# Calculated Hardenability for Improved Consistency of Properties in Heat Treatable Engineering Steels

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**Hardenability is one of the most important parameters controlling the heat treated properties of engineering steels. It affects the consistency of response for microstructure, hardness, strength, toughness, and dimensional change (distortion). This study illustrates that a major benefit of controlling hardenability is improving the consistency of dimensional distortion resulting from heat treatment.**

**To facilitate the supply of steels to hardenability limits, especially restricted hardenability, a new technique was developed for the prediction of Jominy hardenability from chemical composition. The technique, termed the "Database Method," uses measured Jominy hardenability and chemical composition data, contained in a database, to calculate the hardenability for a query composition. Using up to ten known steels, selected from the database with compositions closely matching that of the query steel, a small adjustment is made to the measured hardenability of each known steel allowing for the small difference in composition between the query and chosen steel. The final calculated result for the query steel is taken as the average of the various estimates. The basis of the Database Method is explained, and the advantages are illustrated for selecting engineering grades.**

**Keywords** distortion control, hardenability calculation, ideal critical diameter, steel

## 1. Introduction

Calculated hardenability is increasingly used to allow for specification of heat treatable steels with narrower hardenability limits and to improve the consistency of manufacturing heat treatment response product properties and in-service performance. The ability of steelmakers to manufacture steels with narrower tolerances has improved markedly in recent years, assisted by the development of rapid analysis techniques and methods of trimming compositions closer to the aim points. For some steels, the accuracy of measuring hardenability, using the Jominy end quench test, has become a limiting factor in producing a representative assessment of the cast (Ref 1). Consequently, methods of accurately predicting hardenability from chemical composition have become increasingly important to the steelmaker, processor, and end user.

Today, the hardenability of low-alloy heat treatable steels is almost universally measured and specified in terms of Jominy hardenability and a new technique for predicting Jominy hardenability, the "Database Method," has been developed by British Steel plc in conjunction with British Steel Engineering Steels. Using steels produced to hardenability limits, and especially restricted hardenability limits, improves the consistency of response to heat treatment. For example, the consistency of dimensional changes (distortion) resulting from heat treatment can be improved by using steels with optimum consistency of hardenability. This consistency can be improved greatly by using calculated hardenability.

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## 2. Hardenability Calculation Methods

A number of methods for calculating hardenability developed over the past 50 years, include those using empirical composition factors devised by Grossman and others (Ref 2-5) or systems based on more fundamental metallurgical principles (Ref 6). Equations based on multiple regression analysis of composition and hardenability data, from between 100 to 300 heats, are one of the most commonly used methods for calculating Jominy hardenability (Ref 7-12). Relationships were developed describing entire Jominy curves from a single expression (Ref 7) or a wide spectra of steels from a set of equations, one for each Jominy position (Ref 9). The most accurate equations tend to be "grade specific," covering a fairly narrow range of composition and are used commercially in Scandinavia, the United Kingdom, and Germany (Ref 11, 12).

ASTM A 255, based on the Grossman concept of DI, describes a method for determining Jominy hardenability from composition (Ref 13). This calculates the hardness at each Jominy distance as a function of the quenched end hardness and a distance factor ($D_f$) related to the distance from the quenched end, such that:

$$H_j = H1/D_{fj} \quad \text{(Eq 1)}$$

where $H_j$ is hardness to be determined at Jominy distance $j$, $H1$ is hardness at the quenched end (1.5 mm, related to carbon content), and $D_{fj}$ is distance factor for J-distance $j$ (a function of DI with values from ASTM A 255).

This method assumes a fixed Jominy hardenability curve for a steel with a given carbon content and DI, irrespective of the composition balance giving rise to DI, an assumption that is incorrect (Fig. 1).

