The measurement, prediction and control of Jominy-hardenability of Carburizing steel

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THE MEASUREMENT, PREDICTION AND CONTROL OF JOMINY-HARDENABILITY OF CARBURIZING STEELS

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 1986 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 an earlier technical report about this theme, see Ovako Archive technical report 3/1984.

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.

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

Technical Report 7/1986

The Measurement, Prediction and Control of Jominy-hardenability of Carburizing Steels.

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Introduction

Hardenability is of vital importance to manufacturing economy and product properties.

Variations in hardenability for a given steel grade must be kept to an absolute minimum in order to satisfy todays steel user expectations.

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.

Consistent hardenability is only attained if the steelmaking process is capable of providing a homogeneous steel with a consistent hardenability from heat to heat.

In this report, Jominy-hardenability, its measurement, prediction and control, is discussed.

The Jominy (end-quench) Test

The end-quench (Jominy) test has been in wide industrial use for a long time. It is today the most widely used method for assessment of hardenability of steel.

The Jominy test procedure is fairly straight-forward, but encompasses a number of pit-falls which makes the precision of the test questionable.

Several large investigations of the accuracy of the Jominy-test have been made (1, 2, 3), and the general conclusion is that the highest precision attainable, at least in the steeper parts of the curve, is a ± 2s of ± 2–5 HRC at one single laboratory.

This variability has several causes, and the main ones could be given the headings sampling, sample preparation and hardness testing.

The *sampling* can be controlled by a well designed sampling plan which assures that the test material is taken from material in the same position.

The *sample preparation* suffers random variations in austenitizing parameters and quenching conditions can be countered by stringent handling specifications.

In the testing the main variables are the variations in distances from the quenched end and the hardness testing itself. The hardness test method used (Rockwell or Vickers) affects the precision (Vickers testing being the most precise method) of the results. Use of conversion tables do not fully cover the method differences, which may add to the variations experienced in comparing Jominy-data.

A capability study was conducted on the Jominy-test by selecting single bars of steel from three different steel grades (4).

For each, 20 samples were produced and tested (Vickers hardness testing) under "identical" conditions.

Figure 1 shows the variations, measured as ± 3s, for three steel grades as function of the Jominy-distances. For the first Jominy-distances the "process" capability is of the order 50 HV-units, measured as ± 3s.

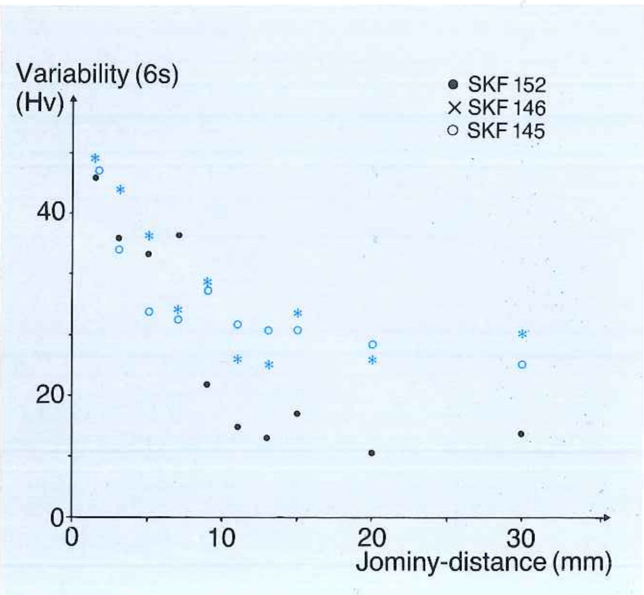

Fig. 1. Capability of Jominy-tests run on one single bar, tested as 20 Jominy-samples for three steel grades.

Figure 2 shows the results as ± 3 standard deviations in the tested points for the steel grade SKF 145. The range experienced for "identical" samples tested under "identical" conditions consumes a significant portion of the total Jominy-band.

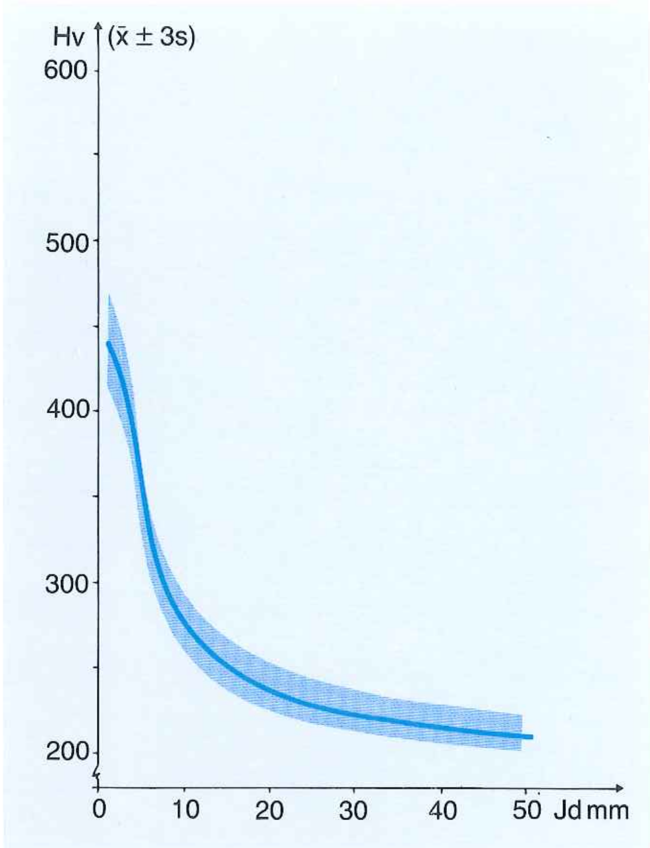

Fig. 2. Hardness variation in 20 Jominy-tests on "identical" samples. Steel grade: SKF 145.

