A TEMPER EMBRITTLEMENT STUDY ON A SERIES OF MEDIUM CARBON CR-MO STEEL TURBINE BOLTS

J.H. Bulloch and J.J. Hickey*

The paper gives a description of a detailed assessment aimed at identifying reverse temper embrittlement (RTE) in a series of forty four medium carbon, Cr-Mo steel turbine bolts. It was observed that the grain size, d, and the phosphorus level of the bolts were the only factors which could be strongly linked to "in service" temper embrittlement behaviour.

An Embrittlement Estimative Diagram, EED, was established through a grain size - %P graph which portrayed two distinct regions, a partial embrittled and a non-embrittled region, which were separated by some critical interface or threshold condition which signalled the onset of RTE.

INTRODUCTION

Steam turbine high temperature bolts, which are subject to temperatures up to 540°C maximum, represent critical components and in some instances, eg. 1 Cr Mo V steels, exhibit fairly good creep strengths but relatively low material toughness properties. As such, any mechanism that can cause a marked toughness degradation during service needs to be carefully assessed. One common mechanism, whose problematic effects have been known for the best part of this century is reversible temper embrittlement, RTE, (1). The present paper describes a set of assessment procedures aimed at identifying which turbine bolts have been embrittled during service.

2. EXPERIMENTAL PROCEDURES

From a small 20 MW steam turbine, a total of 44 bolts fabricated from a 0.4/0.5%C, 1.2/1.5%Mn, 0.2/0.5%Si, 0.008/0.028%P, 0.001/001%Sn, 0.5/0.7%Mo steel were subjected to a magnetic particle inspection, MPI, in an effort to detect if any creep damage (in the form of cracks) was present at the thread root locations. In all cases no cracks were observed. The level of accumulated strain imparted on each bolt during its

* Electricity Supply Board, Dublin 2, Ireland.

entire service life, which was 176,000 hours at around 400°C, could not be established because the original lengths of each bolt were not documented. A small metallographic section was removed from the non-critical keyway location at each bolt head. From each section the following parameters were determined, viz., microstructural type, hardness, bulk chemical analysis and the average grain size. The bolt embrittlement assessment was based on two factors, (a) full size Charpy impact specimen an/or (b) Auger electron spectroscopy, AES. Basically two Charpy criteria were used, viz., the Fracture Appearance Transition Temperature, FATT, and the Room Temperature Fracture Energy, RTFE.

EXPERIMENTAL RESULTS

From the various Charpy impact test data and the AES results it was clearly established that the bolts could be classed under three embrittlement conditions viz., (1) non-embrittled (2) initial stages of embrittlement and (3) partially embrittled. None of the bolts observed in the present study exhibited the fully embrittled condition. The following Charpy (fracture appearance transition temperature, FATT, room temperature Charpy energy, RTCE,) and AES characteristics were typical of the three degrees of embrittlement found in the present study, viz.,

	FATT (°C)	RTCE (JOULE)	% PHOSPHORUS MONOLAYERS
NON EMBRITTLED BOLT	-50 to-60	100-110	ZERO
INITIAL STAGES OF BOLT EMBRITTLEMENT	-30	80-95	ZERO
PARTIAL EMBRITTLED BOLT	0 to + 10	50-60	0.05 to 0.08

The relationship between the average grain size and the microstructure hardness for all the bolts is shown in Figure 1. From this figure it can be seen that generally, although, the hardness increased with increasing grain size no clear trend concerning the propensity of a bolt to embrittlement was evident. Since it was established that some purpose common alloying elements, such as silicon and manganese, can significantly influence the segregation of certain residual metalloids a chemical composition parameter, commonly known as the J-Factor, has been introduced, viz.,

$$\text{J-Factor} = (P + Sn)(Mn + Si) \times 10^4 \qquad (1)$$

This parameter (2) was plotted against the average grain size for each individual bolt and the results are shown in Figure 2. From this Figure it is evident that (1) over the J-factor range 200 to 330 there was no clear embrittlement - composition trends (2) their was a definite effect of average grain size on embrittlement in that embrittlement was observed at grain sizes larger than around 28µm and (3) general embrittlement occurred above a J-Factor of 330 in bolts irrespective of grain size.

