Carburizing steels: Hardenability prediction and hardenability control in steel-making

Technical Report Archive

CARBURIZING STEELS: HARDENABILITY PREDICTION AND HARDENABILITY CONTROL IN STEEL-MAKING

Ovako has an extensive R&D since many years, an area that now is in an even higher intensity. Some of the R&D work is published in our technical reports.

Due to that Ovako of today has had a number of different company names and used various trade marks we have until now chosen to not have these reports publicly available. However, many of these technical reports contain valid data about material and steel grades that we still promote, but with other names etc.

The following Technical Report from 1984 is about how accuracy in steel making may have an effect on processes at customer and final product properties of Carburizing steel.

Data and processes in this report represent state of art at time of publishing, but is still a technology we use in our steel works to control hardenability. There is also a later technical report about this theme, see Ovako Archive technical report 7/1986.

Concerning Hardenability prediction of today. The Ovako Heat Treatment Guide is the modern tool we now offer.
See https://steelnavigator.ovako.com/heat-treatment-guide/

In this Technical Report there is used the following Company names and trade marks that no longer is used by Ovako AB.

SKF Steel; This company name is no longer used. The organization is now part of Ovako AB.

SKF; Is today a separate company with no link to Ovako.

Technical Report 3/1984

Carburizing Steels: Hardenability Prediction and Hardenability Control in Steel-Making

Thore Lund

SKF Steel

Abstract

Hardenability is a very important factor in modern metalworking.
Hardenability, and its control, are of great importance for manufacturing economy and product performance.
Hardenability variation depends largely on the steelmaking practice used.
Consistent hardenability is only attained if the steelmaking process is capable of providing a homogeneous steel with a consistent chemical composition from heat to heat. Extensive process know-how is a prerequisite.
Steel users generally try to limit hardenability variations by using narrow analysis limits for the various alloying elements of a specific steel grade. Nevertheless, large variations arise, even when using strict chemical analysis specifications, because the alloying elements each add to the overall hardenability.
SKF Steel has developed an on-line computer-based hardenability control system for the production of carburizing steels. This system provides a direct link between the steel user (who simply specifies the hardenability desired for a given steel grade) and the steel-making process (which is on-line controlled to produce the steel at the desired hardenability).
This report reviews the concept of hardenability, describes methods for hardenability control and outlines the SKF Steel Extra Hardenability Control System for carburizing steels.

Introduction

Industrial hardening may be divided into two main categories:

— Surface (case) hardening;
— Through hardening.

Surface hardening can be subdivided into two main categories:

— Methods where carbon (and sometimes nitrogen) are diffused into the surface layer and the component subsequently is quenched.
— Methods where the surface is locally heated (for example by induction) and quenched.

Through-hardening is mainly done by one of two methods:

— Martensite hardening, which produces mainly martensite through the entire section.
— Austempering (or bainite hardening), which provides a mainly bainitic structure.

Common to all methods is that it is advantageous to maintain constant process parameters from batch to batch and to have good prior knowledge of the dimensional changes during heat treating.
The hardenability of steel depends largely on its chemical composition. This has long been known and many methods and models have been developed for the prediction of hardenability from composition.
The purpose of the development work reported here has been to bring hardenability control to the source of hardenability — the steelmaking operation.

Hardenability specifications

The most common way to specify hardenability for carburizing steels is defined in the ASTM specification A304-79 (1).

ASTM A304, "Alloy Steel Bars Subject to End-Quench Hardenability Requirements," provides the steel user with three parameters:

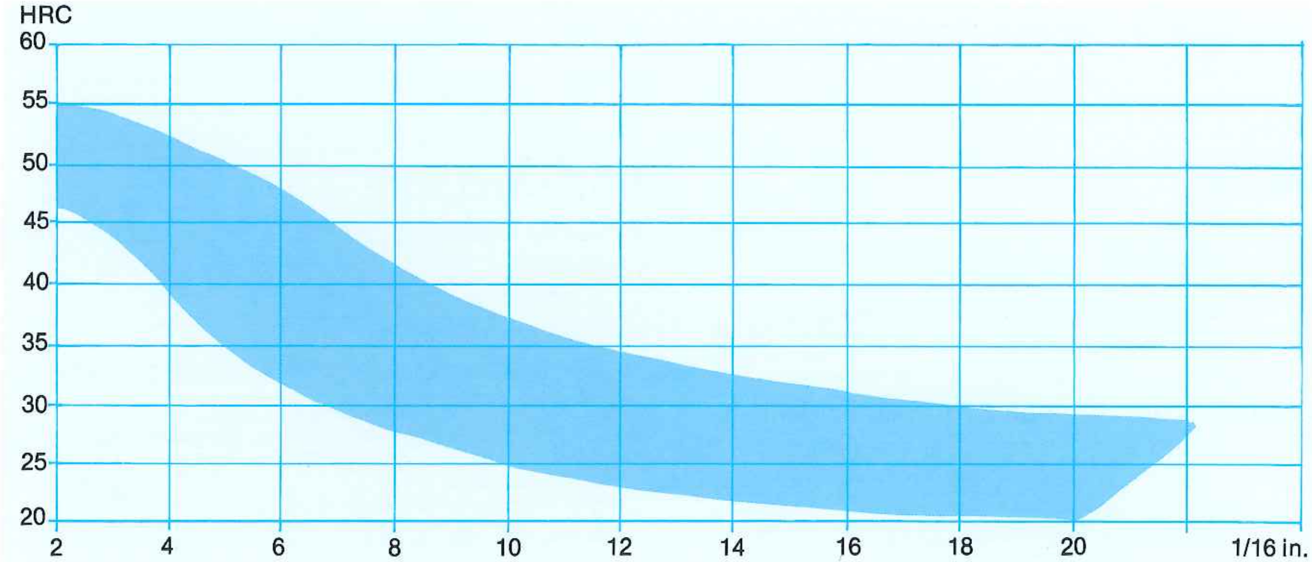
- Chemical composition limits for a number of carburizing and harden-and-temper steel grades;
- Hardenability bands for these steel grades encompassing a maximum and a minimum end-quench (Jominy) curve;
- A method of defining the desired hardenability for a given steel grade.

by the hardenability bands for the steel grade. For SAE 8620H, for example, the permissible variation range is:

Jd (1/16 in.):	1	2	3	4	5
HRC (max-min):	7	10	14	12	11

Steel users with high hardenability demands use specifications with stricter hardenability limits than those specified in A304. SKF Steel has supplied such variants for some time.

