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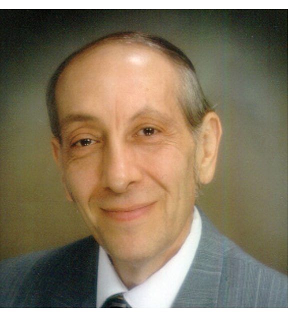
Toughness Revisited

Last time we learned something about the relationship between strength and toughness (Fig. 1).[1] A material may be strong and tough, exhibiting high strains if it ruptures under high loads. By contrast, brittle materials may be strong, but with limited strain values they are not tough. Generally speaking, strength indicates how much load/stress the material can sustain, while toughness indicates how much energy a material can absorb before rupturing.

In our previous discussion on toughness we also talked about the need to discuss the influence of alloying elements, microstructure, heat treatment, embrittlement phenomena and service conditions. Let's learn more.



Effect of Alloying Elements on Toughness

Alloying elements play an important role in influencing a host of mechanical properties (Table 1), not the least of which is toughness. As we all know, steels contain various alloying elements (and impurities) that influence the formation of new phases as well as interact with the crystal structures of austenite, ferrite and cementite. Some of the alloying elements are austenite stabilizers (e.g., manganese and nickel), some are ferrite stabilizers (e.g., silicon, chromium and niobium) and still others are strong carbide formers (e.g., titanium, niobium, molybdenum and chromium). Of these effects, certain alloying elements (e.g., manganese, sulfur, aluminum, calcium and silicon) as well as oxygen influence the type, distribution and morphology of inclusions (e.g., oxides, sulfides, silicates and nitrides). There is a strong effect of inclusions on fracture and mechanical properties. Coarse inclusions also serve as fatigue initiation sites and have been reported to initiate cleavage fracture.

Table 1. Alloying elements with a favorable influence on mechanical properties (alphabetical listing)[3]

Hardenability	Strength	Toughness	Machinability
Boron	Carbon	Calcium	Lead
Carbon	Cobalt	Cerium	Manganese
Chromium	Chromium	Chromium	Phosphorous
Manganese	Copper	Magnesium	Selenium
Molybdenum	Manganese	Molybdenum	Sulfur
Phosphorous	Molybdenum	Nickel	Tellurium
Titanium	Nickel	Niobium	
	Niobium	Tantalum	
	Phosphorous	Tellurium	
	Silicon	Vanadium	
	Tantalum	Zirconium	
	Tungsten		
	Vanadium		

Here's a look at each individual element affecting toughness:[4]

- Calcium improves steel cleanliness by influencing the size, morphology and total number of inclusions; desulfurizes; and reduces the tendency toward directional properties. Calcium also modifies the shape of any remaining sulfide inclusions so as to be less detrimental to mechanical properties. Calcium has no effect on transformations occurring during heat treatment.
- Cerium, while itself a potent deoxidizer and desulfurizer, is added to control the shape of inclusions in steel that has already been deoxidized and desulfurized by other additives. Cerium does not take part in heat-treating reactions.
- Chromium has a tendency to form hard and stable carbides. Chromium strongly affects hardenability, wear resistance, corrosion resistance, resistance to hydrogen attack and resistance to softening at elevated temperature (i.e. greater creep and stress-rupture properties). Chromium has a strong affinity for both carbon and nitrogen.
- Magnesium desulfurizes steel, and by its ability to influence sulfide inclusions improves ductility, formability and directional uniformity.
- Molybdenum is a potent hardenability agent that retards softening at elevated temperature and improves corrosion resistance. During heat treatment, molybdenum steels have a tendency toward surface decarburization. Molybdenum is a strong carbide former and reduces the tendency toward temper embrittlement.
- Nickel is an austenite stabilizer, that is, the A_3 temperature will be depressed and in the presence of carbon so too will the A_1 temperature. Nickel is a solid-solution strengthener, a weak hardenability agent and promotes high toughness (often in combination with chromium and vanadium), especially at low temperatures. While its effects are not strong, nickel does have some influence on heat-treating transformations retarding both pearlite and, to a greater extent, bainite reactions.
- Niobium has two principal uses in steels: as a grain refiner and for the formation of extremely hard and stable carbides and carbonitrides. Niobium has a strong ability to remove carbon from solid solution and thus has a negative effect on hardenability.
- Tantalum improves strength and forms fine precipitates, but increasing tantalum content has a negative effect on ductility.
- Tellurium improves machinability but has no effect on the transformations occurring during heat treatment. Tellurium is a grain refiner and can be added to steel to influence the size, shape, distribution and morphology of sulfide inclusions, the result of which is an improvement in transverse toughness and certain mechanical properties.
- Vanadium promotes fine grain size (i.e. retards grain growth during austenitizing), increases hardenability (when dissolved in austenite, although its effectiveness is diminished somewhat by its high affinity for carbon) and improves wear resistance through the precipitation of carbides and nitrides.