Upon inspection of Figure 3 it is immediately clear that the results indicate the existence of two distinctly separate regions, viz., a partial embrittled regime and a non-embrittled regime. At a phosphorus level of 0.01% an interface between the partial embrittled and the non-embrittled bolt condition, termed the critical embrittled - non embrittled interface, occurred fairly sharply at an average grain size of 24µm, see Figure 3. From Figure 3 it is evident that both the grain size and the bulk phosphorus content, which was identified as the only grain boundary segregant species found in the present study, exerted a powerful influence on the RTE characteristics of the present medium carbon Cr-Mo bolts.

CONCLUDING REMARKS

It has been clearly established that for the present medium carbon Cr-Mo bolts only the average grain size and bulk phosphorus content were the reliable indicators which signalled the occurrence of the start of RTE during service. Indeed the EED shown in figure 3 portrayed a simple visual picture whereby embrittled high temperature bolts could be readily identified, viz., a partial embrittled region or mechanism active region and a non-embrittled region or mechanism inactive region.

The mechanism was RTE and the critical interface or line which separated both these regions can be described by the expression.

$$d \times \%P = 0.24 \qquad (2)$$

where d is in µm and %P is in weight %.

Also illustrated in Figure 3 is the relationship between average grain size, d, and the grain boundary area/unit volume, s_v, where it can be seen that this relationship exhibited a remarkable commonalty with the critical embrittled - non - embrittled interface described by equation (2). Such a similitude strongly suggested that the grain size effect could be rationalised in terms of the available grain boundary area for phosphorus segregation.

An EED and the embrittlement expression given in equation 2, which identified which bolts had suffered the start of reverse temper embrittlement can be rapidly and simply constructed during a planned outage. However such an equation can apply only to this particular turbine service conditions and to this series of medium carbon Cr-Mo bolts. In the present analysis it has been established that during the 176,000 hours service around 40% of the turbine bolts had shown the initial signs of toughness degradation.

The partial embrittled - non embrittled interface obtained from the present study is shown in Figure 4 together with previously reported data (3) for two sets of Cr-Mo-V steel turbine bolts which had seen some 120,000 hours at 490°C. It can be seen that the Cr-Mo-V data exhibited powerful effects of average accumulated service strain, E_{av}, upon the propensity of a bolt to RTE. The present study exhibited trends that showed good agreement with the Cr-Mo-V steel data and indicated that this approach can be used in assessing embrittlement during service of various steel compositions as long as the segregant species is solely phosphorus.

Finally although the present study showed only partially embrittled bolts after 176,000 hours while the Cr-Mo-V bolts exhibited the fully embrittled condition after only 120,000 hours it is suggested that the differences are the results of both temperature and accumulated strain on phosphorus segregation.

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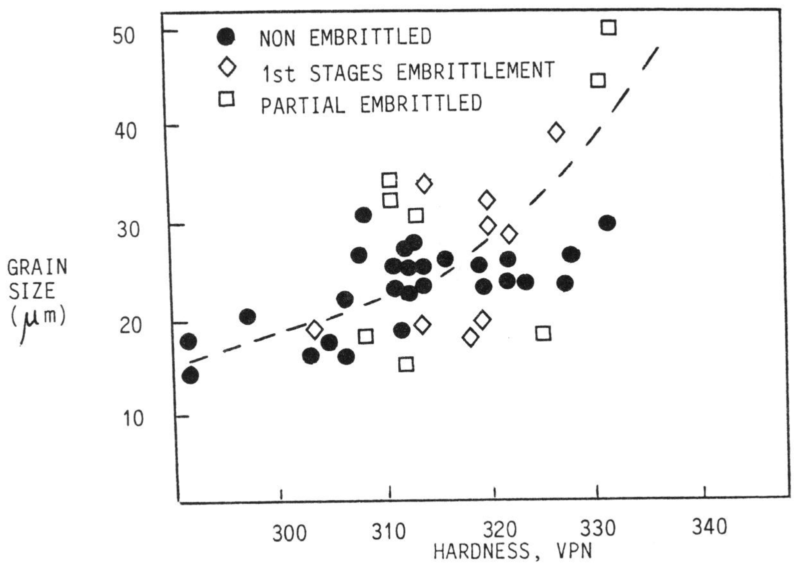

