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Each heat-treatment process should be evaluated to determine its acceptable hardenability range to remain a capable process.

Variation in steel hardenability

Many heat-treating processes cannot tolerate appreciable variations in steel hardenability. For an established in-control process, deviations in chemical composition and starting microstructure may result in a variety of issues including quench cracking, out-of-spec hardness, low ductility, and excessive distortion. Consequently, a hardenability tolerance should be assessed and defined for all new processes to ensure incoming material is properly controlled without being over specified.

HARDENABILITY DEFINED

Hardenability is often used synonymously with "end-quench" or "Jominy" hardenability, a reference to a standardized test that quantifies the hardness of a steel as a function of distance from an austenitized and water-quenched surface [1, 2]. This test has both beneficial and detrimental aspects. It is beneficial in that it allows the chemical composition variation of the raw material (e.g., bar or billet) to be characterized for quality control purposes with relative ease, but is detrimental in that it is limited in translating those results to components processed through a specific heat treatment process. As a result, for the remainder of this discussion, hardenability will be defined generally as the suppression of ferrite/pearlite formation upon cooling from austenite [1]. This definition encompasses those additional effects that are directly dependent on a specific heat treatment process.

CHEMICAL AND MICROSTRUCTURAL INFLUENCES

Chemical effects on hardenability are typically calculated using chemical ideal diameter (DI) – which is defined as the diameter in which the center of a round bar contains 50 percent martensite when quenched from austenite [3]. Grossmann used brine for his quenchant, but ideal diameter typically assumes an "ideal" quench rate, which is infinite [3]. Figure 1 shows the effect of different alloying elements on hardenability through multiplying factors used to calculate DI. The danger with this multiplying factor comparison is that the data represent only one austenite grain size (ASTM grain size 7) and does not take into consideration effects related to the form of the alloying elements in the steel.

In plain carbon steels, a smaller austenite grain size has been shown to markedly, and negatively, influence hardenability [3]. The generally accepted mechanism for this observation is that increasing grain size decreases the grain boundary surface area and, therefore, the number of inhomogeneous nucleation sites for ferrite and pearlite [1]. However, this grain-size effect can be confounding in both low alloy and microalloyed steels. In these steels, the amount of alloying still in precipitate form can be significant at common austenitizing temperatures. In general, having the alloying in solid-solution yields the greatest influence on diffusional transformations, increasing hardenability.

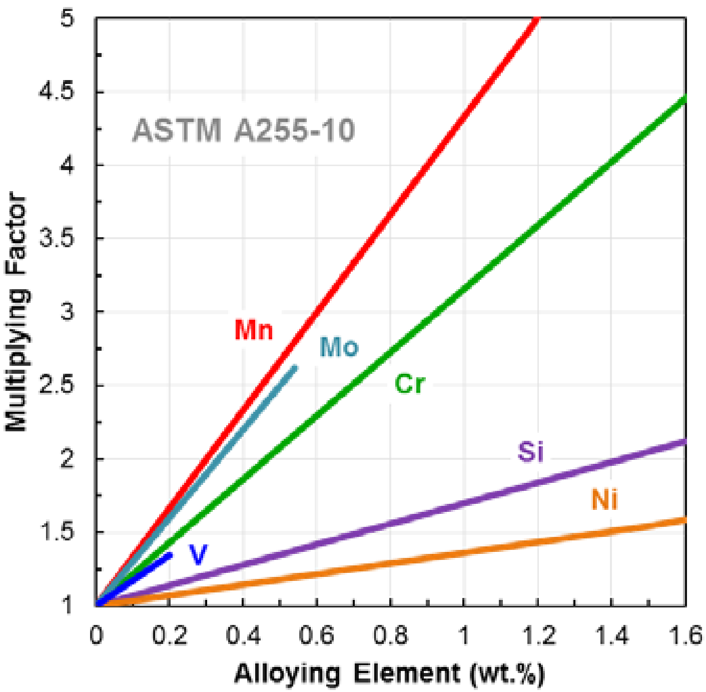

Figure 1. Multiplying factors for most common alloying elements (other than carbon) used to determine ideal diameter in steel. Data plotted from equation provided in ASTM A255-10 [2].