With the exception of the grade specific regression equations, the accuracy of these calculation methods is limited and well below that required to permit the production of steels to the restricted hardenability requirements being increasingly demanded by end users. This has led to the development of the

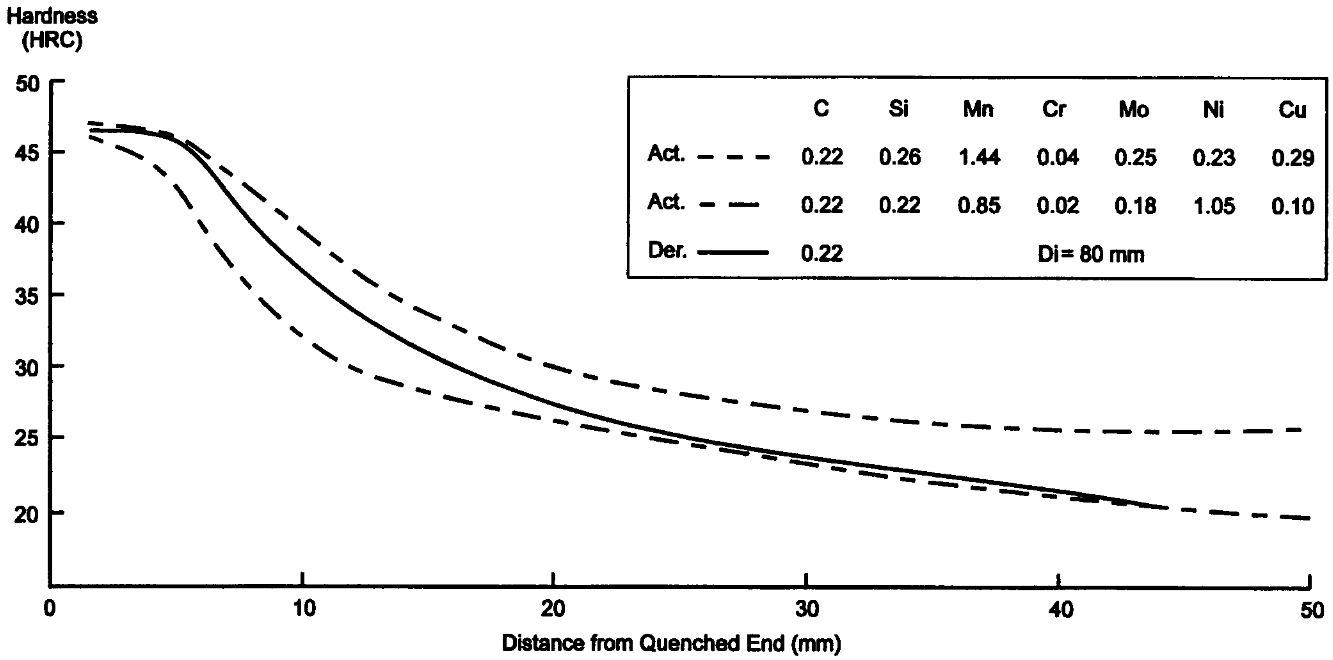


**Fig. 1** A comparison of actual and ASTM A 255 derived hardenability curves (DI = 80 mm)

"Database Method." Although the basis of the ASTM method is used within the Database Method, it is modified to ensure retention of the correct curve shape and hardenability for all types of low alloy steel.

## 3. Database Method

This method uses measured Jominy hardenability and chemical analysis data contained within a random access computer file. The hardenability for a query steel is calculated with reference of up to ten known steels of closely matching composition, five each with lower and higher hardenability, selected from the data file. Selection of the relevant steels involves the use of increasingly narrower composition filters to obtain steels with compositions as close as possible to the query steel. The measured hardenability of each selected steel is adjusted to account for the compositional difference compared with the query steel, and the final result for the query steel is the average of the individual estimates. Thus, the hardenability result obtained is associated with greater confidence in the results than might be obtained from a single hardenability test. While for greater accuracy, ten comparator heats are chosen from the data file, predictions can be made from a smaller number of heats when the population of relevant compositions is small.