For SAE 8620 H, the Jominy-band has a width of about 100 HV-units at the 5 mm Jominy distance.

The 6s capability assessment for *one single bar* of 8620 gave about 50 HV units.

This means that the test in itself, without regard to the sampling variations normally occuring covers about 50 % of the Jominy-band width.

A common requirement on a measurement tool is that it must not use more than 1/10'th of the tolerance to be measured which means 10 HV-units at the 6s level for the Jominy-test.

Hardness testing as such has a larger variability than this, 10 HV units is probably the minimum 6s variation that can be attained at any single laboratory (3).

The conclusion of this (and other similar tests) is that Jominy-testing is not an acceptable tool to asses hardenability with todays requirements.

It should be stressed that all results presented here derive from samples taken from rolled material. The use of miniature directly cast samples was disbandoned some time ago at Ovako Steel due to the large differences experienced between such samples and the heat analysis.

Other hardenability measurement methods suffer similar variabilities, and there seems little chance to improve Jominy-testing to the precision required.

The total Jominy scatter can be expressed as the composite of a set of variances.

The variation sources are:

S_1 Analysis precision
S_2 Jominy sample composition variations
S_3 Jominy sample preparation variations

- machining
- normalizing
- austenitization
- quenching
- grinding

S_4 Jominy measurement variations

- distance variations
- hardness measurement variations

Based on measured variations and capabilities, values for the standard deviations S_1, S_2 and (S_3, S_4) have been calculated by means of computer simulations.

In these simulations, the Jominy-prediction model has been used to establish the expected variation for an average SAE 8620-heat due to the variation in analysis precision and sampling variations.

Figures 3a, 3b and 3c show the variation in hardness calculated at a Jominy-distance of 5 mm.

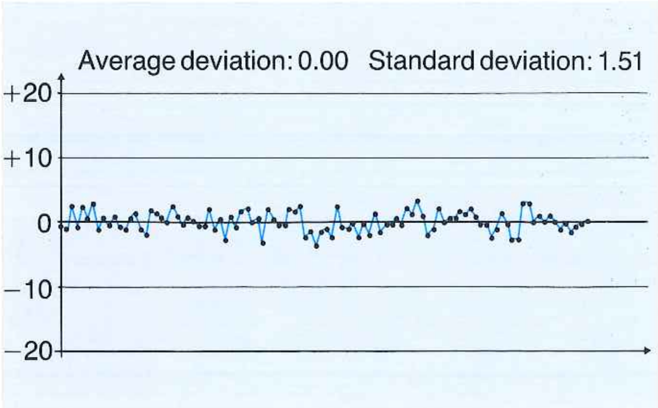

Fig. 3 a. S_1-variation. Differences in Hv-units. Steel grade: SKF 152. Simulated variation based on analysis capability at Jd = 5 mm.

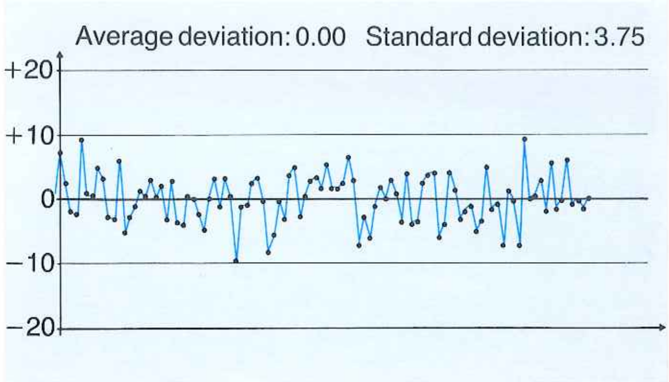

Fig. 3 b. S_2-variation. Differences in Hv-units. Steel grade: SKF 152. Simulated variation based on sampling variation at Jd = 5 mm.

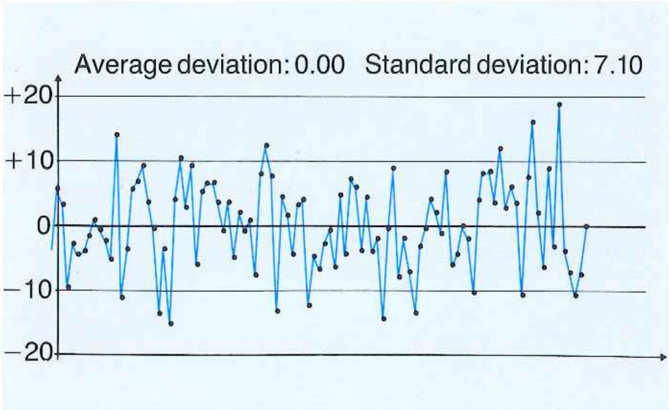

Fig. 3 c. S_3, S_4-variation. Differences in Hv-units. Steel grade: SKF 152. Simulated variation based on measurements capability at Jd = 5 mm. One single bar.