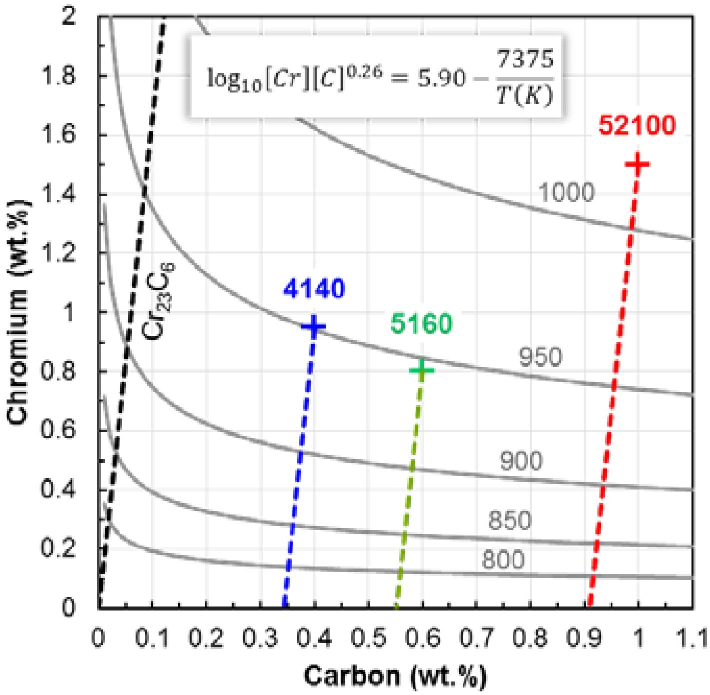

Figure 2. Solubility of chromium carbide ($Cr_{23}C_6$) in austenite with nominal chemical compositions for AISI 4140, 5160, and 52100 indicated. Solubility product data from Ashby and Easterling [4].

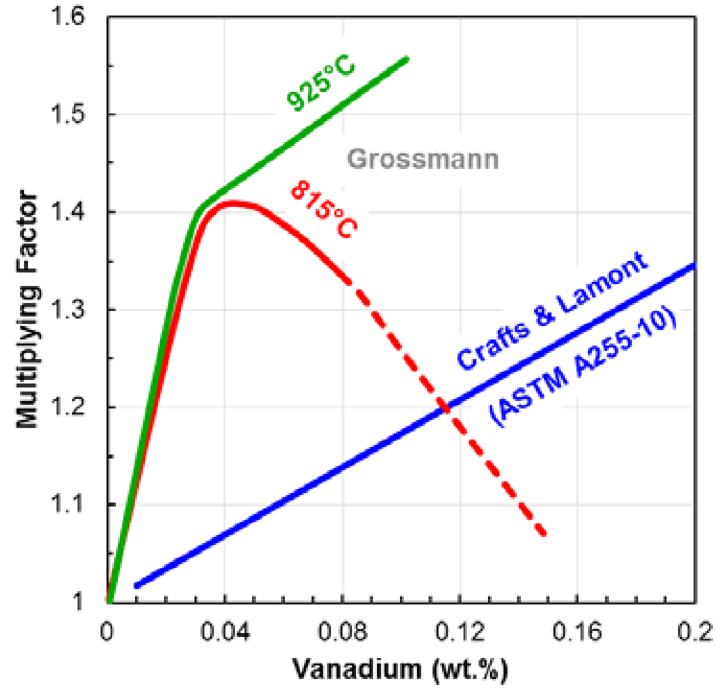

Figure 3. Multiplying factors for calculating the effect of vanadium on the hardenability of steel. Data from ASTM A255-10 [2] and Grossman [3].

Figure 2 shows the solubility of chromium carbide ($Cr_{23}C_6$) in austenite. The nominal compositions for three commonly heat-treated alloys containing chromium (Cr) are indicated: AISI 4140, 5160, and 52100. The dashed line for each alloy represents the precipitation path for $Cr_{23}C_6$ in austenite assuming all Cr has precipitated as $Cr_{23}C_6$. This assumption is not likely accurate, but provides a worst-case scenario for discussion purposes. This data shows that a significant amount of Cr may still be in precipitate form in all three alloys unless austenitized at high temperature, where grain growth will occur. Steels that are hardened from a pearlite or spherodized starting microstructure will have substantially different hardening behavior depending on the carbide size and the austenitizing temperature. This emphasizes the importance of having good quality-control checks and purchase specifications in place to ensure issues do not occur.

Figure 3 shows the influence of vanadium (V), a common microalloying element in steel, on hardenability as a function of austenitizing temperature (from Grossmann [3]) as well as data currently used in ASTM A255 for determining the hardenability of steels [2]. Although the current ASTM standard indicates austenitizing temperature has no dependence, Grossmann showed a clear effect. At V levels typical of modern medium carbon microalloyed steels (approx. 0.08 wt.%), the influence of austenitizing temperature may be significant. Since Grossman's work, the influence of microalloying elements such as V and niobium (Nb) has been investigated in great detail, and the mechanisms found to be relatively complex [5-9]. Therefore, their influence on hardenability is mentioned briefly for awareness only.

CONCLUSION

Fraction of alloy carbides dissolved upon austenitizing may have a significant influence on hardenability, thus requiring careful monitoring of the starting microstructure as well as the chemistry. Each heat-treatment process should be evaluated to determine its acceptable hardenability range to remain a capable process. Influence of both variation in microstructure and chemical composition should be examined independently, if possible.

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