## 4. Adjustment Method

Adjusting the hardenability for the heats selected from the data file is based on the method by Field (Ref 5) and used in ASTM A 255 for determining Jominy hardenability curves from DI (Eq 1). For all Jominy distances, the measured hardness for each known steel is used to estimate the hardness for the query steel. This process uses the ratio of the ASTM calculated hardness values for the query and selected steel. Because the steels selected from the data file are compositionally close to the query steel, only small adjustments to hardness are necessary, thereby achieving accurate estimates of hardness for the query steel at each J-distance and maintaining a correct curve shape for the composition. The adjustment routine used, for each selected composition independently, is as follows (from Eq 1):

$$H_{jq} = H1_q / D_{fjq} \quad \text{(Eq 2)}$$

and

$$H_{jk} = H1_k / D_{fjk} \quad \text{(Eq 3)}$$

where $H1_q$ and $H1_k$ = J1 hardness values for the query and selected steel, respectively. (These values are calculated from the carbon contents for the two steels, and for the most accurate predictions, separate relationships between J1 hardness and carbon content should be derived for each test site.)

$H_{jq}$ and $H_{jk}$ = hardness values at distance $j$ for the query and selected steels, respectively, and $D_{fjq}$ and $D_{fjk}$ = distance factors at distance $j$ for the query and selected steels (from ASTM A 255 for the appropriate DI, calculated from composition). The hardness values for the query and known steel at distance $j$ are related via the distance factors and J1 hardness. Thus combining Eq 2 and 3:

$$H_{jq} = H_{jk} \cdot (H1_q / H1_k) \cdot (D_{fjk} / D_{fjq}) \quad \text{(Eq 4)}$$

From this relationship, the hardness of the query steel at all J-distances $j$ can be calculated from each of the known steels

**Table 1(a) Numerical example of the hardenability calculations used in the Database Method**

| Steel | Composition, wt% | | | | | | | | | DI, mm | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | S | Cr | Mo | Ni | Cu | Al | | |
| Query | 0.48 | 0.35 | 1.00 | 0.03 | 0.10 | 0.03 | 0.10 | 0.10 | 0.035 | 45.4 | DI determined from chemical compositin using |
| Selected | 0.47 | 0.22 | 0.80 | 0.025 | 0.27 | 0.03 | 0.14 | 0.19 | 0.029 | 47.9 | ASTM A 255 factors contained in program |

**Table 1(b) Calculation to determine hardenability for query steel**

| | Jominy distance ($j$), mm | | | | Comment |
|---|---|---|---|---|---|
| | 1.5 | 8 | 16 | 32 | |
| Selected steel (measured hardness, HRC), $H_{jk}$ | 58 | 29.2 | 26.6 | 21 | From datafile |
| Calculated hardness at $J$ = 1.5 mm | | | | | |
| selected steel $H1_k$ | 59.2 | ... | ... | ... | Calculated from carbon content using method |
| query steel $H1_q$ | 59.5 | ... | ... | ... | incorportated in program |
| Distance factor at distance $j$ | | | | | |
| selected steel $D_{fjk}$ | 1 | 1.61 | 2.19 | 2.86 | Determined from DI and incorporated in program |
| query steel $D_{fjq}$ | 1 | 1.67 | 2.28 | 2.97 | |
| **Using equation** $H_{jq} = H_{jk}\left(\frac{H1_q}{H1_k}\right)\left(\frac{D_{fjk}}{D_{fjq}}\right)$ | | | | | |
| Calculated hardness for query steel $H_{jq}$ | 58.3 | 28.3 | 25.7 | 20.3 | (a) |

(a) Values calculated with respect to 10 known steels, selected from datafile, producing 10 estimates of the hardenability for the query steel. Final hardenability for the query steel average of the 10 estimates.

