is significant from the viewpoint that fracture toughness is liable to be lower for materials with higher strengths. Hence it may be expected that the forged wheel material will exhibit superior fracture toughness in comparison to the cast wheel material, unless other overwhelming microstructural factors, originating from the difference in the processing routes of the two types of wheels, are operative.

3.2 FCGR Behaviour

At least two FCGR tests were carried out from each of the two types of wheels. The crack growth resistance obtained from replicate tests matched well, indicating the uniformity of material property for a given crack plane orientation. Fig.1 shows a typical FCGR plot. Similar coincidence of FCGR plots is observed for replicate tests in other specimen orientations in both types of wheels.

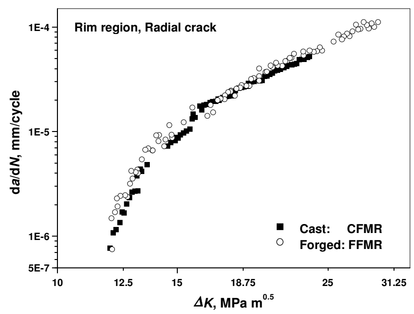

Fig. 1: Typical FCGR behaviour of cast and forged rail wheel in the rim region.

The average values of ΔK_{th}, C and m obtained from multiple tests are listed in Table 2. From a comparison of the characteristic parameters, it can be said that the resistance to fatigue crack growth of the cast and forged materials are very similar for equivalent orientation and location of the crack plane. It can also be seen from Table 2 that the Paris slope m is consistently higher for circumferential crack growth in the rim and radial crack growth in the web for both the cast and the forged material. Table 2 reveals that ΔK_{th} is largely similar, and of considerably high value for tests conducted at $R = 0.1$, at all orientations of crack growth in both regions of the two types of wheel. The latter is indicative of the fact that both wheels retain substantial residual stresses, possibly due to the process of their manufacture. This leads to crack closure which effectively decreases the driving force responsible for crack growth.

Table 2: FCGR characterizing parameters of cast and forged railway wheels.

Wheel / Region-Orientation	C	m	• ΔK_{th}, MPa√m
Cast			
Rim-Circumferential	1.080×10^{-10}	4.073	12.65
Rim-Radial	1.079×10^{-9}	3.345	12.97
Rim-Transverse	6.344×10^{-10}	3.539	12.30
Web-Circumferential	7.056×10^{-10}	3.591	11.90
Web-Radial	3.327×10^{-11}	4.606	12.54
Forged			
Rim-Circumferential	7.387×10^{-11}	4.301	12.18
Rim-Radial	8.209×10^{-10}	3.525	12.07
Rim-Transverse	5.050×10^{-10}	3.682	12.01
Web-Circumferential	7.939×10^{-10}	3.614	11.04
Web-Radial	3.608×10^{-10}	3.924	11.33

3.3 FRACTURE TOUGHNESS TEST

Although there is similarity between the tensile properties and the fatigue crack growth resistance of cast and forged railway wheels, the fracture characteristics of the two types of materials were found to be entirely different. This dissimilarity is best portrayed by the nature of the load-displacement plots obtained during fracture toughness testing in the two cases. Figs.2 and 3 show such plots for specimens extracted from the cast and forged wheels respectively. It can be seen that the cast material (Fig.2) exhibits catastrophic fracture without substantial deviation from elastic deformation behaviour for all locations and orientations of specimens. Materials such as these are amenable to linear elastic fracture mechanics (LEFM) formulation, and it is likely that it may be possible to characterize their fracture behaviour by the LEFM fracture toughness parameter K_{Ic}.

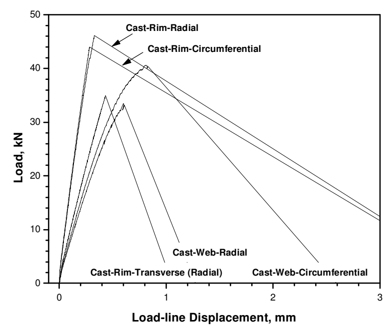

Fig. 2: Load-displacement behaviour of cast rail wheel.

The forged material, on the other hand, shows (Fig.3) considerable plastic deformation and deviation from the elastic loading line as it is stressed. Fracture in these cases is through stable extension of cracks, unlike the catastrophic instability in the cast material. The fracture behaviour can be said to be falling under the category of elastic-plastic fracture mechanics (EPFM), the fracture toughness, in this case, being characterized by the EPFM parameter J_{Ic} obtained from the *J-R* curve. In general terms, it can be said that EPFM materials have a higher fracture toughness than LEFM materials, on a comparative scale. It may be pointed out that the periodic unloading lines in the load-displacement plots in Fig. 3 are used for compliance based crack length measurements in the single specimen technique for ductile fracture toughness determination, as discussed earlier.

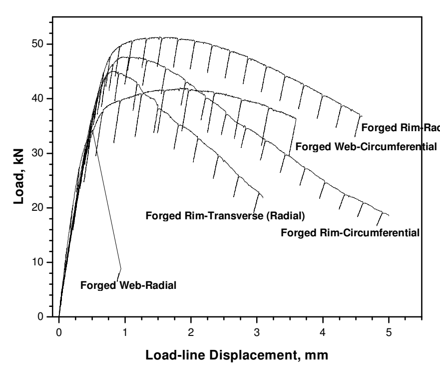

Fig.3: Load-displacement behaviour of forged rail wheel.