Fig. 1 From: ASTM A304-79, 1982 Annual Book of ASTM Standards, Part 5, 1982.



	Method	Points on Charts	Example — End-Quench Hardenability
A	Minimum and maximum hardness values at a designated distance	A-A	HRC 43 to 54 at J3
B	A hardness value at minimum and maximum distances	B-B	HRC 39 at J4 minimum and J9 maximum
C	Two maximum hardness values at two designated distances	C-C	HRC 50 at J5 maximum HRC 34 at J12 maximum
D	Two minimum hardness values at two distances	D-D	HRC 36 at J5 minimum HRC 21 at J16 minimum
E	Any minimum hardness plus any maximum hardness	E-E	HRC 32 at J6 minimum HRC 37 at J10 maximum

Figure 1 shows how ASTM A304 is used provide information on hardenability.

The most common way to define end-quench hardenability is to specify:

a) the steel grade;

b) the hardenability as:
- a maximum and a minimum hardness at the surface (at 1/16 in. — 1.5 mm);
- and a maximum and minimum hardness at one other selected end-quench distance.

Maximum and minimum hardnesses are defined

SKF Steel hardenability specifications

The SKF Steel Extra Hardenability Control Standard (2) allows steel users to specify hardenability demands more directly and accurately.

The customer (ordering) specification comprises:

- The steel grade with the chemistry requirements defined in ASTM A304.
- The end-quench (Jominy) curve desired by definition of up to three points on the curve.

An example of such a specification is:

— Steel grade:	SAE 8620H	
— Hardenability:	Jd (1/16 in.)	HRC
	1	47
	3	40
	6	28

For Extra Hardenability Controlled SAE 8620H SKF Steel applies the following procedure:

a) The hardenability specification is first checked to ensure that the demands being placed are attainable using the chemical analysis limits for SAE 8620H. If not, an alteration in the specification is suggested.

b) The SKF Steel hardenability prediction model is used to determine the chemical composition within the SAE 8620H limits which will fulfill the specified Jominy curve.

c) The steel produced must not deviate from the demands determined in a) by more than a fixed amount. For SAE 8620H, this amount is +/— 1.5 HRC at any end-quench (Jominy) distance below 12/16 in.

Hardenability prediction

The most frequently used hardenability predictors are based on multiplying factors for carbon, grain size and the alloying elements used. These multiplying factors are based on Grossman hardenability tests and give the critical diameter for the steel — defined as the bar section which will produce 50 percent martensite at the center in an ideal quench.

Generally, the critical diameter (D_i) can be computed as:

$$D_i = F_C \cdot F_{Si} \cdot F_{Mn} \cdot F_{Cr} \cdot F_{Ni} \cdot F_{Mo}$$

The multiplying factor for various alloying elements has been analyzed in a number of publications (3, 4, 5, 6, 7, 8).

Figures 2—6 give compilations of data published. The bands indicate the range of the multiplying factors obtained in these investigations.

Another method of predicting hardenability is based on end-quench (Jominy) tests.

One commonly-used predictor was developed by Just (9), and is based on regression analysis of Jominy data.

Just's regression is applicable for end-quench (Jominy) distances larger than 4/16 in. (6.4 mm):

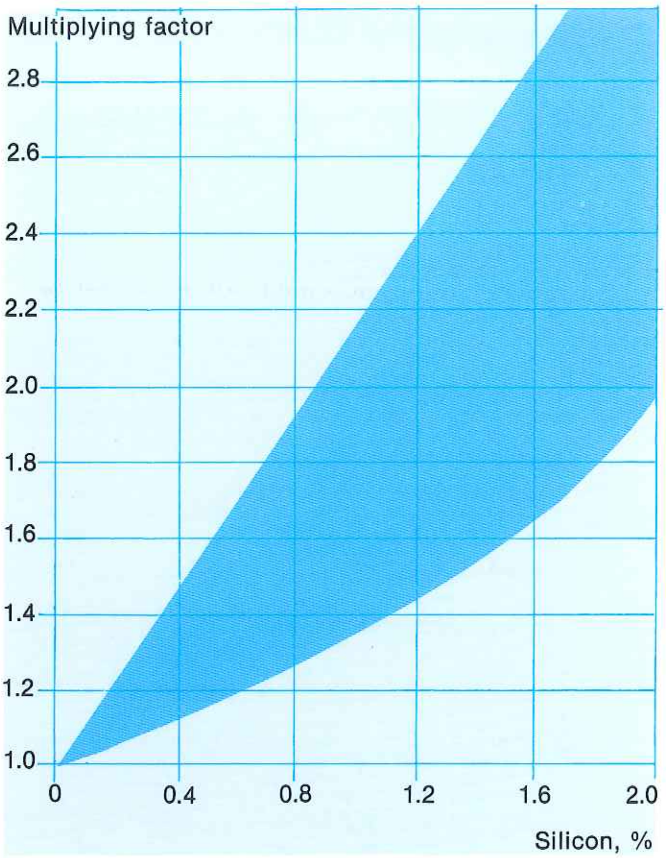


Fig. 2 Multiplying factor for Si.

