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The Embrittlement Phenomena in Hardened & Tempered Steel

While the end-use application of a component dictates its heat treatment, as heat treaters we know that we must achieve a delicate balance between the properties of strength and ductility. Nowhere is this fine line more evident than in the tempering process where precise control of time and temperature are critical to help produce a part with optimized microstructure and mechanical properties.

Essentially, tempering is the modification of this newly formed microstructure toward equilibrium. Almost all steels that are subjected to any type of hardening process are tempered. A temper is a subcritical heat treatment that alters the microstructure and properties. In general, tempering lowers strength and hardness while improving ductility and toughness of the as-quenched martensite. However, this is not always the case. Let's learn more.

What is Temper Embrittlement?

In general, embrittlement is a reduction in the normal toughness of steel due to a microstructural change and chemical effects. Temper embrittlement is a phenomenon inherent in many steels, characterized by reduced impact toughness. It occurs in certain quenched and tempered steels and even in ductile irons with susceptible compositions. This form of embrittlement does not affect room-temperature tensile properties but causes significant reductions in impact toughness and fatigue performance. Although normally associated with tempered martensite, temper embrittlement can also occur if the matrix is tempered to the fully ferritic condition.

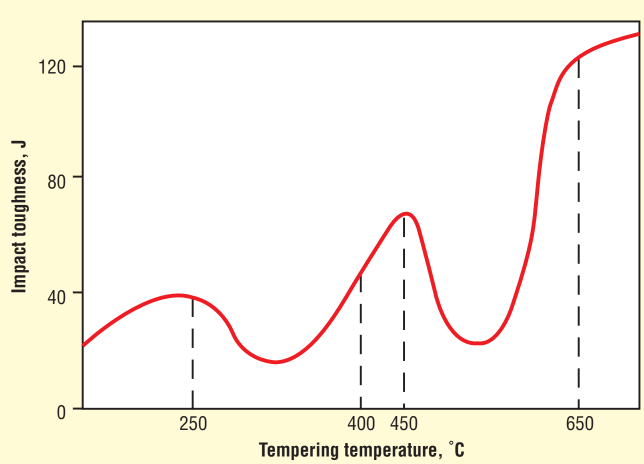


Fig. 1. Effect of temperature on impact toughness[5]

Types of Temper Embrittlement

When tempering steel, several types of embrittlement must be avoided. The first type, tempered martensite embrittlement (TME), is an irreversible phenomenon that occurs in the range of approximately 250–400°C (480°F–750°F) and is often referred to as "blue brittleness" or "350°C (500°F) embrittlement."

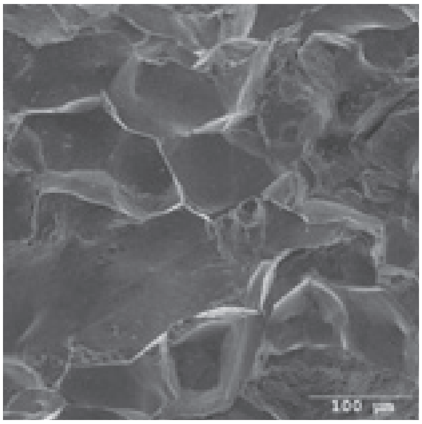
The second type, temper embrittlement (TE), is a reversible phenomenon occurring when steels are heated in or slow cooled through the temperature range of 375–575°C (705°F –1070°F).

Recently it has been reported that a transition from ductile to intergranular fracture in steel having greater than 0.5% C has been observed in martensitic steels tempered at low temperatures. Under tensile or bending stress, these higher-carbon steels are highly susceptible to intergranular fracture in both the as-quenched condition and after tempering at low temperatures generally considered to be safe from these embrittlement phenomena. In view of the fact that tempering is not required to render the microstructure susceptible to intergranular fracture, this type of embrittlement phenomenon is referred to as quench embrittlement. [2]

Why does it happen?