Table 1 summarizes the results for three Jominy-distances.

Table 1

	Standard deviation (HV-units)		
Jd (mm)	S_1	S_2	(S_3, S_4)
1.5	1.2	3.3	9.3
5	1.5	3.8	7.1
11	1.3	3.8	2.6

The total variation of the Jominy-test procedure can be estimated as:

$$S_j^2 = S_2^2 + (S_3, S_4)^2$$

With the data of *Table 1*, the total Jominy-test variation is:

Jd (mm)	S_j (HV)	$6 \cdot S_j$ (HV)
1.5	9.9	59
5	8.1	49
11	4.6	28

The actutal total variations obtained at Jd = 5 mm for an average heat are shown in *Figure 4*.

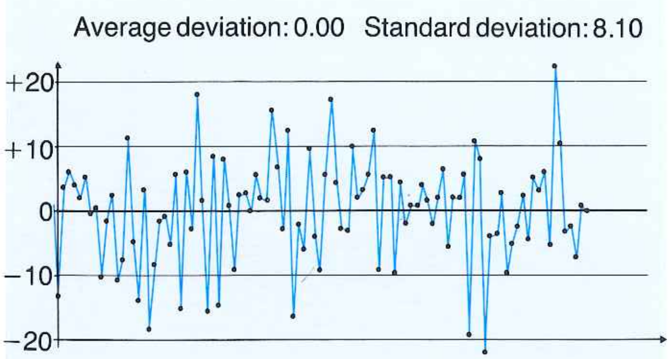

Fig. 4. S_j-variation. Differences in Hv-units. Steel grade: SKF 152. Total Jominy-variation at Jd = 5 mm.

Predicting Jominy-hardenability

Many different hardenability predictors are, and have been in use for some time.

Several of these have good accuracy, and with todays easy access to high capacity computers, are very easy to use.

Most modern predictors are based on regression analysis of large sets of physical Jominy-tests.

Ovako Steel has developed one such model which is based on very large datasets generated over a fairly limited period of time.

The regression model is based on separate regression analyses run with additive and multiplicative models, and all alloying elements and pertinent residuals are included in the models.

The models basically have the form

$$HV = f(C, Si, Mn, P, S, Cr, Ni, Mo, V, Cu),$$

and two regression equations have been derived for each standard Jominy-distance.

The regression calculation is dynamically adjusted with a set of features which are derived for each steel grade and steel grade variant.

Calculated analysis								
C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.205	0.217	0.717	0.008	0.012	0.415	0.358	0.157	0.076

Hardenability data								
Jd (mm)	Jd (1/16″)	Specification Hv	Specification HRC	Calculated Hv	Calculated HRC	Deviation Hv	Deviation HRC	Tolerance Hv
1.5	0.95	470	46.9	471	47.0	1	0.0	1
5.0	3.15	350	35.5	351	35.6	1	0.1	1
9.0	5.67	240	20.3	239	20.1	−1	−0.2	1

Fig. 5. Jominy adaption and prediction.

By a moving average technique, the predictor output is continually checked for drift and changes in processing and testing.

The regression adjustment factors are unique for each steelmaking unit and testing laboratory.

Figure 5 shows an example of a prediction session which gives a fast and reliable estimation of the heat hardenability.

Regression model prediction power

The precision of different prediction models have been tested by many, with varying results.

One basic problem in assessing the precision of a hardenability predictor is the large variation inherent in the test procedure.

With the poor capability of the Jominy-test, it is hard to evaluate the discrepancy between the "true" Jominy curve and the predicted one.

When judging predicted results against measured, the difference between measured and predicted values is a direct function of the variability of the measured data.

This means, in fact, that any predictor which consistently gives estimates which are within the ± 3s band of the measured (average) value for a given heat is a predictor which is just as good as the Jominy-test.

As an example, SKF 152 (SAE 8620) has been studied in some detail.

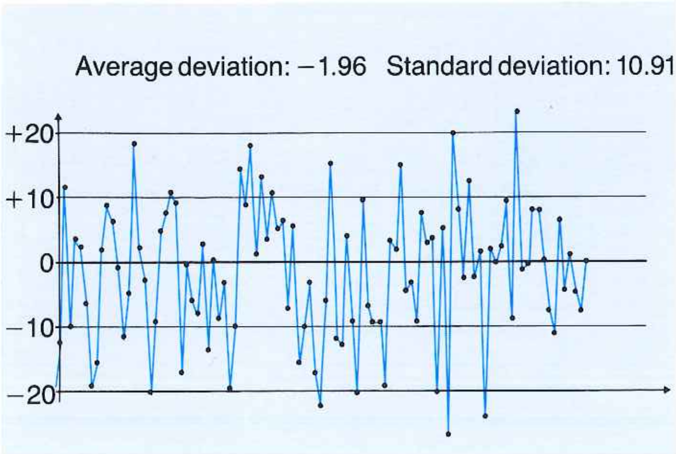

Fig. 6a. Differences in Hv-units. Steel grade: SKF 152. Differences calculated-measured at Jd = 1.5 mm.