**Table 2 Mean errors and standard deviation of errors for hardenability results determined using the Database Method**

| Steel grade | Jominy distance, mm | | | | | | | | | | | | | Entire dataset |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.5 | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 20 | 25 | 30 | 40 | 50 | |
| 0.2% C, 0.8% Cr | | | | | | | | | | | | | | |
| $\bar{X}$ (HRC) | −0.01 | −0.01 | −0.05 | −0.04 | −0.04 | −0.04 | −0.02 | 0.01 | −0.17 | ... | ... | ... | ... | −0.03 |
| $\sigma$ (HRC) | 0.92 | 1.18 | 1.72 | 1.45 | 1.15 | 1.16 | 1.31 | 1.54 | 1.31 | ... | ... | ... | ... | 1.32 |
| N | 60 | 60 | 60 | 60 | 59 | 59 | 58 | 58 | 42 | ... | ... | ... | ... | ... |
| 0.4% C, 1% Cr, 0.2% Mo | | | | | | | | | | | | | | |
| $\bar{X}$ (HRC) | −0.03 | −0.02 | −0.01 | −0.02 | −0.04 | −0.05 | −0.05 | −0.04 | −0.08 | −0.11 | −0.11 | −0.12 | −0.09 | −0.06 |
| $\sigma$ (HRC) | 0.89 | 0.80 | 0.98 | 1.15 | 1.46 | 1.63 | 1.72 | 1.88 | 1.98 | 2.07 | 1.89 | 1.81 | 1.78 | 1.61 |
| N | 239 | 239 | 239 | 239 | 239 | 239 | 239 | 239 | 239 | 236 | 221 | 215 | 204 | ... |

Error is calculated hardness, measured hardness. $\bar{X}$ is mean error. $\sigma$ is standard deviation. N is number of datasets.

selected from the data file (Table 1). Independent determinations are made for each of the known steels and averaged to produce a final estimate of hardenability for the query steel. Averaging the result from a number of estimations minimizes the error associated with any individual result for the known steels and improves confidence in the accuracy of the final estimate of the calculated hardenability for the query steel.

## 5. Characteristics of the Database Method

The data file, for use with the Database Method, can be compiled from any source of measured hardenability and chemical analysis data. For the best results, this data should be produced from a single source to eliminate interlaboratory bias. However, the working of the method is independent of data source.

Calculation of hardenability produces a considerable reduction in error compared with measurement by a single test. For example, comparing the results from ten heats of SAE 8620 with DI values in the range 51 to 53 mm (Fig. 2), the range of hardness at J 5 mm was reduced from 5.5 to 1.7 Rockwell C hardness (HRC) by eliminating hardness testing error. Because multiple estimates are made of the hardenability, the procedure is analogous to performing several tests and averaging the result.

To illustrate the performance of the Database Method, hardenability curves were calculated for populations of 0.2% C-1% Cr case carburizing steels and 0.4% C-1% CrMo direct hardening steels produced by one steelmaker. The data file contained a total of 299 heats, and the hardenability was calculated for each heat, although when the hardenability of a particular heat was being determined, selection of that particular data was not permitted. The difference between the calculated and measured hardness result, for each heat at each J-distance, was determined, and the mean difference (error) and standard deviation of errors was evaluated for all J-distances and for the entire grade, showing the accuracy in the results (Table 2).

The overall accuracy in the result varies with steel type and J-distance agreeing with the observation that the hardenability of some grades is inherently more variable than others. For example, the maximum standard deviation of error for the 0.2% C-1% Cr steel occurred between J 5 to 7 mm, the location showing the most rapid change of hardness. The accuracy of the results from the Database Method is comparable with published regression equations (Fig. 3) for 1% Cr steels.

The software for the Database Method can be PC-based and permits the operator to examine all aspects of the data used to derive the hardenability for the query steel. It is suitable for a wide range of heat treatable steels because predictions can be made from a small amount of data for a grade, and the results are reliable across the composition ranges for existing data. In this respect, it is superior to methods based on regression equations, which for accurate predictions need to be grade specific and for which predictions become increasingly less reliable as compositions approach the data extremes.

The steelmaker, processor, and end user all benefit from prediction and tighter control of hardenability. The steelmaker benefits from:

- More rapid and representative assessment of heat hardenability than from a test
- Elimination of pre-despatch testing
- Potential for use in-line during steelmaking, where it can be used to account for variation in residual elements, thus allowing the steelmaker to adjust composition for improved consistency of hardenability control
- Periodic monitoring of prediction errors to detect long term trends influencing hardenability, such as changes in residual element levels

The processor benefits from improved consistency of intermediate properties, response to processing, and response to final heat treatment, minimizing, for example, distortion variability. The end user benefits from improved consistency of final component properties and performance.

