Daniel H. Herring | 630.834.3017 | dherring@heat-treat-doctor.com

Fundamentals of Heat Treating: Ideal Diameter

A quantitative measure of a steel's hardenability is expressed by its DI, or ideal diameter, value. This abbreviation comes from the French phrase "diamètre idéal" and refers to the largest diameter of steel bar that can be quenched to produce 50% martensite in its center (Fig. 1). The quench rate of the bar is assumed to be infinitely fast on the outside; that is, it has sufficient quench severity so the heat removal rate is controlled by the thermal diffusivity of the metal and not the heat transfer rate from the steel to the quenchant. Typically, water or brine provides these infinitely fast quench conditions. The larger the ideal diameter value, the more hardenable is the steel.

DI values are an excellent means of comparing the relative hardenability of two materials as well as determining if it is possible to harden a particular cross section (or ruling section) of a given steel. DI values are influenced by the hardenability (chemical composition) of a material, the grain size and the severity of quench. It is important to note that hardness in steel is determined by carbon content while hardenability is determined by the alloy chemistry, which also includes carbon. Elements such as copper and vanadium play a large role in hardenability. Also, a number of customers today are using boron as an inexpensive, yet effective element, to increase hardenability. Therefore, DI values vary greatly depending on material, from less than one inch (25 mm) for say an AISI 1045 steel to over of 7 in. (178 mm) for an AISI 4140 steel.

A more hardenable steel allows the heat treater to form martensite even in the middle of a thick bar (where cooling rates are slow), whereas a less hardenable steel can achieve a martensitic structure only in thin sections, where the cooling rates are fast. Steels that form martensite in thicker sections are those in which the nucleation and growth of ferrite and cementite is slow and can be avoided. Many solute additions slow down the formation of ferrite, as do larger grain sizes (e.g., ASTM 6 vs. ASTM 8) because fewer grain boundaries are present to act as ferrite nucleation sites. Therefore, alloy additions and grain-coarsening steps are used to make steel more hardenable.

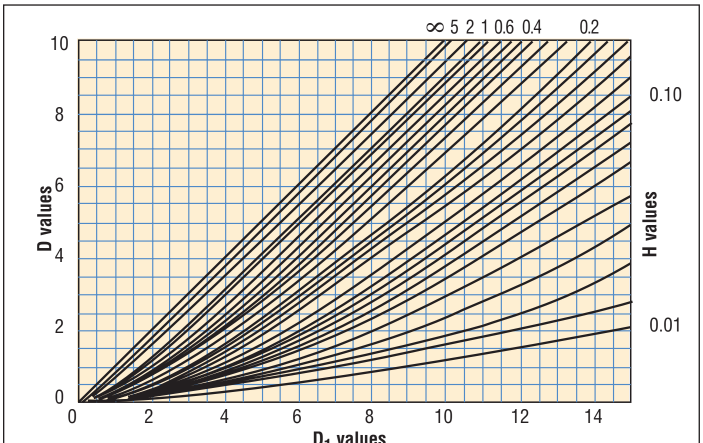

Fig. 1. Relationship between actual critical diameter, or D (the largest size bar that, after being quenched in a given medium, contains greater than 50% martensite.) and ideal diameter, or DI (size of bar hardened to 50% martensite in a "perfect" quench medium) for determining the quench severity (H). In a perfect quenchant, the surface of the bar is assumed to cool instantaneously to the temperature of the quenching medium.

While DI values are calculated for cylindrical bars, the hardenability of various product shapes can be estimated using DI values for equivalent rounds; cooling rates are influenced by surface-to-volume ratios. The hardness of steel having varying amounts of martensite can then be determined by means of a Jominy hardenability test. Jominy data can also be used to estimate the quench severity necessary to produce a given hardness distribution in a particular steel.

Calculating the ideal diameter

Ideal diameter can be calculated fairly precisely if you know the austenite grain size and alloying elements present in the steel of interest. ASTM Specification A255-02 (Standard Test Method for Determining Hardenability of Steel) assumes a grain size of 7 in its calculation because, statistically, most steels are close to this grain size value.

Let's calculate the DI value for a given steel with an ASTM No. 8 grain size and a chemical composition of 0.30%C, 0.20%Si, 0.40%Mn, 0.15%Ni, 0.95%Cr and 0.15%Mo. The ideal diameter is calculated using Equation (1) with individual values listed in Table 1. For elements other than carbon, locate the element percentage in the carbon column and then read across to find the alloy factor under the appropriate element listed.

$$DI = DI\ Jominy \times fMn \times fSi \times fNi \times fCr \times fMo \qquad \text{(Eq 1)}$$

Our calculation then becomes

$$DI = 0.17 \times 1.14 \times 2.33 \times 1.055 \times 3.052 \times 1.45 = 2.10\ \text{in.}\ (53.34\ \text{mm})$$

Thus, it is not possible to harden a cylindrical cross section or equivalent round representing an actual shape greater than 2.1 in. (53 mm) and still obtain at least 50% martensite in the core, no matter what the quenchant is!