Figures 6a, b and c show the deviations obtained between calculated values (with the Ovako Steel model) and the measured values at three Jominy-distances for 30 heats of SKF 152.

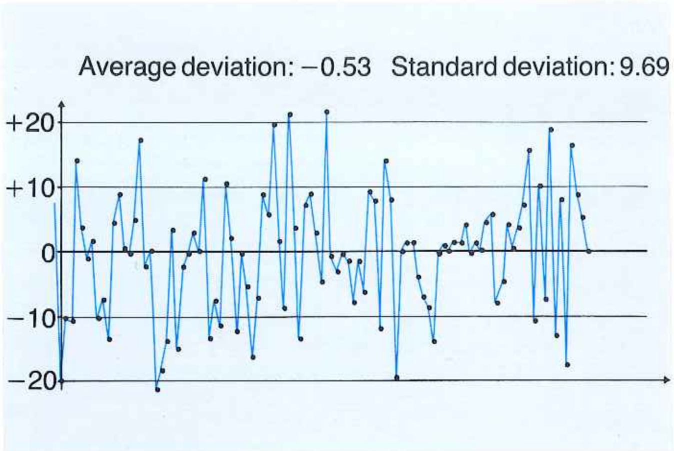

Fig. 6b. Differences in Hv-units. Steel grade: SKF 152. Differences calculated-measured at Jd = 5 mm.

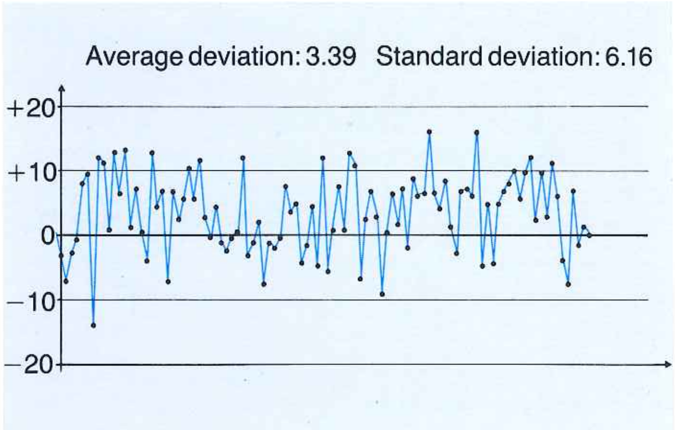

Fig. 6c. Differences in Hv-units. Steel grade: SKF 152. Differences calculated-measured at Jd = 11 mm.

The total variation in the difference between calculated and measured Jominy-hardness (S_v) is a function of the analysis precision (the calculation is based on the heat analysis precision, S_1), the precision of the calculation model (the model represents the "true" Jominy-value more or less well, S_m,) and the total precision of the Jominy-testing, (as earlier defined, S_j):

$$S_v^2 = S_1^2 + S_m^2 + S_j^2$$

The values obtained from the test shown in *Fig. 6* gives the results shown in *Table 2*.

Table 2

Jd (mm)	Standard deviations (HV) S_v	S_1	S_j	S_m (calculated)
1.5	10.9	1.2	9.9	4.4
5	9.7	1.5	8.1	5.0
11	6.2	1.3	4.6	3.9

A comparison of the capabilities of the model (S_m) and the Jominy-testing (S_j) is given in *Table 3*

Table 3

Jd (mm)	Capability of testing and of model $6 \cdot S_j$ (HV)	$6 \cdot S_m$ (HV)
1.5	59	26
5	49	30
11	28	23

The capability of the model clearly is better than the capability of the testing.

The average deviations between calculated and measured Jominy-hardness is quite small as shown in *Table 4*

Table 4

Jd (mm)	Average deviation between calculated and measured (HV)
1.5	-2.0
5	-0.5
11	3.4

It should again be stressed, that the large variability in the testing makes a detailed evaluation of the model precision difficult unless the comparison is based on an average of several Jominy-tests on material sampled from consistent material.

The Jominy-test procedure should soonest be replaced by standardized calculation models.

Such models are available, and can be united into simple and effective national and international standards.

A procedure often used today to evaluate predictor precision is to compare some results of single Jominy tests to calculated results. This is not acceptable.

The poor precision of the Jominy test makes single heat comparisons worth little unless very many heats are considered. The comparison of different predictors against single Jominy tests gives poor information on the predictors accuracy. For any such comparison several "identical" samples must be tested, and the predictions must be compared to the measured distribution average.

Hardenability Control

Selecting a good hardenability predictor provides the basis for good hardenability control.

A steel user requires the same hardenability from heat to heat for a given component in order to be able to minimize processing cost and maximize product properties.

The standard procedure today is that the user specifies a hardenability band inside the range of hardenabilities which are represented by the maximum and minimum compositions for a certain steel grade.

Since long, steel makers have tried to meet this request by reduction of the variation in composition for each alloying element.

This route, however, is not very effective due to the additional effects of the element variations.

At Ovako Steel another route has been selected.

Based on the regression hardenability models a computer software package has been designed which, in interaction with the plant process computers, transforms a hardenability requirement into a set of processing specifications.

With the aid of this procedure it has been possible to develop a procedure where an exact customer requirement is fed to the computer modules and the steel-making then is engineered to give a heat of steel which meets the requirements with very high precision.