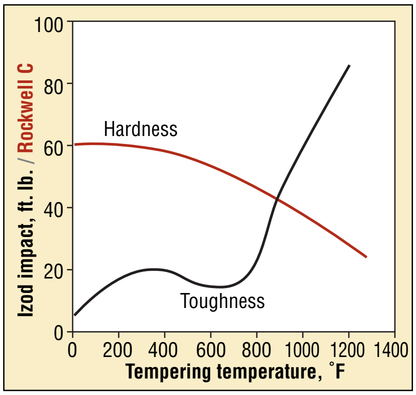


Fig. 1. Relationship of hardness and toughness of 4140 steel after tempering for one hour[2]

- Zirconium forms stable compounds with oxygen, sulfur, nitrogen and carbon, thus helping to control nonmetallic inclusions and the fixation of nitrogen (primarily in boron steels). The presence of zirconium in quenched-and-tempered steels also reduces grain coarsening/sensitivity and permits the use of higher hardening or carburizing temperatures. Zirconium raises the yield/tensile ratio and improves ductility and impact strength, particularly in the transverse direction. In highly alloyed steels, ductility decreases while hardness improves. Its usefulness is limited for economic and processing reasons.

Embrittlement Phenomena[5]

High-strength quench-and-tempered steels are subject to a variety of embrittlement phenomena including quench embrittlement, tempered-martensite embrittlement, temper embrittlement, hydrogen embrittlement and liquid-metal embrittlement, to name a few. In addition, stainless steels are affected by sigma-phase embrittlement.

The steel's carbon content has a significant impact on toughness under various tempering conditions (Fig. 2). The effects on toughness can be categorized as follows:

- Tempered martensite (blue) embrittlement (TME) is irreversible and results in a loss of room-temperature impact toughness and fracture resistance. It manifests itself by ductile, cleavage and intergranular modes of fracture. Tempering in the range of 250-400°C (480-750°F) can result in TME. The interactive effect of both tempering temperature and carbon level on the magnitude of the temper-embrittlement effect is seen in Figure 2.

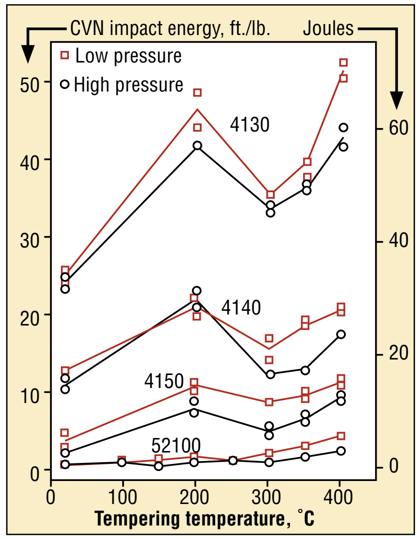


Fig. 2. Charpy V-notch energy absorbed in fracture of 41xx-series and 52100 steels tempered at various temperatures[5]

- Temper embrittlement (TE) results in the loss of ductility (or the increase in the ductile-to-brittle transition temperature) after tempering in the range of 375-575°C (700-1070°F) or slow cooling through this range. Impurities such as phosphorous, tin, arsenic and antimony strongly influence the susceptibility of a material to TE. In general, heating to temperatures above the embrittlement range for several hours followed by rapid cooling can reverse the effects.
- Quench embrittlement is an intergranular mechanism of brittle fracture, especially in high-carbon (≥ 0.50% C) steels during austenitizing and quenching. Tempering is not required. It is similar to quench cracking, which is due to high surface tensile stresses during quenching. Carbon and phosphorous play a significant role.
- Sigma-phase embrittlement results from the precipitation of an iron-chromium compound after holding austenitic or ferritic stainless steels for long periods of time in the range of 560-980°C (1050-1800°F). Slow cooling through the range of 1040-650°C (1900-1200°F) produces the same effect as does quenching from this range followed by subsequent heating in the range of 560-850°C (850-1560°F).

Effects of Primary Processing on Toughness

In addition to a large number of inclusions, cracking during solidification and hot working may introduce flaws that compromise performance. In the case of hot working, incipient melting, precipitation of particles or ferrite formation in the austenite grain boundaries and resultant microvoid formation are believed to be the mechanisms involved. By way of example, the microstructure of a hot-worked 5,000-pound roll (Fig. 3) reveals large chromium carbides in an intergranular network, creating a part with extremely poor fracture toughness. **IH**

Fig. 3. Hot-working problems on a D2 roll
(Photograph courtesy of Aston Metallurgical Services Co., Inc.)

For the conclusion and references, use this Mobile Tag or www.industrialheating.com/htdr311

Final Thoughts

To understand toughness, one must have a clear understanding of the role of alloying elements as well as the various microstructural influences affecting the end-use application. In addition, the relationship of ductility to toughness needs to be at the forefront of our thinking.

Toughness is a complex subject, and our articles provide only a brief overview. The reader is encouraged to use the references provided and other materials for a more in-depth treatment of the subject. **IH**

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