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The effect of sulfide type on the fracture behavior of HY180 steel

James L. Maloney [a], Warren M. Garrison Jr. [b,*]

[a] The Timken Company, 1835 Dueber Avenue S.W., Canton, OH 44706-0930, USA
[b] Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

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Abstract

In this paper are discussed the effects of sulfide type on the fracture toughness of HY180 steel. Manganese was added to one heat and the sulfides in this heat were MnS. Lanthanum additions but no manganese additions were made to the second heat and the sulfur was gettered in this heat as particles of La_2O_2S. Neither lanthanum nor manganese additions was made to the other two heats. These two heats were modified by small titanium additions. The sulfur in these two heats was gettered as particles of Ti_2CS. After the usual heat treatment for HY180 steel the fracture toughness of the heat in which the sulfur was gettered as MnS was 256 MPa $\sqrt{m}$. The fracture toughness of the heat in which the sulfur was gettered as La_2O_2S was 344 MPa $\sqrt{m}$. The fracture toughness of this heat was greater than the fracture toughness of the heat in which the sulfur is gettered as MnS because the particles of La_2O_2S are larger and more widely spaced than the particles of MnS. The fracture toughness of the two titanium modified heats were 478 MPa $\sqrt{m}$ and over 550 MPa $\sqrt{m}$. Void generation studies indicate that void generation is more difficult at particles of Ti_2CS than at particles of MnS or La_2O_2S. The improved fracture toughness of the heats in which the sulfur is gettered as Ti_2CS is attributed to the particles of Ti_2CS having greater resistance to void generation than particles of MnS or La_2O_2S.

Keywords: Fracture toughness; Steel; Inclusion; Void nucleation; Ductile fracture

1. Introduction

Ductile fracture is the growth and coalescence of voids typically nucleated at second phase particles. In a given material several particle types can be present. Normally, there is one particle type at which voids are nucleated first, either by particle fracture or by separation of the particle–matrix interface. These particles are referred to as primary particles. Voids nucleated at primary particles either grow to impingement or coalesce by a void sheet mechanism. Void sheet coalescence [1] of the voids nucleated at the primary particles requires fracture of the ligaments between these voids, often by the coalescence of voids nucleated at secondary particles which are particles more resistant to void nucleation than the primary particles and at which voids are nucleated much later in the fracture process.

In steels the primary particles are the non-metallic inclusions which can be sulfide, oxide and nitride particles. Non-metallic inclusions tend to be larger than other second phase particles in steels, ranging in diameter from about 0.1 to 10 μm or more. The inclusions are embedded within a fine-scale microstructure. The secondary particles, considered to be part of the fine-scale microstructure, include the fine carbides, nitrides and carbo-nitrides inherited from the austenitizing temperature and particles precipitated on tempering. Secondary particles directly influence fracture if they nucleate voids. Secondary particles inherited from the austenitizing temperature can indirectly influence toughness by pinning austenite grain boundaries during austenitizing and thus influence austenite grain size. Secondary particles precipitated on tempering can, if present in sufficient

* Corresponding author.
E-mail address: wmg@andrew.cmu.edu (W.M. Garrison Jr.).

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volume fractions, influence the flow behavior of the material.

When fracture is by micro-void coalescence the fracture toughness of steel is determined by both the fine-scale microstructure and the inclusions. It has been known for many years that if the fracture mode is ductile the toughness of ultra-high strength steels is dependent on inclusion volume fraction with the toughness increasing as the inclusion volume fraction is decreased. However, studies of ductile fracture suggest there are two other ways to minimize the detrimental effect of inclusions on toughness.

One approach to improving fracture toughness is to increase the inclusion spacing. The Rice and Johnson [2] model predicts that the crack tip opening displacement at fracture (δ_{IC}) should scale with the inclusion spacing when the inclusion volume fraction and fine-scale microstructure are held constant. That is, the toughness would increase if small, closely spaced inclusions could be replaced by larger, more widely spaced inclusions. The question then becomes how can one achieve larger and more widely spaced inclusions. We have shown previously that lanthanum additions to getter the sulfur in AF1410 steel result in larger and more widely spaced non-metallic inclusions than when the sulfur is gettered as CrS [3,4]. The increased spacing was associated with significantly higher toughness. As far as we know lanthanum additions have been made only to AF1410 and its higher strength modifications.