In order to clarify the procedure, a number of steps in the hardenability specification procedures used today is discussed below.

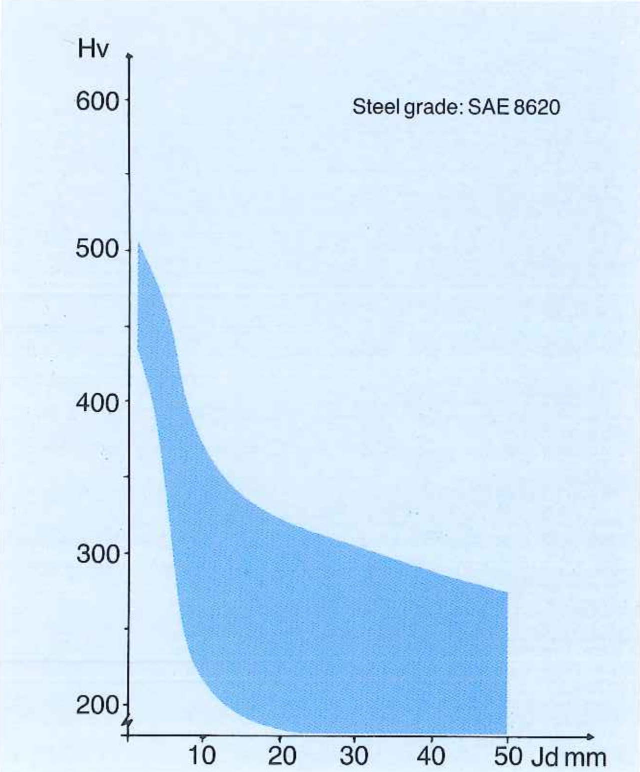

Fig. 7. Jominy-band calculated from max- and min- compositions for SAE 8620.

Chemical specifications

Chemical analysis limits have been used for a very long time to limit variations in steel properties.

As there is a direct relationship, as earlier shown, between chemical composition and hardenability, a specification of chemical composition automatically gives a limitation in hardenability scatter. However, this scatter is fairly wide.

As an example, *Figure 7* gives the Jominy-band for standard SAE 8620 based on the calculated end-quench curves for the minimum and maximum compositions. The hardenability range is quite wide.

Customers requiring tighter control on hardenability then defined a set of steel grades with more narrow specification of the hardenability. These steels, denominated H-band steels, have a defined Jominy-band.

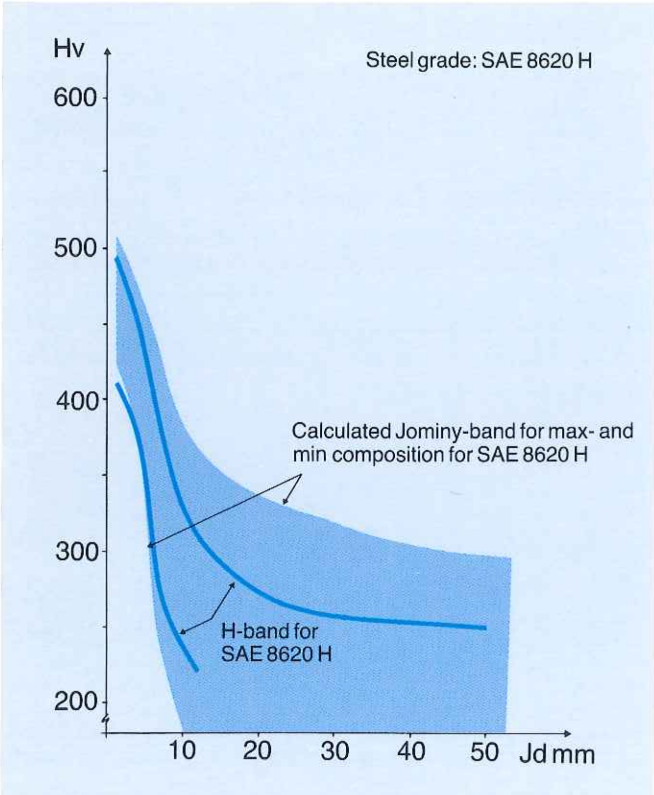

Fig. 8. Calculated and standardized Jominy-bands for SAE 8620 H.

Figure 8 shows the calculated maximum and minimum Jominy-curves for the steel grade SAE 8620H, and within this band, the H-band for this steel.

While the H-band narrows down the hardenability variations, the scatter still is quite wide. The H-band is too wide for many applications, and the dimensional changes resulting when the full band is used are significant.

This has led to the development of Ovako Steels controlled hardenability concept.

The three-point concept

In the Ovako Steel controlled hardenability concept the hardenability specification is expressed as three point on a Jominy-curve within the hardenability range of the steel grade.

The chemical specification for the steel grade remains the same, but the requested hardenability is met with high precision.

To enable stringent definition of the precision, and control of the results against the specification, measured hardenability curves on single Jominy-samples cannot be used.

The Ovako Steel controlled hardenability procedure defines precision and fulfillment of specifications as the difference between hardness *before* (i.e. the specified hardenability in three point on a Jominy-curve) and the *calculated* hardness *after* the production of the heat, based on the heat analysis.