Remember that the DI calculation is empirical. There are many different DI equations with each giving slightly different answers so companies often use more than one.

Practical examples

A carburizing grade of steel was found to have low core hardness after final machining. However, this low hardness condition affected less than 20% of the thousands of parts manufactured. All of the material complied with the material specification for chemistry and Jominy hardness at the J8 location. Analysis of DI values calculated from the mill heat chemical composition for each batch predicted which batches were most likely to display low core hardness. A procedure was then developed to check steel mill heat lots for the sub-

Table 1 Alloy factors for calculating ideal diameter [4]

% C	Base ideal diameter (DI Jominy) for ASTM grain size No. shown			Alloy factor (fx): x = element				
	No. 6	No. 7	No. 8	Mn	Si	Ni	Cr	Mo
0.05	0.0814	0.0750	0.0697	1.167	1.035	1.018	1.108	1.150
0.10	0.1153	0.1065	0.0995	1.333	1.070	1.036	1.216	1.300
0.15	0.1413	0.1315	0.1212	1.500	1.105	1.055	1.324	1.450
0.20	0.1623	0.1509	0.1400	1.667	1.140	1.073	1.432	1.600
0.25	0.1820	0.1678	0.1560	1.833	1.175	1.091	1.540	1.750
0.30	0.1991	0.1849	0.1700	2.000	1.210	1.109	1.648	1.900
0.35	0.2154	0.2000	0.1842	2.167	1.245	1.128	1.756	2.050
0.40	0.2300	0.2130	0.1976	2.333	1.280	1.146	1.840	2.200
0.45	0.2440	0.2259	0.2090	2.500	1.315	1.164	1.972	2.350
0.50	0.2580	0.2380	0.2200	2.667	1.350	1.182	2.080	2.500
0.55	0.2730	0.2510	0.2310	2.833	1.385	1.201	2.188	2.650
0.60	0.2840	0.2620	0.2410	3.000	1.420	1.219	2.296	2.800
0.65	0.2950	0.2730	0.2551	3.167	1.455	1.237	2.404	2.950
0.70	0.3060	0.2830	0.2600	3.333	1.490	1.255	2.512	3.100
0.75	0.3160	0.2930	0.2700	3.500	1.525	1.273	2.620	3.250
0.80	0.3260	0.3030	0.2780	3.667	1.560	1.291	2.728	3.400
0.85	0.3360	0.3120	0.2870	3.833	1.595	1.309	2.836	3.550
0.90	0.3460	0.3210	0.2960	4.000	1.630	1.321	2.944	3.700
0.95	-	-	-	4.167	1.665	1.345	3.052	-
1.00	-	-	-	4.333	1.700	1.364	3.160	-

ject parts prior to purchase of raw material to assure that a minimum DI value is maintained.

In another example, a gear manufacturer found it necessary to continually make size adjustments prior to carburizing in an attempt to control distortion and compensate for lot-to-lot material variation. The steel, while meeting specification requirements, was found to be at the extremes of the control range. For this material, typical "H" band steel at two points of Jominy control (J4 and J8) had a range of 12 to 14 HRC from high to low. Even "RH" (restricted hardenability) steel was found to have a 7 to 8 HRC hardness difference at the J4 and J8 positions. The solution was to specify DI values in a narrow control range, and the result was predictable part growth after carburizing and the elimination of a costly manufacturing step.

Where do we go from here?

Today, to better predict lot-to-lot distortion, manufacturers are specifying (and steelmakers are producing) material to extremely tight DI ranges (e.g., 2.0 to 2.3) to ensure achieving size control on critical parts instead of trying to hold a tighter Jominy hardenability range. This is especially the case if no post heat treat operations will be performed. Ideal diameter is an invaluable tool in the heat treater's arsenal. **IH**

Bibliography

- Dale Weires, The Boeing Co., private correspondence
- Scott Hyde, The Timken Co., private correspondence
- Grossman, M.A. and Bain, E.C., *Principles of Heat Treatment,* ASM Intl., 1964
- Totten, G.E. et. al., Limitations of the Use of Grossman Quench Severity Factors, ASM Intl., 1997
- ASM Hdbk, Vol 4: Heat Treating, ASM Intl., p 72-74, 1991

Additional related information may be found by searching for these (and other) key words/terms via BNP Media LINX at www.industrialheating.com: ideal diameter, critical diameter, hardenability, Jominy hardenability test, quench severity.