A PROPOSAL FOR A NEW EMPIRICAL RELATIONSHIP BETWEEN DYNAMIC AND STATIC MECHANICAL PROPERTIES OF CMn AND CrMo LOW-ALLOY CAST STEELS.

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ABSTRACT

The aim of this work is to investigate the fatigue performance of low-alloy cast steels used to produce cast components, which must be heat treated in order to obtain suitable mechanical properties. Experimental results of tensile strength and fatigue properties were used to analyse existing relationships between dynamic and static mechanical properties in steels. Previous linear relationships only accurately predict the endurance limit in limited levels of tensile strength of CMn and CrMo low-alloy cast steels. A parabolic relationship between endurance limit and static tensile strength parameter has been proposed in this work. This relationship was obtained for different chemical compositions, heat treatments and microstructures of these cast steels with static tensile strengths ranging from 300 to 1300 MPa.

Key Words: CMn and CrMo low-alloy cast steels, dynamic and static mechanical properties, endurance limit

1 INTRODUCTION

A great deal of engineering components are subjected to repeating loading and vibration. Fatigue has become progressively more prevalent, and today it is often stated that fatigue accounts for at least 90 percent of all service failures due to mechanical cause.[1] Repetitive or cyclic loading is by far the most common cause of structural failure in cast steel. Cyclic stressing well below yield point values can lead to the initiation and growth of fatigue cracks which ultimately become large enough to cause failure [2]. Thus, the mechanical engineer is mainly concerned with the effect on lifetime of external loading parameters (e.g. torque, bending moments, pressure) and the derivation of equivalent stresses and strains, safety factors, stress concentration factors, etc. that are used to provide a reliable design. This is usually attempted via a monoloading fatigue endurance S-N curve, also called Wöhler curve [3]. As all of the mechanical characteristics vary at one and the same time, they should be simultaneously considered. However, it is not easy to determine an empirical relationship among them.

For cast steels, the fatigue strength or endurance limit is generally in the range of 40 - 50 percent of the ultimate tensile strength [2,4]. Several research studies focussed on analysing the influence of different heat treatments on endurance limit have been carried out [5]. Microstructures, internal stresses, isotropy of mechanical properties and inclusions of cast steels may also be significant factors for evaluating fatigue properties of these materials [6]. To avoid surface stress concentration which could immediately initiate a crack, surface finishing of the specimen is another important factor to take into account in order to determine accurately the endurance limit [3]. Heterogeneity in chemical composition of the material gives rise to micro and macro segregations, causing microstructural changes and, as a consequence, mechanical properties changes among different parts of the specimen. The presence of defects, inclusions or microporosities, in turn, become stress concentration centres [7,8]. All of them are factors which decisively affect the endurance limit.

Investigations have been performed to seek empirical relationships between the endurance limit and other mechanical properties such as ultimate tensile strength and yield strength or both. These relationships used to be expressed in a linear form where the constant of proportionality was regardless of chemical composition and heat treatment of the steel [2,4,9]. Analysis of the

experimental results of this work shows that these linear relationships only accurately predict the endurance limit in limited levels of tensile strength properties. A parabolic relationship has been proposed for a wide range of the static tensile strength parameter [10,11] (300 - 1300 MPa) in CMn and CrMo low-alloy cast steels.

2 MATERIALS AND EXPERIMENTAL PROCEDURES

The chemical composition of the commercial cast steels used in this work is shown in Table 1. These steels were produced by direct arc furnace melting. The steels samples were machined from cast coupons directly obtained during the manufacturing process of cast components.

A conventional normalizing heat treatment was performed to fix a similar initial state in all of the steels. Tempering at 923 K/1 hour/air-cooling after normalizing (N+T923) and tempering at 823 K and 923 K/1 hour/air-cooling after quenching (Q+T823 and Q+T923) were carried out.

Rotating bending fatigue tests with a stress ratio $R = -1$ were performed in a Schenk type high-speed (6000 r.p.m) testing machine (Capacity: ± 26 N.m). Figure 1 shows the smooth high-strength steel specimen used in these fatigue tests. Endurance limit is defined as the highest variable stress applied which did not cause failure by fatigue in three specimens consecutively tested for 10 million uninterrupted cycles [12].