The actual precision that can be attained depends to some extent on the steel grade, but the basic rule is that the difference between the specified value and the value predicted for the heat shall not be greater than 10 HV-units (about 1 HRC unit) in any of the three points specified. For the most commonly used carburizing grades.

In practice, the procedure in using controlled hardenability is as follows:

1. **Define the steel grade desired,** and the corresponding Jominy-band, see *Figure 7*. Note that the potential Jominy-band for most steel grades is wider than the standardized H-bands.

   Also be aware that changes in the chemistry specifications of a steel grade directly influences the Jominy-band.

   If any doubt exists, Ovako Steel will provide the Jominy-band which can be physically met for any steel grade desired.

2. **Select the desired Jominy-curve** within the Jominy-band. Define three points (combinations of hardness and Jominy-distance) on this curve, see *Figure 9*.

   Be aware that there are restrictions on the possible Jominy-curves attainable for a certain steel grade.

   When Ovako Steel receives a hardenability specification, a careful check-out is made to assure that the specification is physically feasible.

   Again, if definition problems exist, Ovako Steel will give full support in the specification definition.

3. **Production** of the steel will be made against the specification which goes on file as a specific steel grade variant.

   Different specifications of hardenability may be made for one and the same steel grade.

   For instance two different gears with different section thickness that are both produced from SAE 8620 may require different hardenability.

   The produced heat of steel is certified to the calculated hardenability and the correspondance to the hardenability specification.

   The predicted Jominy-hardenability of the heat shall deviate less than 10 HV units from the specification in any point, *Figure 10*. This apply to the commonly used carburizing grades.

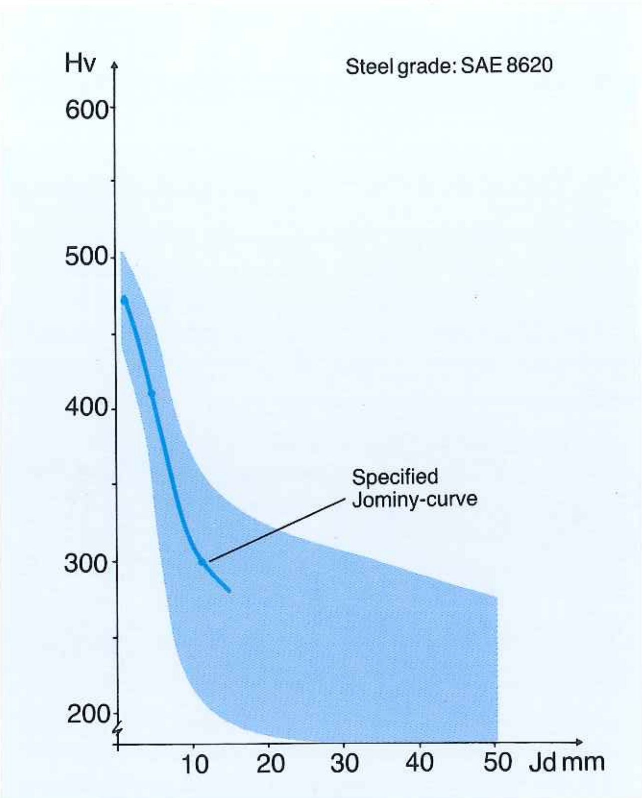

Fig. 9. Example of Jominy-specification for SAE 8620.

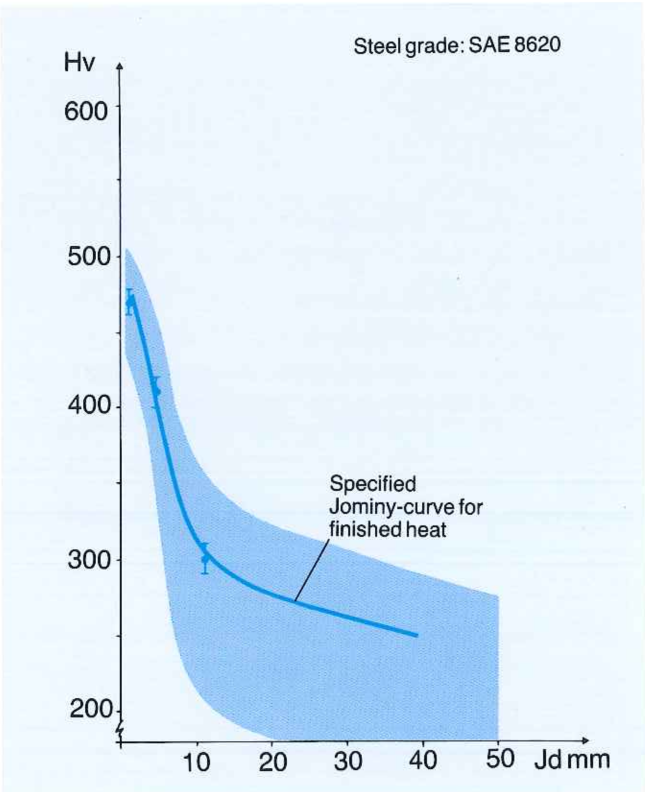

Fig. 10. Specified and predicted hardenability for finished heat.

Production follow-up

The controlled-hardenability concept has been used at Ovako Steel for some time.

Figure 11 shows the results for recently produced controlled-hardenability heats.

The data in *figure 11* give the relationship between the specified and the attained (as calculated on base of the heat analysis) hardness in the points specified.

