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Fractography survey on high cycle fatigue failure: Crack origin characterisation and correlations between mechanical tests and microstructure in Fe–C–Cr–Mo–X alloys

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Abstract

Raw materials were cast from different specific processes in order to produce cleaner steels with a reduced amount of inclusions. Studied materials that are HSS hardened alloys belonging to the Fe–Cr–C–X system were shared out in four groups depending on the tempering temperature and the presence of secondary and primary carbides. Both inclusions and carbides were roughly assessed by means of Image Analysis.

Forging was done on all studied materials with different reduction ratios in order to highlight the texture influence on mechanical properties.

High cycle fatigue tests were made using the boundary method to allow a quick evaluation of results.

Fractographic analyses carried out on broken samples led to the definition of four failure modes depending on the nature and the location of the point from which the crack was initiated in one hand, and the roughness of striations in the propagating area over and around the initiation point. Internal and surface crack initiation points were found, the latter being more harmful than the first ones. Though oxides appeared to be more detrimental than other inclusions, primary carbides were also found to be both crack initiation candidates and crack propagation enhancers.

Various parameters likely to influence high cycle fatigue failures were finally defined, the most significant one dealing with the nature and location of embedded precipitates and the forging reduction ratio.

Keywords: Tool steels; High cycle fatigue; Forging; Inclusions; Carbides; Boundary method; Fractography; Crack initiation; Soakness

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1. Introduction

Complex Fe–C–Cr–Mo–X systems, where X consists of V and/or W elements, are custom alloys for tool steels or high speed steels (HSS) as they exhibit excellent hardness and good wear resistance at higher temperatures [1]. The final microstructure is directly influenced not only by the solidification rates at the time of casting, but also by the later heat or thermo mechanical treatments.

Fe–C–Cr–Mo–X alloys can thus contain in their hardened matrix desired precipitates such as carbides, and also more or less exogenous and endogenous inclusions, depending on the way casting process was performed [1–4].

Inclusions are present in all commercial materials as a result of deoxidising additions, impurities or entrained exogenous material. Inclusions are common sites for fatigue crack nucleation and are known to be particularly deleterious in high strength steel [5].

Considerable studies have been done on weakening the influence of inclusions on fatigue behaviour, especially on its nature and size features [6–9]. Reducing inclusions size leads to increased fatigue behaviour [7–9] and a methodology

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Nomenclature

A–S	studied material main coding
A_L–S_L	raw material (A–S) in a longitudinal direction
A_T–S_T	raw material (A–S) in a transversal direction
AED	average equivalent diameter of a precipitate (from Image Analysis)
BM	boundary method, for quick evaluation of transition range in fatigue tests
BSE	backscattered electron in SEM analysis
CIH	crack initiation halo
D	distance between the two levels of alternating load in boundary method
EAF	electrical arc furnace, as conventional casting
EDX	energy dispersive by X-rays
ESR	electro slag remelting (casting process)
FCI	failure crack initiation
FM1–FM4	failure mode 1 to failure mode 4
FRR	forging reduction ratio
GCF	giga cycle fatigue
HCF	high cycle fatigue
HSS	high speed steel
HV30	Vickers hardness with a 30 kg load
ICIP	internal crack initiation point
$K\alpha$ ($L\alpha$)	element spectrum line linked to electron orbital energy in EDX Analysis
L_1 (L_2)	Level 1 (Level 2) as probabilistic load near the range of transition in BM
LCF	low cycle fatigue
M_xC_y	carbide formulation with C for carbon and M for metallic element
MCIP	multiple crack initiation point
MED	maximum equivalent diameter of a precipitate (from Image Analysis)
MG1–MG4	material group 1 to material group 4, as a distribution related to the presence of secondary and primary carbides
n	Number of tested specimens per level while using BM
N_g	defined greater number of cycles to failure
ODA	optically dark area
P_F	probability of fatigue failure while using BM
r	number of broken specimens after HCF test while using BM
R_P	ultimate tensile strength (UTS)
S_a	alternating load for fatigue tests
SCIP	surface crack initiation point
SE	secondary electron in SEM analysis
SEM	scanning electron microscopy
$S_{FL,1}$ ($S_{FL,2}$)	alternating load related to Level 1 (Level 2) while using BM
UTS	ultimate tensile strength (R_P)

had been proposed to define the maximum defect size allowable in a casting component.

Fatigue crack initiation (FCI) usually occurs on the specimen surface in low cycle fatigue (LCF). However, there are more and more data which show that fatigue cracks initiate from the specimen subsurface when the cyclic lives are higher (or at a lower stress level). Furthermore, another study led to the hypothesis that the cause of fatigue failure in the surperlong life regime was due to the mechanical fatigue threshold for a small crack emanating from a non-metallic inclusion which was reduced by an environmental effect associated with hydrogen trapped at non-metallic inclusions (ODA concept) [6,8,10–12].

While subsurface crack initiation behaviour has been clearly detected in many materials under any testing conditions, the mechanism has not been fully understood [10].

Thus, studies dealing with features other than either inclusions or internal defects to explain fatigue failure are rare. In fact, carbides contrary to inclusions are expected in tool steels and their volume fraction is nearly controlled in order to yield the defined microstructure which could achieve the desired metallurgical properties [13]. Thus, the question of how carbides could influence fatigue behaviour remains of concern.

High cycle fatigue (HCF) tests are performed to focus on every weakening feature that could have an influence on fatigue behaviour, in the field of endurance life over 10^7 cycles. Therefore, using HCF tests could allow highlighting of carbides influence in extreme conditions together with inclusion effects.

As fatigue tests are known to enhance possible crack initiation points (geometry defects and stress concentration) [14,15], HCF tests could set an overall harmfulness gradation between inclusions and carbides while focussing on any harmful point that is a crack initiation candidate.

It is well known that the more a precipitate is weakened, the more the fatigue failure will be initiated early on this point [6,7,11,16]. And once the crack starts, there are other metallurgical features which support its propagation [6,7,11]. Then again, such a study could enhance carbides effect on propagation stage of fatigue failure.

In this work, four groups of Fe–C–Cr–Mo–X system were studied with respect to tensile and fatigue, the former distribution depending on whether fully martensitic matrix contained primary eutectic carbides or not.

These materials were of cleaner steel since a reduced inclusions amount was set through appropriate processes.