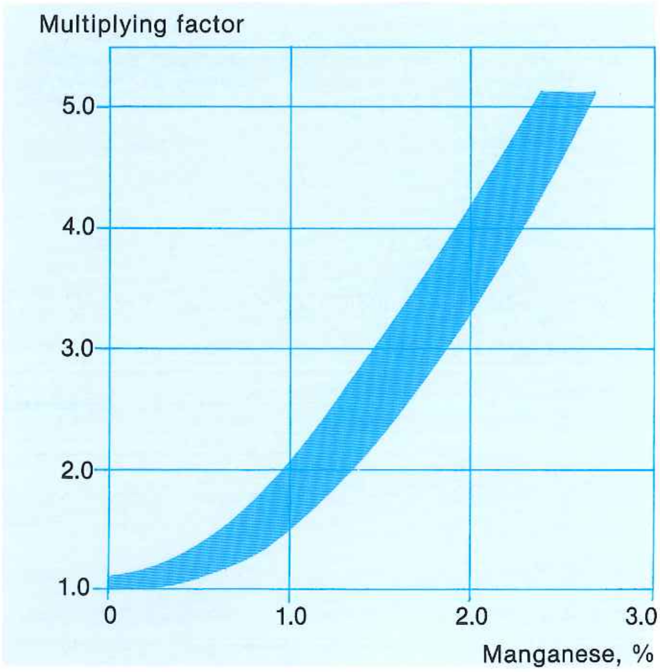


Fig. 3 Multiplying factor for Mn.

$$J_D = 88 \cdot \sqrt{C} - 0.0135 \cdot D^2 \cdot \sqrt{C} + 19 \cdot Cr + 6.3 \cdot Ni + 16 \cdot Mn + 35 \cdot Mo + 5 \cdot Si - 0.82\, K_A - 20 \cdot \sqrt{D} + 2.11 \cdot D - 2$$

J_D = Hardness in HRC at the end-quench distance D.
D = The end-quench (Jominy) distance in 1/16 in.
K_A = The ASTM grain size.
C, Cr, Ni, Mn, Mo, Si are in weight (%).

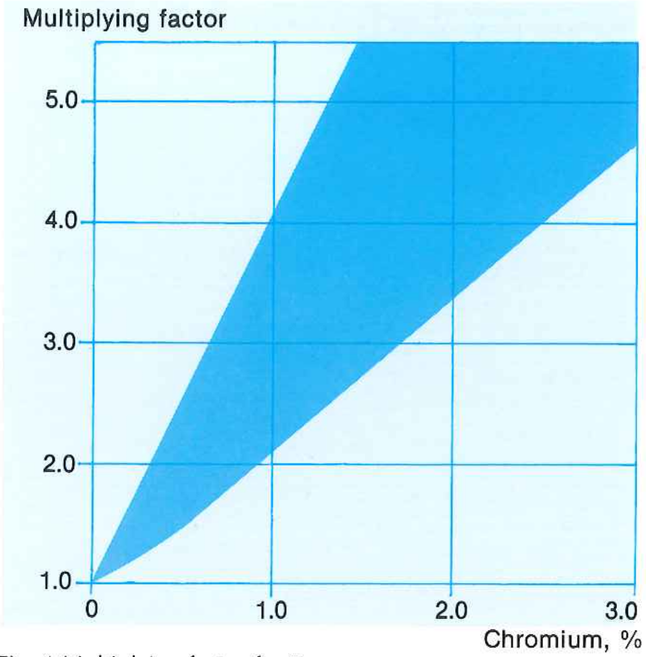


Fig. 4 Multiplying factor for Cr.

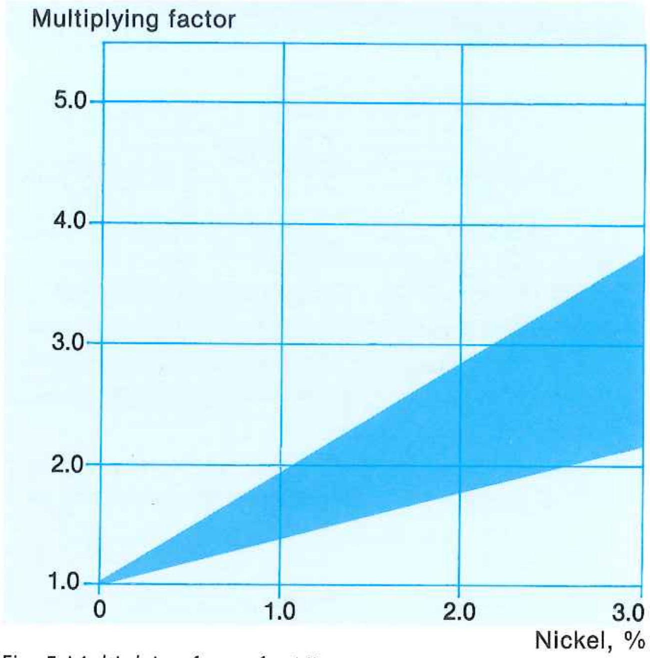


Fig. 5 Multiplying factor for Ni.

The Just predictor is frequently used, but its prediction power is limited (10). Similar results have been obtained at SKF Steel.

Just's predictor has an obvious advantage in that it applies simple calculus. But it also has two distinct drawbacks: it presupposes that the alloying elements have a constant hardenability contribution over all Jominy-distances; and it does not consider residual elements.

For carbon, the Just predictor indicates changes in the carbon factor, but the variation with end-quench (Jominy) depth is very small.

SKF Steel has developed a hardenability predictor for end-quench (Jominy) testing (11). It was developed by performing regression analyses of test data from end-quench tests of a large number of standard production heats of carburizing, harden-and-temper and through-hardening steels.