Included are a large number of steel grades well representing the industrially used carburizing steels.

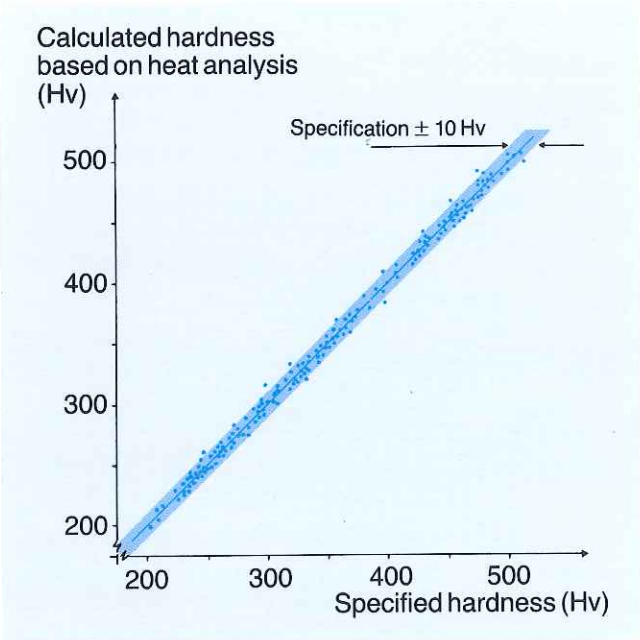

Fig. 11. Differences between specified and calculated (for finished heat) hardness for controlled-hardenability produced heats of several steel grades.

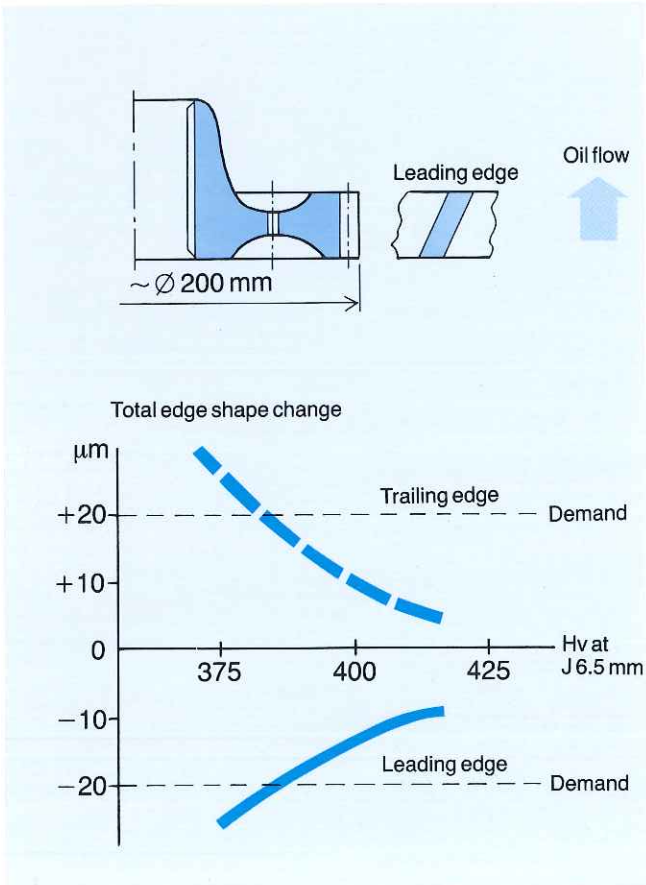

Fig. 12. Dimensional changes of gears in case-hardening.

Hardenability Variations and Properties

Variations in hardenability gives variations in dimensional changes during heat treatment and variations in product properties.

These phenomena have been studied and discussed in many publications and what follows mainly intends to point out some of the benefits of close control of steel hardenability.

Dimensional changes

Figures 12 and 13 give examples of the relationship between steel hardenability and dimensional change.

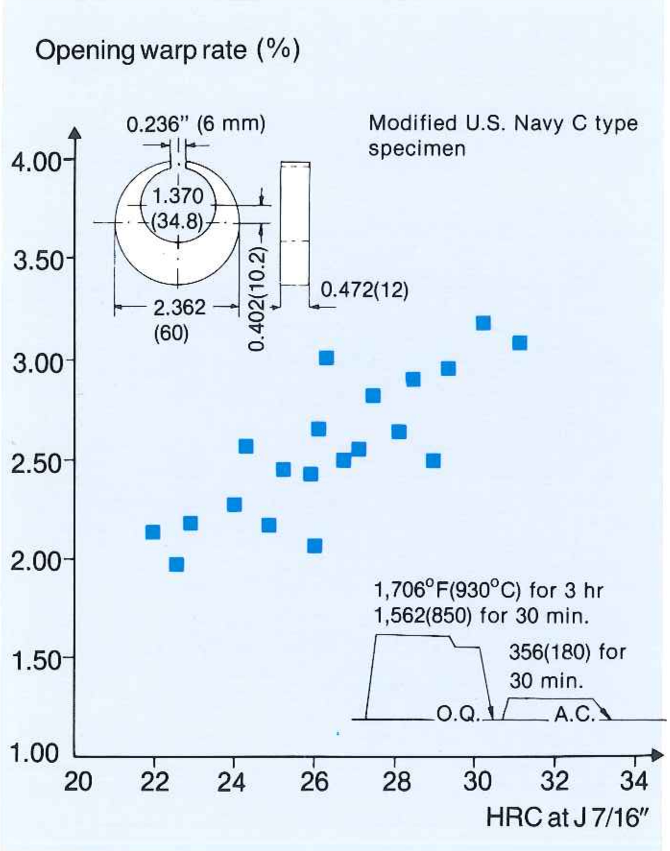

Fig. 13. Warping and core hardness for SAE 8620 H standard steel.