Over 500 specimens were tested in order to obtain reliable results although a scatter inherent to fatigue test was inevitable due to the nature of the material itself and operational factors.

3 RESULTS AND DISCUSSION

Figures 2 and 3 show S-N curves (Stress against the Number of cycles to failure in log scale) of three CMn and CrMo steels for N+T923, and Q+T923 heat treatments which were used as examples. Endurance limit values were accurately determined by means of these S -N curves.

Figure 4 represents S-N curves corresponding to CS29CMn and CS39CrMo steels for N+T923, Q+T823 and Q+T923 heat treatments. As shown below, the endurance limit values obtained from this Fig. 4 have been considered anomalous results.

Table 2 shows the results of the endurance limit (σ_w) of all the cast steels in the three heat treatments tested. Table 2 also shows the experimental results

of ultimate tensile strength (σ_u) and yield strength (σ_o) reported in previous researches [13,14] as well as the static tensile strength (σ_s) and proportionality factor K obtained according to

$$\sigma_s = \left(\frac{\sigma_u + \sigma_o}{2} \right) \dots\dots\dots (1)$$

$$\sigma_w = K\sigma_s \dots\dots\dots (2)$$

The values of the proportionality factor K show a significant variation which approximately ranges from 0.3 to 0.5 without considering the anomalous values. Figure 5 represents the variation of the proportionality factor K in relation to the σ_s parameter. A simple observation of this figure shows also that the proportionality factor K decreases as σ_s increases. It is also shown in this figure that the proportionality factor K could be certainly considered as a constant within limited ranges of the σ_s parameter. As a consequence, a linear relationship between the endurance limit and the σ_s parameter could be expected only in these ranges.

The overall analysis of all the experimental results allows to establish a relationship between K and σ_s . Figure 6 shows the straight line obtained by a linear fit whose equation is

$$K = 0.7 - 4 \cdot 10^{-4} \sigma_s \dots\dots\dots (3)$$

According to equations (2) and (3), the empirical relationship between the endurance limit and the static tensile strength parameter is

$$\sigma_w = 0.7\sigma_s - 4 \cdot 10^{-4} \sigma_s^2 \dots\dots\dots (4)$$

Figure 7 shows the non-linear relationship between σ_w and σ_s . This parabolic relationship, which does not claim to be of a general application, is the most suitable for the CMn and CrMo low-alloy cast steels used in this work according to the experimental results obtained.

At first and under metallurgical considerations, the endurance limit should increase as the static tensile strength parameter increases. Several results in Table 2 were considered anomalous due to an opposite tendency to that mentioned above. However, factors such as chemical composition, heat treatment and the final microstructure of the steel can justify a reduction in the endurance limit as σ_s parameter increases. The parabolic relationship proposed allows to predict this reduction. Figure 7 shows that from the maximum in the curve of equation (4) (over $\sigma_s=900$ MPa), the endurance

limit decreases as the σ_s parameter increases. This behaviour corresponds to the results of the endurance limit of steels with higher carbon content ($>0.25\% \text{C}$ in CMn and $>0.30\% \text{C}$ in CrMo). Their tempered martensite microstructures show a high degree of acicularity apart from a greater microstructural heterogeneity produced by segregations. These segregations are much more marked in these steels than in those of a lower carbon content where the microstructures are more homogeneous and stable. Two representatives examples are illustrated in Figs. 8. Figure 8a shows the as-Q+T923 microstructure of the CS29CMn steel. This microstructure maintains the acicular shape of the martensite and segregations on grain boundaries related to manganese sulfide globular inclusions (type I) [15]. Figure 8b shows that the as-Q+T823 microstructure of the CS39CrMo steel maintains the acicularity in the martensite and a marked segregation associated with chains of eutectic type inclusions on grain boundaries (type II) [15].