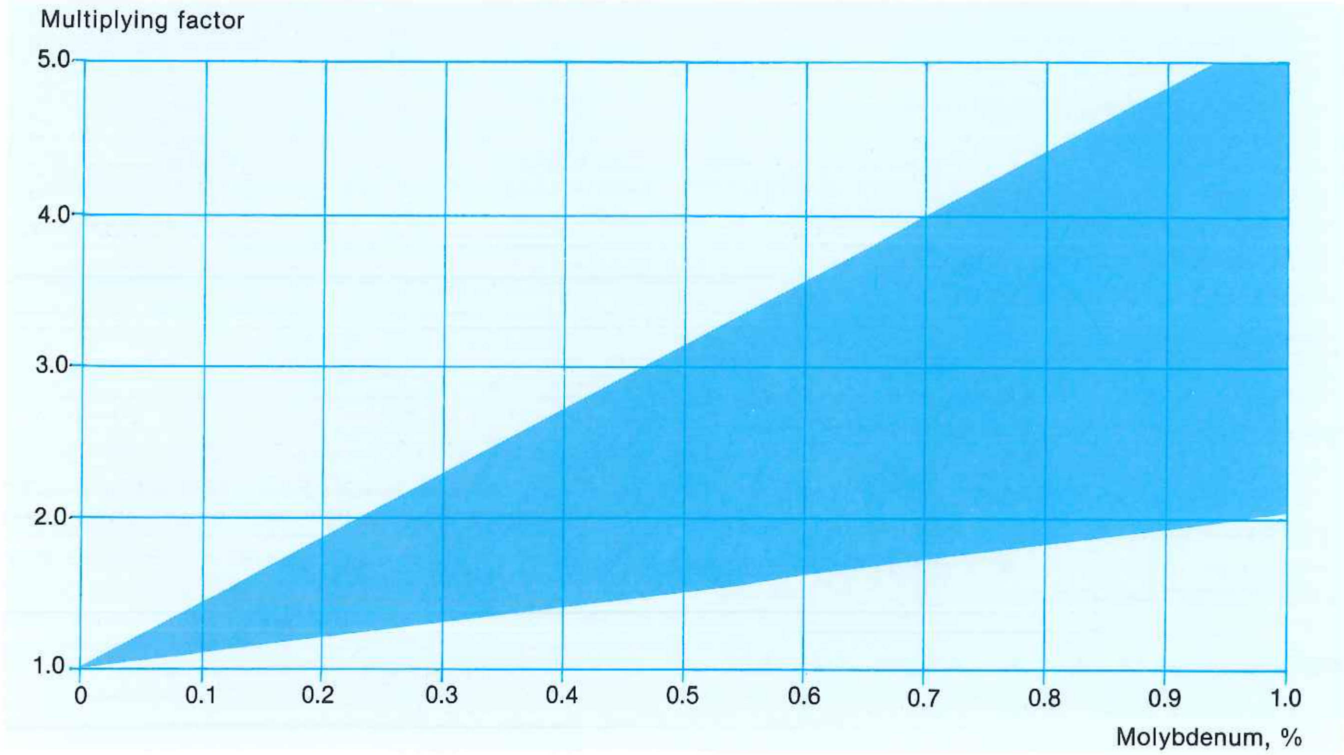


Fig. 6 Multiplying factor for Mo.

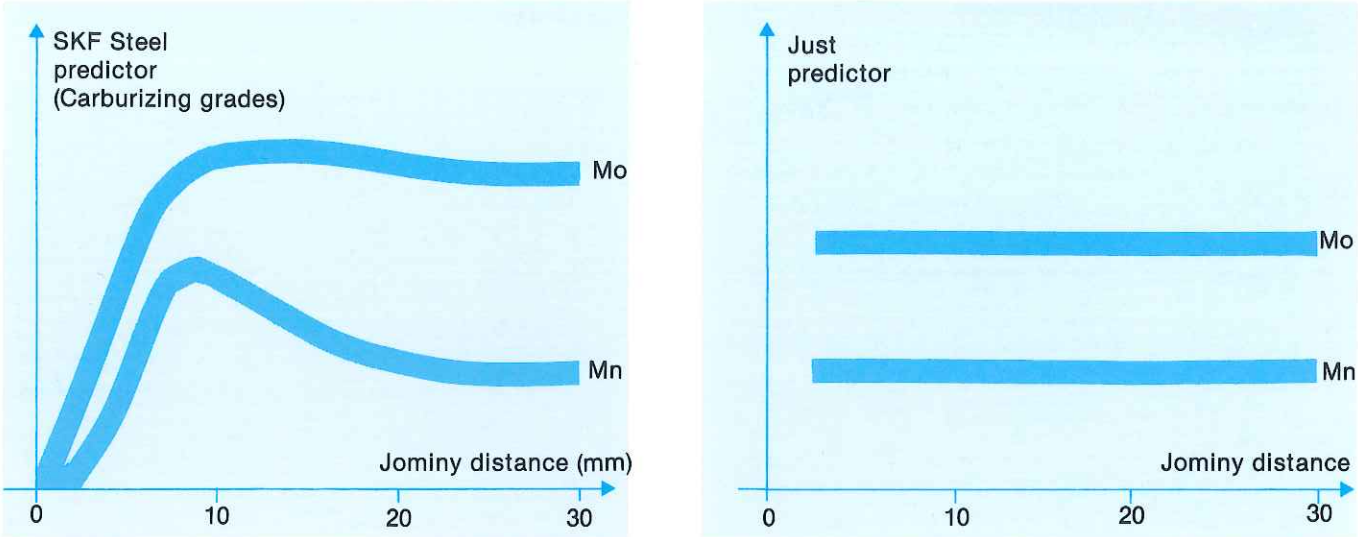


Fig. 7 Hardenability contributions of Mn and Mo in the SKF Steel and Just models.

Separate regression equations were obtained for each of the three steel types and separate regressions were derived for a number of end-quench distances. Thus, the predictor yields a set of distinct points on the end-quench curve for the steel grade selected.

The steel grades included in this analysis were specifically selected to encompass the range of carburizing steels currently in use. The same selections were made for harden-and-temper, and through-hardening steels.