Fig. 12 (5) shows the dimensional changes occurring in gears in relation to the hardness attained. Fig. 13 (6) shows the warping as a function of Jominy-hardenability.

Close control of hardenability gives direct advantages in turning and grinding. A consistent hardenability provides predictable and consistent dimensional changes.

Mechanical properties

Figure 14 (7) shows the tensile strength variation normally experienced if the full Jominy-band is utilized, and compares this to the variation attained when controlled-hardenability is used.

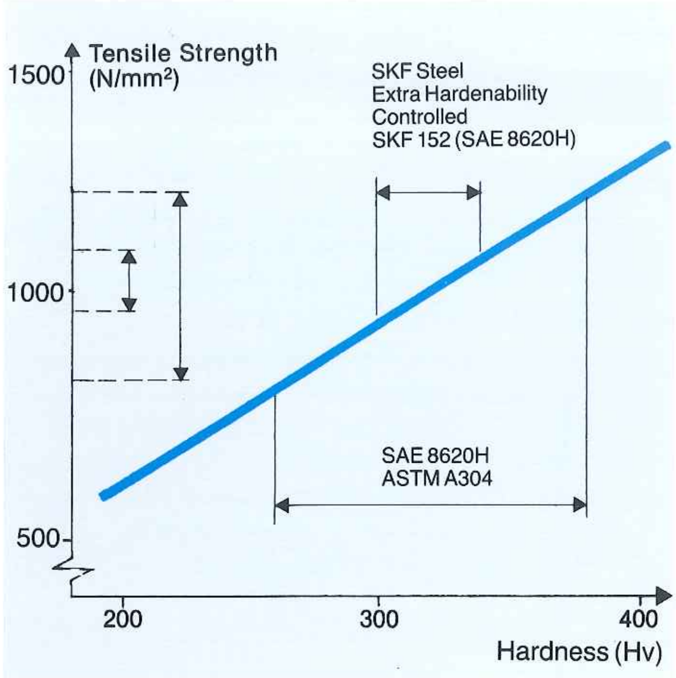

Fig. 14. Tensile strength variations.

Figure 15 (8) relates hardness variations to core strength and fatigue properties of gears. Through closely controlled hardenability properties can be maximized and reliably so from heat to heat.

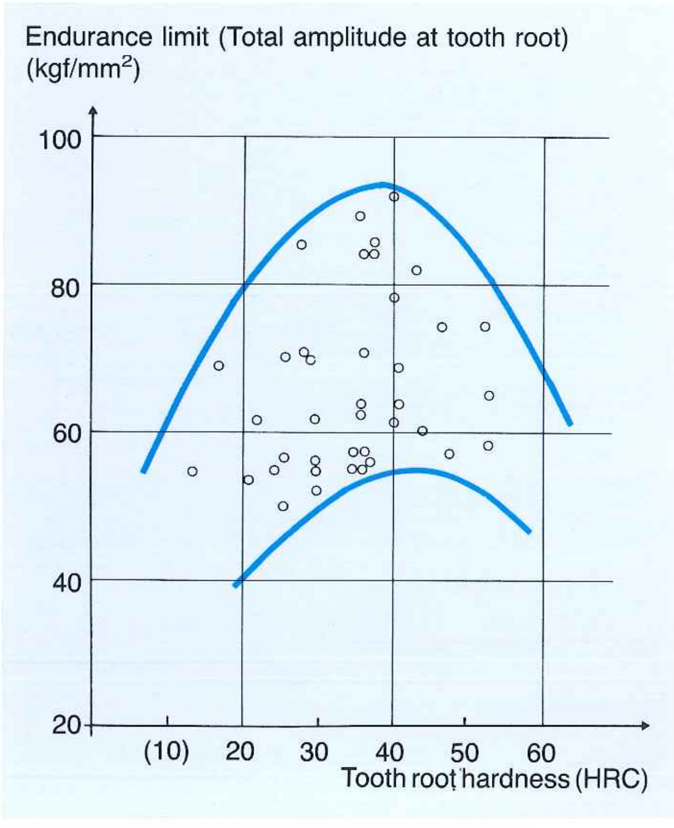

Fig. 15. Influence of tooth root hardness on the endurance limit of carburized gears.

Conclusions

Physical Jominy-testing provides large experimental scatter, and does not provide the measurement capability required to meet demands on closely controlled hardenability.

Today, Jominy-testing can be effectively replaced by hardenability predictors of high precision which are easy to use. Physical Jominy-testing should soonest be replaced by standardized hardenability predictors.

The Ovako Steel controlled-hardenability procedure provides a unique possibility to attain consistent and exact hardenability, and provides unique possibilities to tailor hardenability demands for specific applications.

Close control of hardenability is a prerequisite for good production economy and high product reliability.

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