It may be noted in Fig.3 that the plot for web-radial specimen of forged wheel exhibits catastrophic behaviour, similar to that observed in cast wheel specimens. For LEFM-type fracture behaviour, a critical load P_Q can be identified, as per the method of ASTM standards E-399 [4] or E-1820 [3] (both are equivalent), and a tentative fracture toughness K_Q can be calculated from it. For this, the pre-fatigue crack length a_o has to be accurately determined post-test by averaging a number of measurements made along the crack-front. K_Q will be qualified as K_{Ic} if the following dimensional and load criteria are satisfied

$$(W\text{-}a_o) \text{ and } B \geq 2.5\left(\frac{K_Q}{\sigma_{YS}}\right)^2 \quad \ldots (1)$$

$$\frac{P_{max}}{P_Q} \leq 1.1 \quad \ldots (2)$$

Since LEFM based fracture toughness could not be validated for both the cast and the forged wheel material, attempt was made to obtain EPFM based characteristic fracture toughness values given in terms of the *J*-integral. All of the forged wheel specimens, except those extracted from the web region with radial orientation of crack, yielded *J-R* curves from which the critical resistance to fracture, J_Q, could be obtained. For the specimens obtained from the cast wheel, and the forged web-radial specimens, in which unstable crack propagation ensued prior to the onset of ductile crack extension, *J-R* curves or J_Q values could not be elicited. J_{Qc} values were calculated for these cases as per the method for determination of fracture instability toughness given in Appendix 6 of ASTM standard E-1820 [3].

The average values J_Q obtained for the various types of specimens are listed in Table 3. Included in Table 3 are the minimum requirements of thickness and remaining ligament (W-a_o) for valid fracture toughness measurement, obtained from the size criterion given earlier. Footnotes at the bottom of the table clarify which of the fracture toughness values are obtained as J_{Ic} and which as J_c.

Table 3: Qualified fracture toughness of cast and forged railway wheels. The minimum thickness requirements are given.

Wheel: Region-Orientation	J_{Ic} or J_c, kJ/m^2	min B, (W-a_0), mm
Cast		
Rim-Circumferential	25.52#	2.87
Rim-Radial	27.55#	2.80
Rim-Transverse	27.44#	3.08
Web-Circumferential	62.42#	7.75
Web-Radial	44.57#	5.42
Forged		
Rim-Circumferential	140.74*	4.73
Rim-Radial	143.05*	4.98
Rim-Transverse	61.09*	2.24
Web-Circumferential	145.33*	6.37
Web-Radial	75.94#	10.24

* obtained as J_{Ic} # obtained as J_c

From Table 3, it can be said unequivocally that the material of cast rail wheels has, in general, a lower fracture toughness than that of forged rail wheels. It appears that the material of the web of cast wheels has a superior resistance to fracture than that of the rim region. In the forged rail wheel, the rim material is equal, if not better, than the web region in terms of fracture resistance. For radial cracks growing in the web region, and transverse cracks in the rim region, the fracture toughness seems to be the lowest in forged wheels. However, even here the toughness is above that of the cast wheel material. Examination of the microstructures of the cast wheel revealed the presence of large amount of inclusions in the pro eutectoid ferritic regions as shown in Fig. 4a. The microstructure of the forged wheel, on the other hand, was observed to be clean (Fig. 4b). Presence of such inclusions can adversely affect the fracture behaviour of the material. The inferior fracture toughness of the cast wheel compared to the forged wheel can therefore be attributed to the existence of such second phase particles.

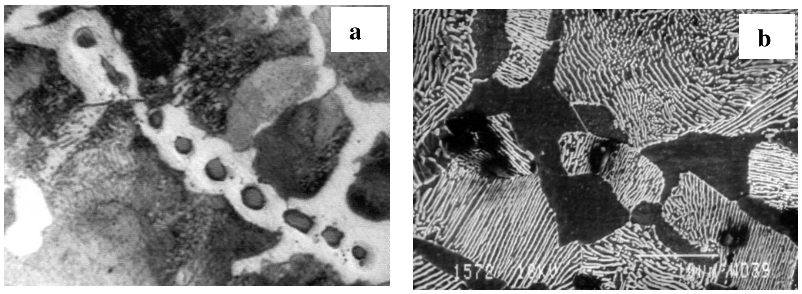

Fig. 4: Microstructure of (a) cast wheel (b) forged wheel

4 CONCLUSIONS

From the comparison of the fatigue and fracture behaviour of cast and forged railway wheels, the following generalised conclusions could be arrived at:

i) The material of cast wheel shows higher strength properties and lower ductility properties in comparison to the material of forged wheel. In both types of wheels, the strength properties were higher in the rim region in comparison to the web region.

ii) The fatigue crack growth resistances of the cast and forged material appear to be similar for equivalent orientation and location. For both cast and forged rail wheel, the Paris slope is higher for circumferential crack growth in the rim and radial crack growth in the web.

iii) The fracture toughness of the cast and forged rail wheel materials could be characterized only by parameters based on the *J*-integral. LEFM parameters like K_{Ic} could not be qualified to be valid.

iv) In general, the forged material exhibited superior fracture toughness in comparison to the cast wheel material. Resistance to fracture was lowest for radial crack growth in the web of forged wheels; however, even this was better than the highest fracture toughness displayed in the cast material.

5 REFERENCES

1) ASTM standard E 8M-00, *Test Methods for Tension Testing of Metallic Materials [Metric]*, American Society of Testing and Materials, PA, 2000

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4) ASTM standard E 399-90 (Reapproved 1997), *Test Method for Plane-Strain Fracture Toughness of Metallic Materials*, American Society of Testing and Materials, PA, 2000

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6) ASTM standard E 1737-96, *Test Method for J-integral Characterization of Fracture Toughness*, American Society of Testing and Materials, PA, 1996