Figure 7 shows a comparison of the hardenability factors derived for Mn and Mo according to the SKF Steel model for carburizing grades and Just's model.

Alloying elements (including carbon) have a variable effect on hardenability in relation to the different end-quench (Jominy) distances.

The ideal diameter can also be determined with the SKF Steel model by applying the relationship between 50 percent martensite hardness and carbon content (12) and Jd at 50 percent martensite (10).

Grain size

Aluminium deoxidation is normally used in modern high quality steelmaking.

Aluminium deoxidation in combination with an efficient separation of the deoxidation products (in an ASEA-SKF ladle furnace, for example) allows for the production of steel with very low amounts of oxidic non-metallic inclusions and consistent fine-grain treatment.

The grain size of SKF MR carburizing steels is maintained within narrow limits during thermal processing.

This has significantly reduced the importance of grain size in hardenability prediction.

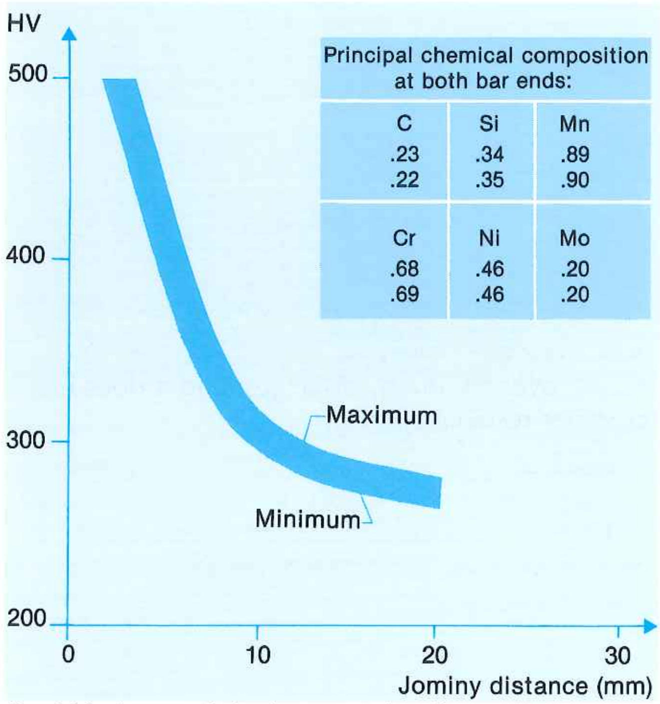


Fig. 8 Hardness variation in 20 samples of SAE 8620 taken from one bar.

Variability in Jominy-testing

End-quench (Jominy) tests are complicated by the large number of critical process steps involved. Variations in sampling, sample preparation, austenitization, quenching, specimen grinding and hardness testing all contribute to a fairly large experimental scatter.

Figure 8 shows the result of one test conducted at SKF Steel (13). One bar of grade SAE 8620H was selected and the chemical composition at both ends was determined.

The bar was divided into 20 Jominy samples and standard Jominy tests were run.

Similar results (a random scatter of about +/— 2 HRC) have been reported by Jernkontoret (14). When the same steel is tested at different laboratories, scatter increases to around +/— 3 to +/— 5 HRC (15); *Figure 9.*

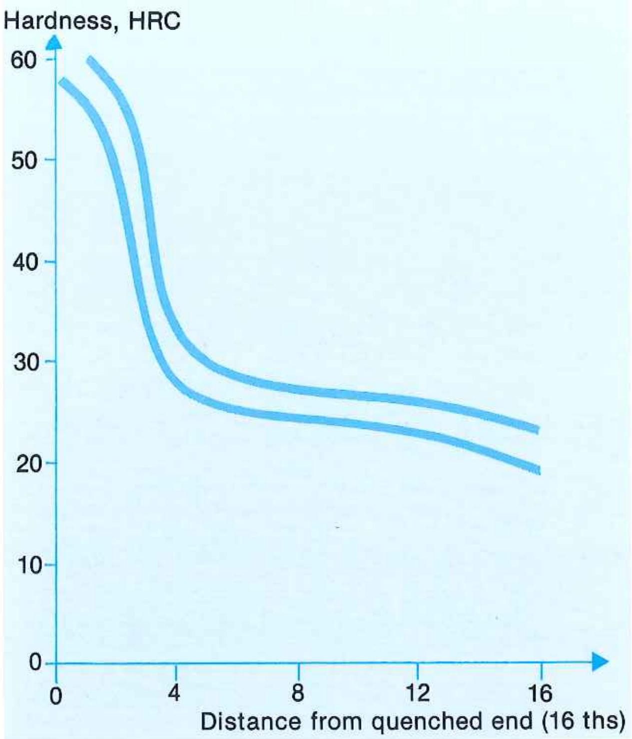


Fig. 9 Scatter bands illustrating reproducibility between different organisations using the standard Jominy system.

Variations in hardness testing are significant in themselves — around +/— 2 HRC in Rockwell tests and about +/— 1 HRC for Vickers tests (15). Obviously, a substantial number of tests must be used as the basis for regression models of end-quench curves.

The SKF Steel model

The SKF Steel model has been in *"off-line"* use for some time. Data on the deviations between predicted and measured Jominy-data have been compiled.

Figure 10 shows the absolute difference between predicted and measured Vickers hardness levels (2σ) for SAE 8620H. As a comparison, the variation range (2σ) obtained in the tests done on one single bar is given in *Figure 8.*

As shown, the deviations obtained with the SKF Steel model are well within the experimental scatter of end-quench testing.