Almost any prediction technique can be used to rank steels in terms of hardenability. However, the Database Method is useful when the prediction is required to provide an accurate assessment of the true hardenability. It can be used across a wide range of low alloy grades providing an assessment from a small data set of steels of similar composition. The method

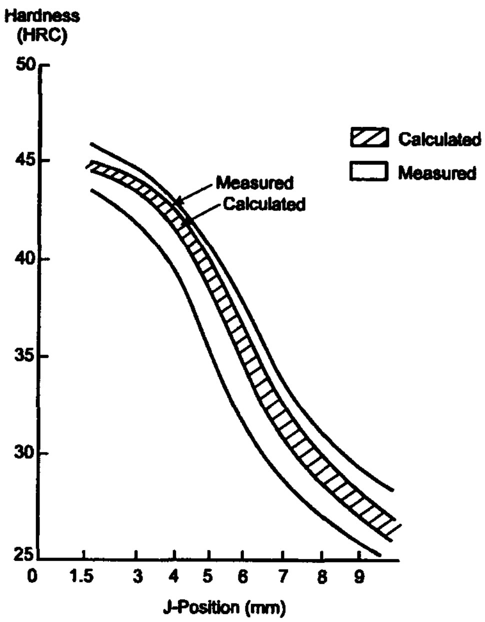


**Fig. 2** Reduction of scatter obtained by calculating hardenability for ten heats of SAE 8620 (DI range 51 to 53 mm)

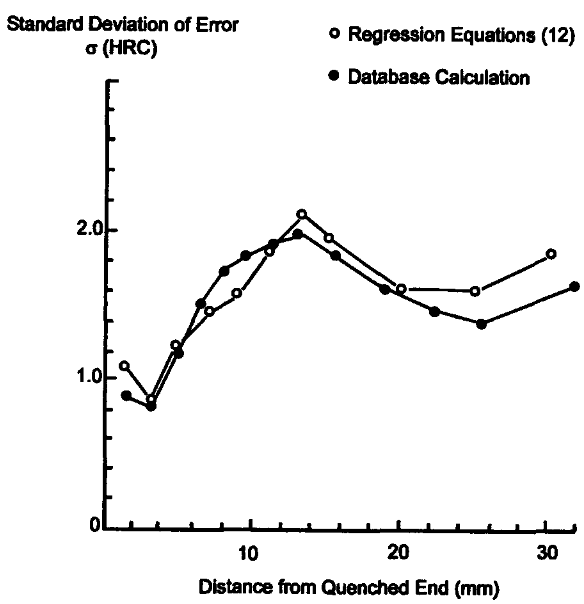


**Fig. 3** Comparison of standard deviation of error for hardenability predictions performed using the Database Method and published regression derived equations (Ref 12) using steel 0.2-0.4% C-0.8% Cr

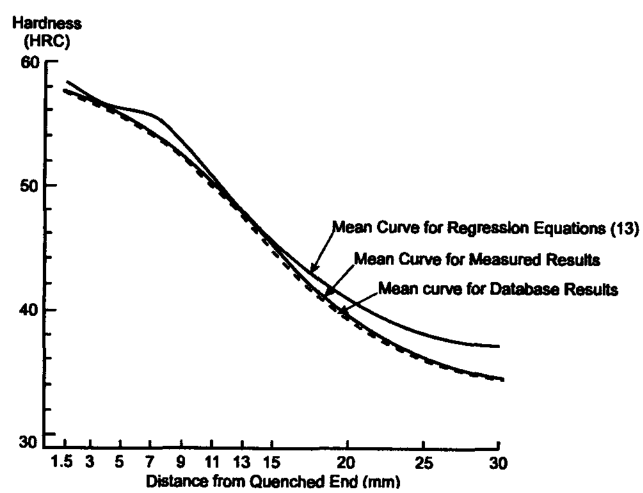


**Fig. 4** Comparison of measured hardenability with calculated results obtained using the Database Method and from published regression derived equations (mean hardenability from 30 heats of 0.20% C-0.8% Cr steel). (Note the difference in curve shape.)

seeks to use ten closely matched steels from the database to predict the hardenability of a query steel. This has been found to be optimum, and there is little improvement in accuracy from taking a larger population. Predictions can be made from a smaller population when there is insufficient measured data and, although accuracy of the results may be slightly reduced, this can be reported to the operator. In comparison, it should be noted that a population in excess of 100 heats is required to produce reliable regression equations for a steel grade or closely related steel grades.