FIGURE 1 HARDNESS VERSUS GRAIN SIZE

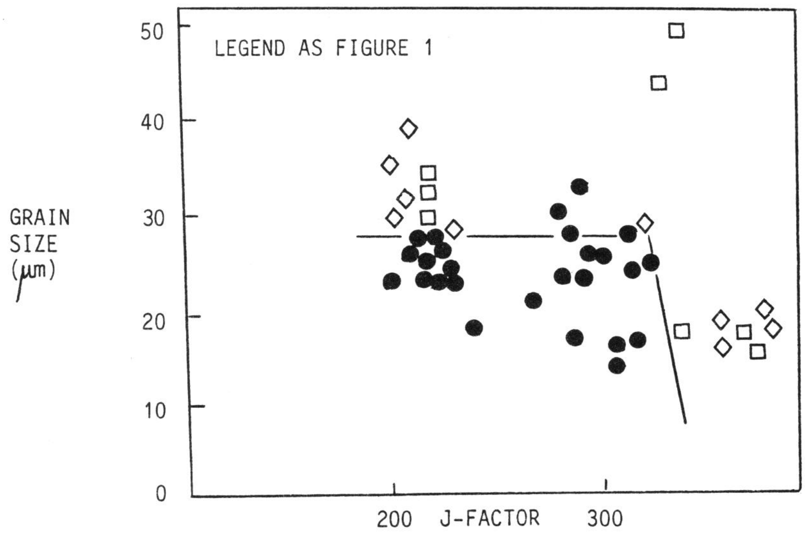

FIGURE 2 GRAIN SIZE VERSUS J-FACTOR

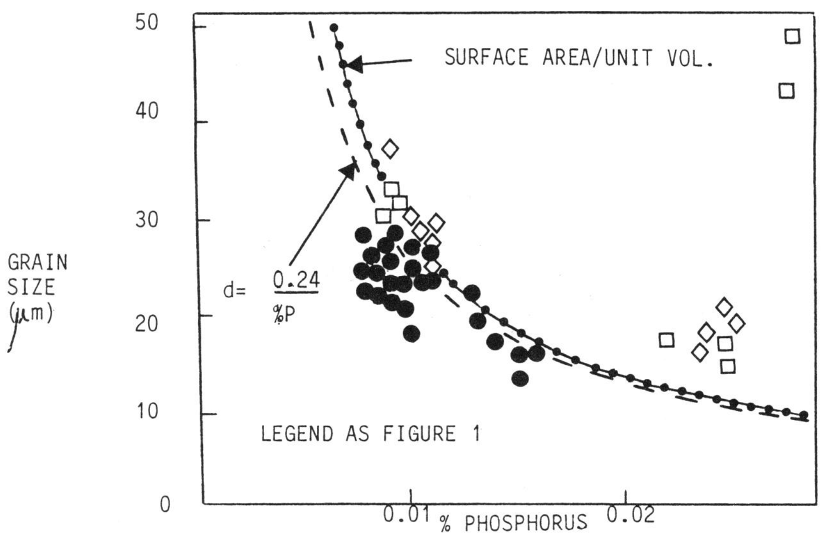

FIGURE 3 GRAIN SIZE VERSUS % PHOSPHORUS

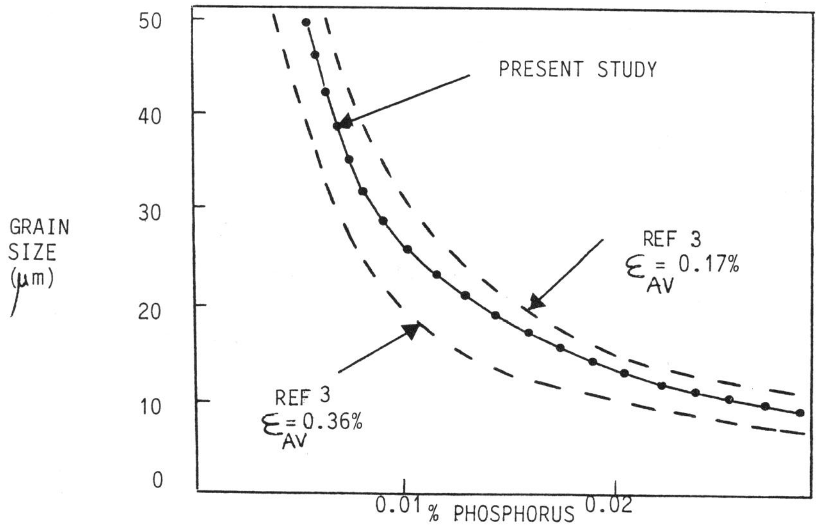

FIGURE 4 GRAIN SIZE VERSUS % PHOSPHORUS