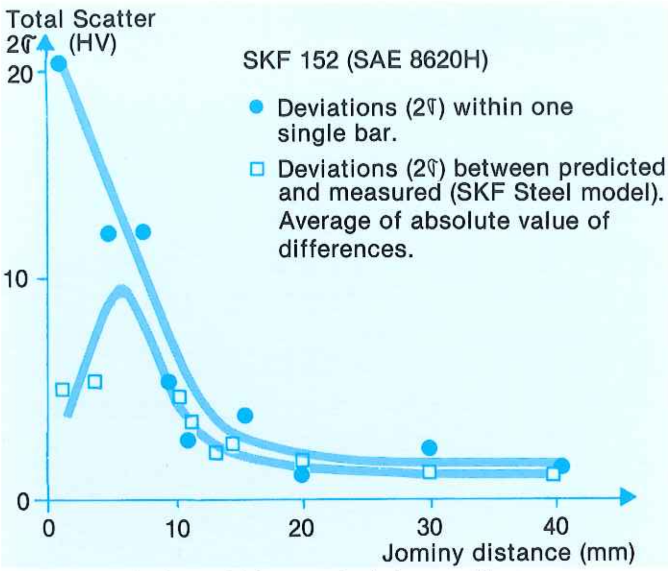


Fig. 10 Deviations within one single bar, and between measured and predicted end-quench data.

Hardenability variations

Many material parameters are affected by variations in hardenability.

Two such parameters are particularly important: strength and dimensional changes during heat treatment.

Figure 11 shows the variation of tensile strength for SAE 8620H when using ASTM A304 and the SKF Steel Extra Hardenability Controlled variant of SAE 8620H. The hardness variations at the Jominy-distance of 5 mm have been used as a basis of comparison.

Figure 12 shows the dimensional change with the core hardness for a steel similar to SAE 4118H (16).

As in *Figure 11,* hardness variations at a Jominy-distance of 5 mm have been used for comparison of ASTM A304 and SKF Steel Extra Hardenability Controlled SAE 4118H.

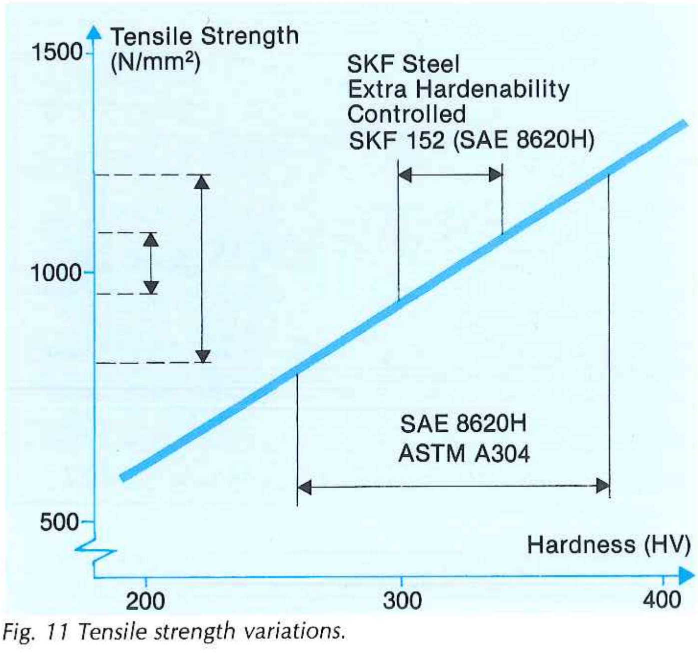


Fig. 11 Tensile strength variations.

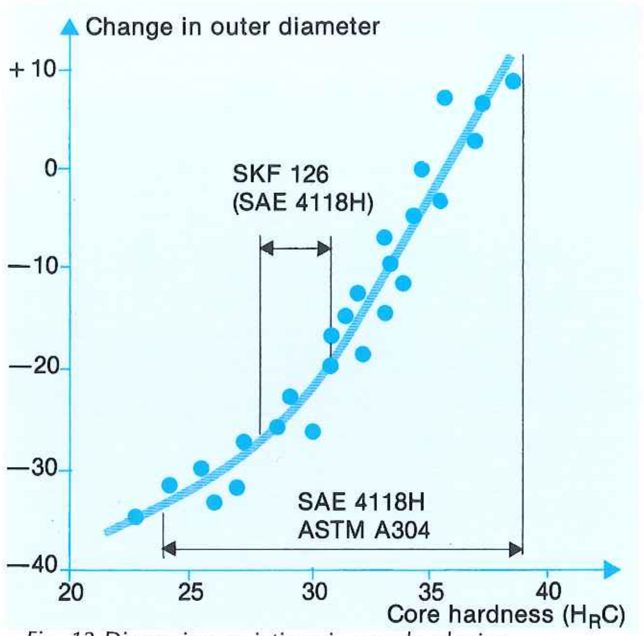


Fig. 12 Dimension variations in case-hardening.

"Reverse" Jominy-prediction

It is, of course, useful to be able to accurately predict hardenability.
Following teeming, however, little can be done to affect the steel's chemical composition.
To have an effect on hardenability, steel-user specifications must be met during the steelmaking process.
The SKF Steel hardenability predictor has therefore been developed one stage further. By use of a set of computational strategies, a "reverse" model has been designed.

This design takes a description of an end-quench curve and computes the proper steel chemical composition within the analysis limits for the steel grade selected.
Thus, a desired hardenability is used to predict steel composition.
This reversed model facilitates on-line control of hardenability in steel-making.

On-line hardenability control

Figure 13 illustrates how the SKF Steel model has been applied in the steelmaking process.
The two steelmaking units at SKF Steel in Hällefors and Hofors utilize the same software.
The interaction between the model and steel-making operation occurs in all instances where the chemical composition of the steel melt changes.
Initially, the desired "crude" chemistry of the steel is used to determine the starting values of carbon and other alloying elements.
All melt samples taken are analyzed directly. The process computer immediately makes the chemical composition available to the hardenability model.
The specification is reused by the model to calculate any necessary adjustments of the steel melt.
This process is continued until the hardness specification is met within the required tolerances.