A major benefit of using the Database Method is the retention of a true curve shape. Figure 4 illustrates this for a 0.2% C-0.8% Cr steel using data from 30 heats. The calculated hardenability curve determined from published regression equations varied slightly from the mean curve determined by measurement, while the result obtained from the database retained a true representation. This difference may be of little consequence when the objective is to assess the relativity of a particular steel type. However, it can be important for development purposes where true hardenability levels are required to evaluate different steel types or in production where the system is used for release purposes or to derive aim points.

Calculation accuracy can be limited by the reliability of the data from which the prediction is derived, although predictions from a composition using multiple estimates minimizes problems due to hardness testing error. If the processor or end user used a multi-source of material, a data file can be built up for the composition, hardenability data supplied, and a representative hardenability can be calculated from such a composite file, although the best consistency is obtained from a single source.

To date, the Database Method has only been evaluated for use with carbon and low alloy steels. However, the method has potential for use with boron steels.

## 6. Heat Treatment Distortion

Dimensional change or distortion resulting from heat treatment is an inevitable fact. While such dimensional changes can create problems, in gear manufacture for example, this is often accommodated by machining to a suitable "green" size so that the dimensions move towards those required after heat treatment. However, with the accuracy required in modern components (e.g., gears), variability of distortion can be a significant problem.

There are a number of factors that affect variability. For example, quench rate is important, and temperature gradients introduced during quenching can introduce distortion into steels that do not transform (Fig. 5). This is compounded in heat treatable steels where variation within a quench system can give rise to differences in microstructure and evolution. Limiting the range of hardenability for steel production will improve the consistency of these factors and hence, the variability of distortion from heat to heat (Ref 14).

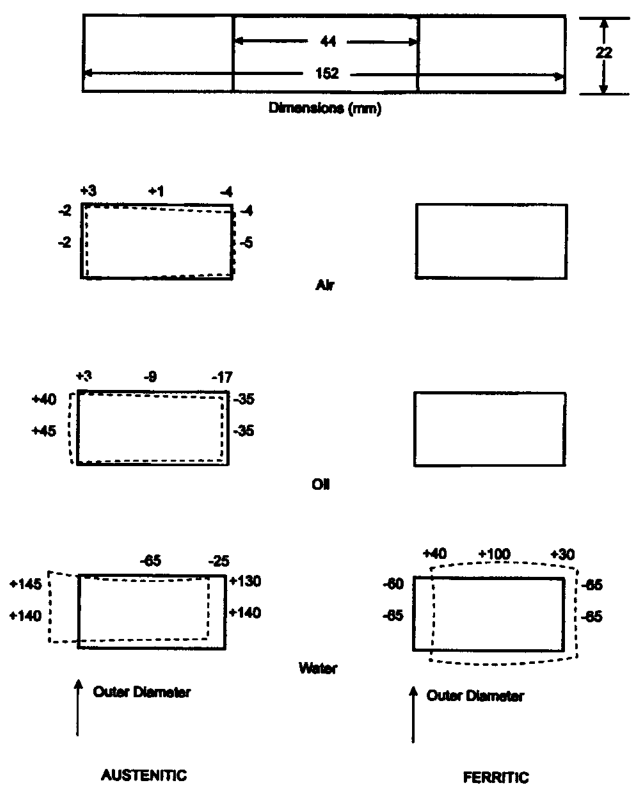


**Fig. 5** Change of dimensions due to quench rate. (stainless steels showed no transformations or change in dimension diameter/thickness mm × $10^3$)