Tempered martensite embrittlement and temper embrittlement are examples of intergranular embrittlement. A common factor in such failures is the presence of elements that segregate to the grain boundaries. The chemical reaction rate or kinetics of segregation are such that they exhibit "C" curve behavior in the 350°C –550°C (660°F –1020°F) range. In other words, segregation does not occur uniformly. Both types of embrittlement are in part related to grain-boundary segregation of impurity elements (e.g. arsenic, antimony, phosphorus, and tin). Usually indicated by an upward shift in ductile-to-brittle transition temperature, both types of embrittlement develop during thermal processing after austenitizing and quenching to martensite.

Tempered martensite embrittlement is thought to result from the combined effects of cementite precipitation on prior-austenite grain boundaries or interlath boundaries and the segregation of impurities at prior-austenite grain boundaries.



SEM photo of intergranular temper embrittlement *(Courtesy of Matco Associates Inc.)*

Temper embrittlement that occurs in the range of 375–575°C (705–1070°F) is believed to be due to segregation of impurity elements (P, Sn, As, Sb) to prior austenite grain boundaries. This causes decohesion of the boundaries, resulting in the tendency for low-energy intergranular fracture under certain loading conditions.

Which steels are affected?

All steels are susceptible, so the real question becomes how susceptible and what factors affect that susceptibility. For example, while plain-carbon steels may contain some of the impurity elements that will cause the embrittlement phenomenon to occur, the segregation of these elements is often enhanced by or caused by the presence of other alloying elements in substantial quantities. As a result, alloy steels generally have more susceptibility than carbon steels.

It is important to understand that the degree of embrittlement is affected by the prior austenite grain size and hardness. So, if we are dealing with a fine-grained plain-carbon steel of low hardness, it may not experience embrittlement symptoms despite its phosphorous content whereas a more highly alloyed Cr-Ni steel used at higher hardness is more susceptible to impurity content.

Widely used alloying elements such as chromium, nickel and manganese tend to promote temper embrittlement with the highest embrittlement effect observed in Cr-Ni and Cr-Mo steels. Small additions of molybdenum in Cr-Ni steels (0.2-0.3% *in solution*) can diminish temper embrittlement being caused by phosphorus. Temper embrittlement can be diminished by keeping silicon and phosphorus levels as low as possible, adding up to 0.15% molybdenum and avoiding the embrittlement heat-treating conditions.

Susceptibility also depends on impurity control, and here is where the steelmaking process is critical. For example, in plain carbon and Cr-Mo steels (those with no Ni) where phosphorous is the most important embrittlement element, the percentage can be controlled by the steelmaking process. In steels that contain significant amounts of nickel, antimony and tin are more potent embrittlement elements. Phosphorous has an effect, but not as large as it has in plain carbon and Cr-Mo steels. It should be noted, however, that antimony and tin in plain-carbon steels could cause other hot-working issues.

How can we correct it?

Tempered martensite embrittlement (TME) is irreversible and its effects are permanent. By contrast, the effects of temper embrittlement (TE) can be reversed. This is done by re-tempering above the critical temperature of 575°C (1070°F), then cooling rapidly, or by re-austenitizing and cooling rapidly. Impact toughness can be restored. If necessary, this process can be repeated.

A Simple Example

Alloy steel, which is susceptible to temper embrittlement, will exhibit a relationship such as shown below (Fig. 1). The lower-temperature energy trough, 250–400°C (480°F–750°F), is indicative of tempered martensite embrittlement while the trough at the higher temperature, 450-650°C (840–1200°F), represents temper embrittlement.

Summing Up

The susceptibility of a given steel to temper embrittlement depends on a number of factors including grain size, hardness, steel grade and the impurity control in the steelmaking process itself. Not all steels and not all steelmaking processes are equal.

Finally, as heat treaters we must avoid the temptation to temper to a given hardness value without understanding the consequences of our actions. Since we do not have a simple embrittlement test that can be used on the shop floor, we must understand the phenomenon and question specifications that put us into temper-embrittlement ranges. **IH**

In general, embrittlement is a reduction in the normal toughness of steel due to a microstructural change and chemical effects... Tempered martensite embrittlement and temper embrittlement are examples of intergranular embrittlement. A common factor in such failures is the presence of elements that segregate to the grain boundaries.

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Additional related information may be found by searching for these (and other) key words/terms via BNP Media LINX at www.industrialheating.com: temper embrittlement, martensite, ductile fracture, intergranular fracture, ductile-to-brittle transition