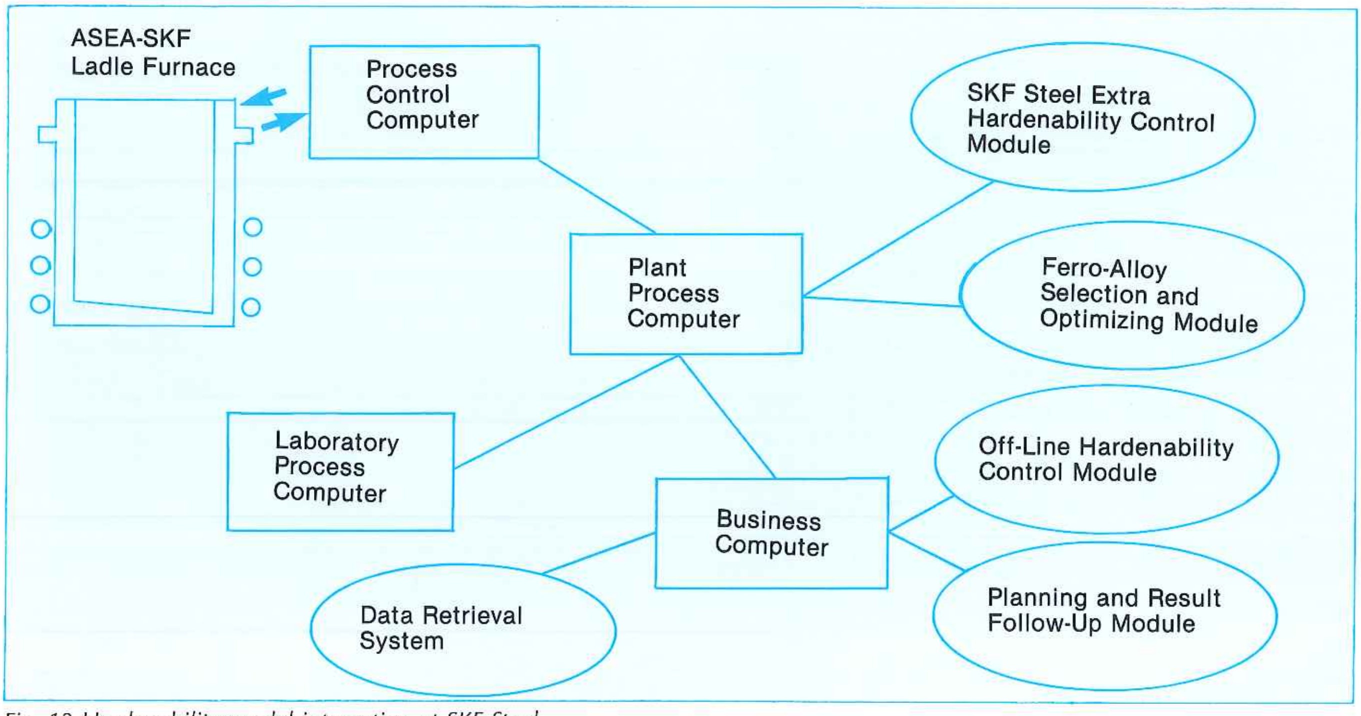


Fig. 13 Hardenability model integration at SKF Steel.

The SKF Steel extra hardenability control specification

The following example shows how the details of the hardenability specification are used.

Customer demand

A gear box manufacturer reguires a controlled hardenability variant of SAE 8620H for use in a gear which is precision machined prior to case hardening. Constant hardenability from batch to batch is imperative for minimizing hard machining.
Using the H-band for SAE 8620H (*Figure 14*), the steel user pinpoints his desired end-quench (Jominy) curve by specifying three points:

Jd (mm)	Jd (1/6 in.)	HV
1.5	~ 1	460
5	~ 3	370
9	~14	270

The customer gives SKF Steel this hardenability specification (the hardenability table and the steel grade SAE 8620H).

SKF Steel off-line check

At SKF Steel, the customer specification is checked first by the model in the off-line mode.
Here, the customer's hardenability specification is fed into the computer model and a crude calculation of the required steel composition is made. The results are then checked against two main criteria:

a) That the hardenability desired is within limits for the steel grade selected.
b) That the specification points fall on an end-quench (Jominy) curve permissible within the analysis range for SAE 8620H.

Obviously, there are any number of ways of setting three points within the H-band of SAE 8620. To make it possible to meet the specification, the points must provide a physically possible end-quench curve.
After the hardenability specifications have been checked, SKF Steel agrees to supply a steel which does not deviate from the initially calculated end-quench curve by more than the specified value. In this example, this value is +/— 1.5 HRC or +/— 10 HV at any Jominy-distance below 12/16 in.

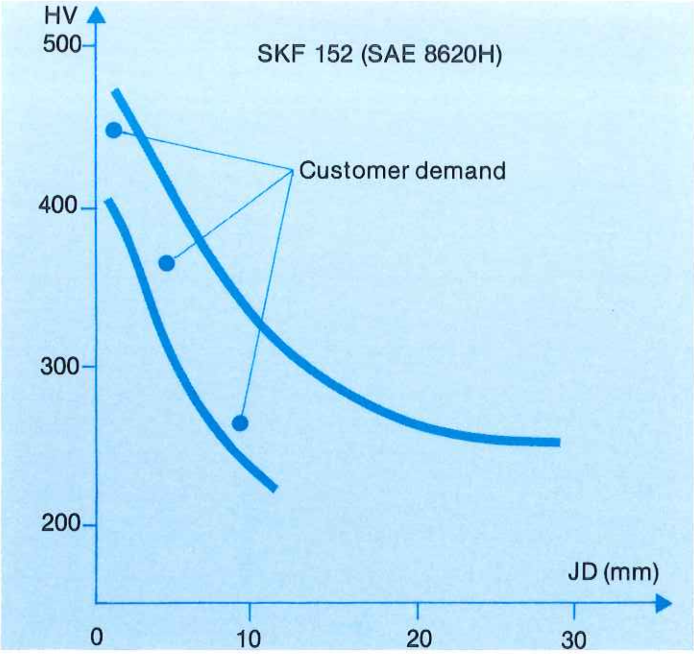


Fig. 14 H-band for SAE 8620H (based on ASTM A304).

