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Unlike tempered martensite embrittlement, temper embrittlement is reversible. The use of small additions of molybdenum reduces the susceptibility of steels to TE.

Temper embrittlement in steels

Temper embrittlement (TE) occurs in quenched and tempered steels that increases the Ductile to Brittle Transition Temperature (DBTT) and reduces fracture toughness with tempering or service temperatures in the range of 375-575°C.

INTRODUCTION

In my previous column, I discussed tempered martensite embrittlement (TME). Another type of embrittlement, temper embrittlement, may develop in steels tempered in the range of 375-575°C (707-1,070°F). While there are similarities in the effects of TME and TE, they are two separate phenomena due to the two different temperature ranges. Tempered martensite embrittlement occurs rapidly, usually within one hour, while temper embrittlement takes many hours to develop. Temper embrittlement is of major concern in thick sections that are tempered at elevated temperatures. Even if tempered above the critical range, the interior of the thick sections cools slowly from the tempering temperature through the range of temper embrittlement. It can also occur in large weldments of susceptible steel. TME occurs rapidly during tempering and is independent of section size or cooling rate after tempering. TE is reversible by heating to above 575°C (1,070°F) after holding for only a few minutes at temperature [1], while TME is non-reversible [2].

Temper embrittlement shows itself as a loss of toughness, typically measured by a reduction in Charpy V-notch impact energy and an upward shift of the ductile-to-brittle transition curve after exposure to specific temperature ranges (Figure 1). Fracture surfaces transition from predominantly ductile microvoid coalescence to intergranular or quasi-cleavage appearance, indicating weakened grain-boundary cohesion.

MECHANISM

The mechanism of temper embrittlement is unclear, but is associated with the segregation of impurities, such as phosphorus, to prior austenite grain boundaries [1] [3] [4] [2] [5] [6]. Auger electron spectroscopy (AES) shows high concentration of impurities segregated to grain boundaries, but also gradients of alloying elements such as nickel, which enhance the segregation of phosphorus to prior austenite grain boundaries. In the case of nickel, grain boundary carbides reject nickel as the carbides grow, forming a nickel concentration gradient at the prior austenite grain boundaries [7]. Molybdenum supports the formation of $(Mo,Fe)_3P$ or Mo-P clusters which prevent the segregation of phosphorus to the grain boundaries [1] [8].

COMPOSITION EFFECTS

Temper embrittlement is most prominent in low-alloy steels, especially Cr-Ni grades used in heavy-wall pressure vessels, reactors, rotors, and similar equipment. Weldments and the weld metal need to be considered, too, for susceptibility to temper embrittlement.

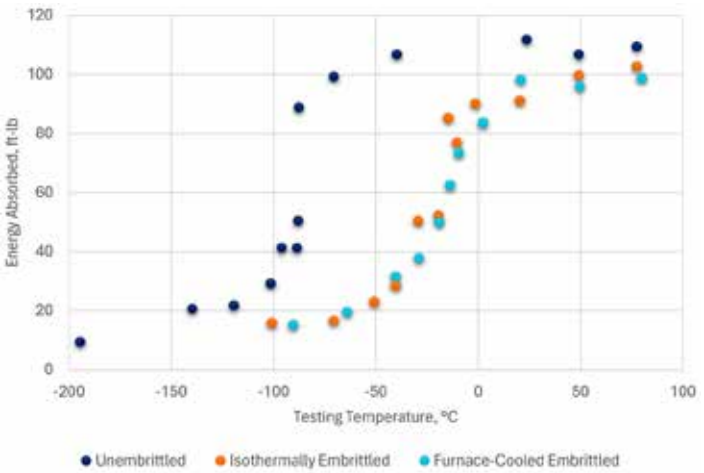

Figure 1: Shift in impact transition temperature to a higher DBTT temperature because of temper embrittlement of SAE 3140 subjected to the critical range for temper embrittlement [1] [9]

The impurities most detrimental are antimony, phosphorus, tin, and arsenic. Low concentrations of less than 0.01 percent of these impurities can result in temper embrittlement [2]. Silicon and manganese in high concentrations can also increase the susceptibility to TE [1]. For the most part, provided that the manganese content is below 0.5 percent, plain carbon steels are not thought to be susceptible.

Susceptibility depends strongly on steel chemistry and austenite grain size. Larger prior-austenite grains, higher levels of retained austenite, and certain combinations of alloying and impurity elements promote severe embrittlement, whereas micro-alloy additions such as molybdenum [8], tungsten, vanadium [4], and rare-earth elements can mitigate it [1].

The susceptibility of steels to temper embrittlement can be estimated using two different compositional parameters: the Watanabe J factor [10] and the Bruscato X factor [3]

$$J = 10^4([Mn] + [Si])([P] + [Sn])$$
$$X = (10P + 5Sb + 4Sn + As)/100$$

For the Watanabe J factor, the compositions are given in Wt%, and for the Bruscato X factor is given in ppm. To avoid compositions that risk temper embrittlement, the Watanabe J factor should be less than 180 [11], or the Bruscato X factor should be less than 20.

A more general expression for avoiding embrittlement is provided by Sugiyama et al [12]:

$$P_E = C + Mn + Mo + \frac{Cr}{2} + \frac{Si}{4} + 3.5(10P + 5Sb + 4Sn + As)$$

Where composition is given in weight percent. In general, P_E less than 2.8-3.0 are adequate to avoid temper embrittlement.

As indicated above, the impurity elements of phosphorus, antimony, tin, and arsenic are all associated with temper embrittlement. Phosphorus is readily removed by modern steelmaking and ladle metallurgy. However, antimony, tin, and arsenic are not readily removed. Careful control of scrap is necessary to minimize these impurities prior to steel making.

CONCLUSION

Temper embrittlement increases the Ductile to Brittle Transition Temperature (DBTT) and reduces fracture toughness with tempering or service temperatures in the range of 375-575°C. Unlike tempered martensite embrittlement, temper embrittlement is reversible. It is caused by segregation of impurity elements phosphorus, antimony, tin, and arsenic segregating to prior austenite grain boundaries. The use of small additions of molybdenum reduces the susceptibility of steels to temper embrittlement.

Should there be any questions regarding this article, or suggestions for further articles, please contact the editor or myself.

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