One objective of this paper was to examine the extent to which lanthanum additions improve the toughness of HY180 steel.

Another method of minimizing the detrimental effect of inclusions on toughness is to make the inclusions resistant to void nucleation. Bray et al. [5] investigated the fracture behavior of two commercially produced heats of HY180 steel made in the early 1970s. One of these heats had a fracture toughness of 285 MPa $\sqrt{m}$ which was much higher than the fracture toughnesses of other HY180 heats made at that time. The second heat considered, also produced in the early 1970s, had a fracture toughness more typical of HY180 heats produced at that time, 193 MPa $\sqrt{m}$. Comparing the microstructures of these two HY180 heats Bray et al. [5] concluded the only significant microstructural difference between them was sulfide type. The sulfides in the heat having a typical fracture toughness were MnS while the sulfides in the heat having an unusually high fracture toughness were Ti_2CS. The higher toughness of the heat in which the sulfides were Ti_2CS was attributed, on the basis of void generation studies, to the particles of Ti_2CS being more resistant to void nucleation than the particles of MnS. Both of these heats contained about 0.005 wt% sulfur which is about five times greater than the sulfur levels of heats of HY180 made today.

Two other objectives of the work were to determine if gettering of sulfur as Ti_2CS could be achieved in a straightforward way by keeping the manganese low and making small additions of titanium during vacuum induction melting and to investigate the extent to which gettering sulfur as Ti_2CS rather than as MnS or La_2O_2S would improve fracture toughness at sulfur levels more typical of current practice for HY180 steel.

The final objective was to investigate crack tip blunting behavior for these materials. In earlier work it was found that for high work hardening rates the crack tips blunted smoothly while for steels with low work hardening rates the blunting crack tips blunted to vertices. When a crack tip blunts to two vertices or corners it is seen as a square in cross-section, When the crack tip blunts to three vertices it is seen as a triangle in cross-section. The cross-sections of blunted crack tips will not only indicate blunting behavior but will also permit the investigation of fracture initiation. When a crack tip blunts to vertices fracture initiation is associated with shear cracks extending from the vertices. When the crack blunts smoothly crack advance is associated with the coalescence of the crack tip with voids growing just ahead of the blunting crack tip. The four microstructures investigated all have very low work hardening rates so it is believed they will blunt to vertices.

HY180 steel has a nominal composition (in wt%) of 0.10C/10Ni/8Co/2Cr/1Mo and is normally heat-treated by austenitizing, quenching and tempering [1]. The usual practice is to temper this steel for five hours at 510 °C, the tempering temperature at which this steel achieves its maximum yield strength. The relatively high yield strength after tempering at 510 °C is associated with cobalt enhanced secondary hardening due to the precipitation of fine M_2C particles where the M is molybdenum and chromium. The excellent toughness of this alloy after tempering at 510 °C has been attributed, at least in part, to an absence of intralath cementite particles after tempering at this temperature [6].

We will discuss briefly some results obtained with the steel AF1410. AF1410 is a higher strength version of HY180. AF1410 contains 0.16 wt% carbon rather than 0.10 wt% carbon and it contains 14 wt% cobalt rather than 8 wt% cobalt. It has a nominal composition (in wt%) of 0.16C/10Ni/14Co/2Cr/1Mo and is normally heat-treated by austenitizing, quenching and tempering at 510 °C for five hours. It has a typical yield strength of 1500 MPa while the yield strength of HY180 is about 1250 MPa.

In the work reported here four experimental heats of HY180 steel were investigated. One experimental heat contained an addition of 0.31 wt% manganese and the sulfides were MnS. A second was modified by lanthanum additions and in this heat the sulfur was primarily gettered as La_2O_2S. The other two experimental heats contained no manganese or lanthanum additions but