System entry

When the check is completed, the customer specification goes on file as a variant of SAE 8620H along with a customer identity number. Any subsequent orders from this customer for steel with the same hardenability will be processed directly using the same hardenability specification. When the actual heat of steel is readied for production, the hardenability model will automatically select the values for alloy additions and initiate the required control procedures.

Steelmaking

The samples taken during melting and refining are used by the model to compute the required analysis adjustments. The model is linked directly to the ferro-alloy selection and dispensing system. By successive adjustments, the heat is refined to a chemical composition which meets the required hardenability specification within the chemical composition limits for the steel grade selected.
In this example, the initial control produced an aim value for Mn of 0.85 percent. During alloying, the Mn content in one sample was 0.88 percent. This overrun in Mn was automatically compensated for by the model which adjusted hardenability by decreasing the final Cr-content slightly.

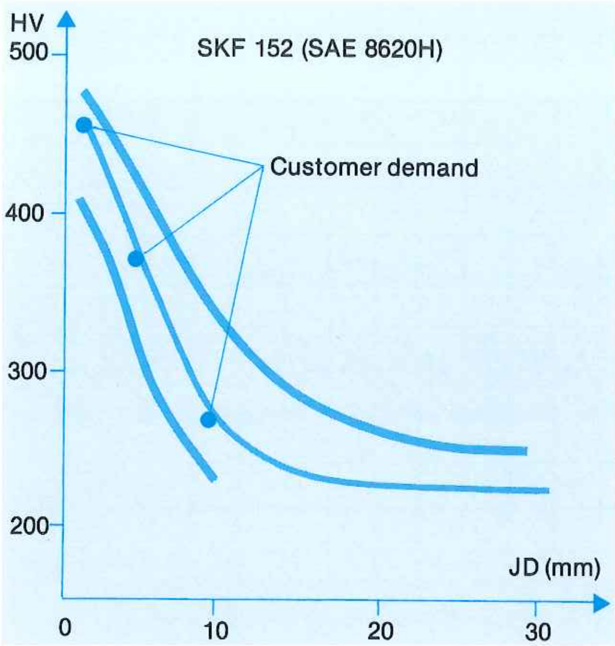


Fig. 15 Jominy-curve for finished heat.

Finished steel

The finished steel had a chemical analysis which gave the end-quench (Jominy) curve shown in *Figure 15* —as calculated by the predition model. Further data on the SKF Steel Extra Hardenability Controlled Carburizing Steels is available in (2).

Future developments

As noted earlier, prediction models for harden-and-temper and through-hardening steels have been developed.

Presently, these models are being evaluated.

References

1. *ASTM A304-79, 1982 Annual Book of ASTM Standards, part 5, ASTM.*
2. *SKF Steel Extra Hardenability-Controlled Carburizing Steels, SKF Steel Pamphlet RD-16.*
3. *Kramer I.R., et al, "Factors for the calculation of hardenability," Trans. AIME, Vol. 167, 1946, p. 670.*
4. *Crafts W. and Lamont I.L., "Effects of some elements on hardenability," Trans. AIME, Vol. 158, 1944, pp. 157—167.*
5. *Kramer I.R., et al, "Effect of sixteen alloying elements on the hardenability of steel", Trans. AIME, Vol. 158, 1944, pp. 138—148.*
6. *Grossman M.A., "Hardenability calculated from chemical composition," Trans. AIME, Vol. 150, 1942, pp. 227—255.*
7. *Boyd L.C. and Field J., "Calculation of standard end-quench hardenability curve from chemical composition and grain size," AISI contribution to the metallurgy of steel, 1945, No. 12.*
8. *Brophy G.R. and Miller A.J., "An appraisal of the factor method for calculating the hardenability of steel from composition," Trans. AIME, Vol. 167, 1946, pp. 654—669.*
9. *Just E., "New formulas for calculating hardenability curves," Met. Progr., Nov. 1969, p. 87.*
10. *Doane D.V., "Hardenability preditions and applications," Hardenability concepts with applications to steel, AIME 1978, pp. 349—396.*
11. *Thyr Andersson, SKF report NL81D004, SKF Engineering and Research Centre, 1981.*
12. *Hodge J.M. and Orekoski M.A., "The relationship between hardenability and percentage of martensite in some low alloy steels," Trans. AIME, Vol. 167, 1946, pp. 627—642.*
13. *Johansson G., SKF Steel report SUC 2/83.*
14. *Eriksson T., Jernkontoret report 412/74, Jernkontoret 1974.*
15. *Brown G.T., "Re-appraisal of the Jominy-test and its application," Hardenability concepts with applications to steel, AIME 1978, pp. 273—289.*
16. *Daido Steel Co., "Structural Steels treated by the ULO-process," Daido Steel Technical Note, Feb. 1981.*

SKF Steel

Technology
P.O. Box 133, S-182 12 Danderyd, Sweden
SKF

RD 33 US 03.84

Happy Printing Marketing & Publishing, Stockholm 1984

Disclaimer
The information in this document is for illustrative purposes only. The data and examples are only general recommendations and not a warranty or a guarantee. The suitability of a product for a specific application can be confirmed only by Ovako once given the actual conditions. The purchaser of an Ovako product has the responsibility to ascertain and control the applicability of the products before using them.

Continuous development may necessitate changes in technical data without notice. This document is only valid for Ovako material. Other material, covering the same international specifications, does not necessarily comply with the properties presented in this document.

Ovako AB
SE-111 87 Stockholm, Sweden
Phone: +46 (0)8 622 13 00

www.ovako.com