4 CONCLUSIONS

1. The analysis of the experimental results obtained in this study demonstrates that the existing linear relationships between the endurance limit and the ultimate tensile strength do not accurately predict the fatigue behaviour in a wide range of strength properties.
2. The proportionality factor K in these linear relationships was considered as a constant. This work allows to conclude that K is a function of a parameter called static tensile strength which is defined by the arithmetical mean of the ultimate tensile strength and the yield strength.
3. A new non-linear empirical relationship between endurance limit and static tensile strength has been proposed. This is a parabolic relationship which, although does not claim to be of a general application, is the most suitable according to the experimental results obtained for the CMn and CrMo cast steels used in this work.
4. The parabolic relationship proposed allows even to predict fatigue behaviours unjustified in principle. This relationship takes into account the microstructure of the steels and the presence of metastable microconstituents and heterogeneities which cause brittle areas, stress concentration, failure susceptibility, and produce a considerable reduction in endurance limit.

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Table 1 Chemical composition (mass %).

Steel	C	Mn	Si	P	S	Cr	Ni	Mo
CS17CMn	0.17	1.30	0.40	≤0.020	≤0.022	0.15	0.15	≤0.05
CS21CMn	0.21	1.30	0.32	≤0.020	≤0.025	≤0.10	≤0.10	≤0.05
CS29CMn	0.29	1.50	0.45	≤0.020	≤0.020	≤0.10	≤0.10	≤0.05
CS43CMn	0.43	1.49	0.30	≤0.020	≤0.022	≤0.10	≤0.10	0.08
CS16CrMo	0.16	0.65	0.17	0.018	0.022	0.95	-	0.21
CS27CrMo	0.27	0.65	0.26	0.012	0.027	1.00	-	0.28
CS30CrMo	0.30	0.71	0.27	≤0.020	0.029	1.10	-	0.21
CS39CrMo	0.39	0.58	0.38	0.016	0.021	1.02	-	0.26

Table 2 Mechanical properties of tested steels.

Steel	Heat Treatment	σ_u (MPa)	σ_o (MPa)	σ_s (MPa)	σ_w (MPa)	K	Observations
CS17CMn	N+T 923	550	378	464	245	0.53	
	Q+T 823	748	710	729	333	0.46	
	Q+T 923	643	565	604	265	0.44	
CS21CMn	N+T 923	564	388	476	255	0.54	
	Q+T 823	792	666	729	314	0.43	
	Q+T 923	686	588	637	265	0.42	
CS29CMn	N+T 923	657	455	556	216	0.39	Anomalous
	Q+T 823	897	847	872	314	0.36	Anomalous
	Q+T 923	739	675	707	216	0.30	Anomalous
CS43CMn	N+T 923	789	501	645	274	0.42	
	Q+T 823	1000	948	974	314	0.32	Anomalous
	Q+T 923	800	724	762	294	0.39	
CS16CrMo	N+T 923	559	421	490	255	0.52	
	Q+T 823	867	803	835	314	0.38	
	Q+T 923	720	632	676	343	0.51	
CS27CrMo	N+T 923	705	533	619	294	0.47	
	Q+T 823	1068	1000	1034	353	0.34	
	Q+T 923	882	804	843	304	0.36	
CS30CrMo	N+T 923	735	559	647	304	0.47	
	Q+T 823	1205	1117	1161	301	0.26	Anomalous
	Q+T 923	975	881	928	343	0.37	
CS39CrMo	N+T 923	833	637	735	255	0.35	Anomalous
	Q+T 823	1294	1218	1256	294	0.23	Anomalous
	Q+T 923	1039	945	992	265	0.26	Anomalous

Figure 1- High-Strength steel specimen for rotating bending fatigue tests

Figure 2- S-N curves for CMn cast steels: (a)CS17CMn, (b)CS21CMn and (c)CS43CM

Figure 3- S-N curves for CrMo cast steels: (a) CS16CrMo; (b) CS27CrMo and (c) CS30CrMo

Figure 4- S-N curves for the CS29CMn and CS39CrMo cast steels: (a) CS29CMn and (b) CS39CrMo

Figure 5- Variation bands of the proportionality factor K against the static tensile strength parameter (σ_s)

Figure 6- Relationship between the proportionality factor K and the static tensile strength parameter (σ_s)

Figure 7- Non-linear relationship between the endurance limit (σ_w) and the static tensile strength parameter (σ_s)

Figure 8-(a) As-Q+T293 microstructure of the CS29CMn steel and (b) As-Q+T823 microstructure of the CS39CrMo steel. Etched in 2% Nital (2mL nitric acid + 10L propan-2-ol).