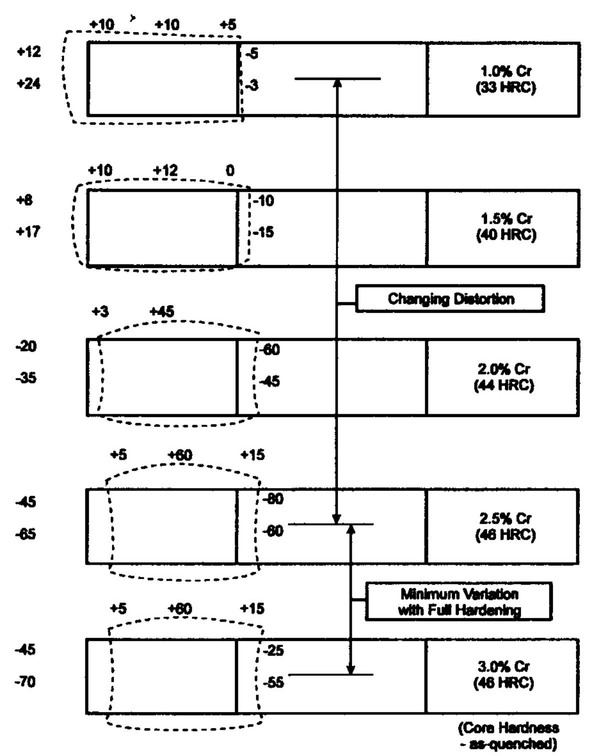


**Fig. 6** Effect of hardenability on dimensional change (mm × $10^3$). Heat treatment consists of carburize at 925 °C, cooling to 840 °C, and an oil quench.

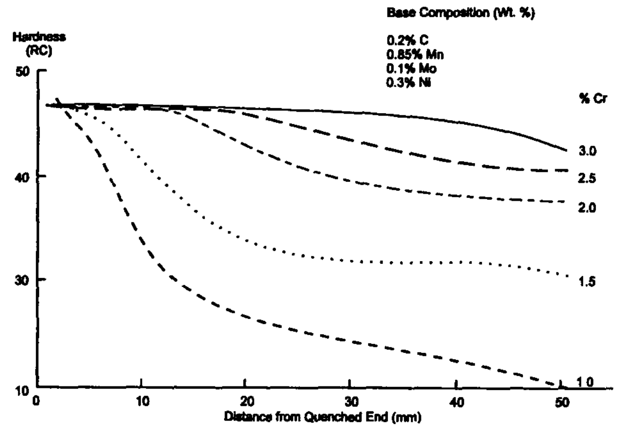


**Fig. 7** Effect of chromium on the Jominy hardenability for steels in Fig. 6

Figure 6 shows an example of the change in distortion characteristics, with respect to hardenability for a steel with a constant base composition and increasing chromium content (hardenability). Washerlike steel discs were produced to the dimensions shown in Fig. 5, carburized, and quenched in oil. Prior to heat treatment, steps were taken to minimize other possible residual stresses that may have been produced during manufacture. Before and after heat treatment, the discs were measured to an accuracy of $\pm 2 \times 10^{-4}$ mm. The distortion changed systematically with increasing hardenability. As the chromium content was increased beyond that needed to produce full hardening, there was little further dimensional change.

Although the variation in hardenability of the tested steels was relatively large (Fig. 7), the results illustrate its significant effect. Where the section size was sufficient to produce a variation in the as-quenched microstructure with a change in hardenability, this was accompanied by a variation in dimensional change. There was minimal variation in dimensional change with increasing alloy content beyond that required to produce full martensitic hardening of the section.

The observation concluded from this work is that distortional variability, from heat to heat, can be minimized by using steels with minimum variation in hardenability. Today, many steels are produced to restricted hardenability. This parameter can be assessed by calculation, providing an accurate representation of a heat. Thus, techniques for predicting hardenability can be seen as an additional tool for control of distortion.

## 7. Conclusions

Calculation techniques can be used to provide a good representation of hardenability:

- The Database Method can be used because it calculates hardenability from existing data and provides a method of describing the hardenability of steels of different types with a high degree of accuracy.
- Compared to other systems, it is reliable for a wider range of compositions and can make accurate predictions when only a limited amount of data on similar steel types is available.
- It is applicable to the full range of steels for which Jominy testing is performed, including, in principle, boron treated grades.
- Furthermore, variability in distortion, which is a major problem for the manufacturers of parts such as gears, can be minimized by using steels produced to closely controlled hardenability limits, a factor that is assisted by the availability of accurate calculation systems.

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