A CRITICAL OVERVIEW OF QUENCH SEVERITY QUANTIFICATION[1]

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Abstract

Every metallurgist has been trained to think of quench severity in terms of DI values and Grossman H-Values. Every metallurgy handbook published since Grossman´s work in the early 1950´s utilize the famous H-Value tables indicating numerical H-Value data for water, oil, brine under low, moderate, high and violent agitation rates. Although these values are seldom used successfully in any predictive way, they continue to be incorporated in various handbooks (including the authors´own contributions) even today. Relatively recently various attempts have been made to provide a more meaningful and useful quantitative characterization of quench severity. The more important of these approaches will be critically reviewed and method that has been ignored until recently that addresses the shortcomings of these previous methods, quench factor analysis (which is more typically used for aluminum quenching studies) will be reviewed.

Key words: Heat treatment; Quench severity.

ANÁLISE CRÍTICA DA QUANTIFICAÇÃO DA SEVERIDADE DE TÊMPERA

Resumo

É muito comum pensar em severidade de têmpera em termos de valores de Di e valores de H de Grossman. Todo livro publicado de metalurgia, desde o trabalho pioneiro de Grossman na década de 50, utiliza as famosas tabelas de valores de H, indicando números para a água, óleo e salmoura, sob baixa, moderada, alta e violenta taxas de agitação. Embora esses valores sejam usados sem muito critério para predizer a severidade, atualmente eles ainda continuam a ser incorporados em vários handbooks (incluindo as próprias publicações dos autores). Recentemente tem havido uma certa preocupação em fornecer uma caracterização quantitativa mais precisa e útil desse parâmetro. Neste artigo serão revistos os aspectos mais importantes desse assunto, com métodos que até recentemente foram ignorados, como a análise do fator de têmpera (quench factor), que tem sido mais usado para estudos de têmpera em ligas de alumínio.

Palavras-chave: Tratamento térmico; Severidade de têmpera

INTRODUCTION

Hardness is one of the primary quality and tensile strength indicators in quench and tempered steels. The ability of a quenchant to harden a particular steel under specific quenching conditions traditionally has been experimentally determined by performing cross-sectional hardness surveys on quenched bars. However, quench severity estimation by this method is subject to reproducibility problems due to procedural and lot-to-lot chemistry variations in the steel.

Historically, Grossman quench severity, or H-Factors as they are commonly known, have been used to describe quench severity.[1,2] The Grossmann H-Factor is defined as the ratio of the effective heat transfer co-efficient (h) at the part surface divided by twice the thermal conductivity (k) of the metal: $H = h/2k$.
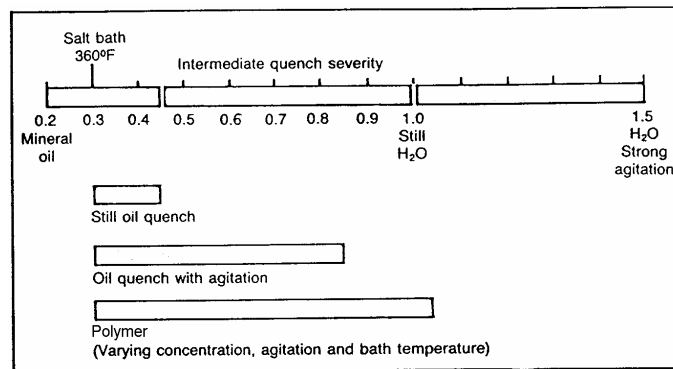

Figure 1. Illustration of a typical H-Factor chart suggested for use in polymer quenchant selection.
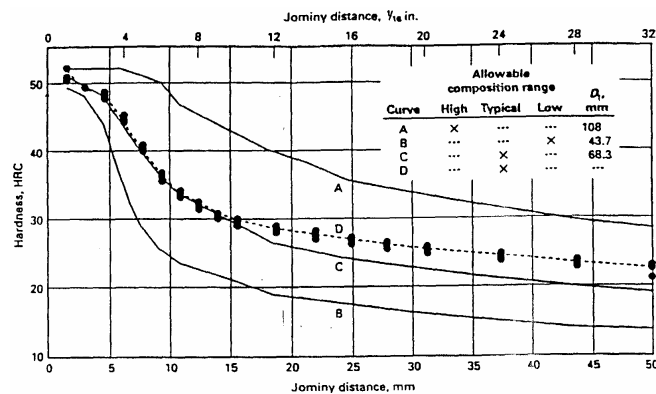

Figure 2. Jominy curves of low, intermediate and high hardenability AISI 4140 steel.

Recently, there has been increasing use of H-Factor characterization of quenchants. Variations of Figure 1[3] have been published to illustrate: oil quench severity equivalency, and quenchant selection with respect to H-Factors.[4] Recently, similar charts have been used to suggest the suitability of particular polymer; poly(alkylene glycol), poly(vinyl pyrrolidone), poly(sodium acrylate) and poly(ethyloxazoline) for quenching particular steel alloys and cross-sections..In view of the apparently increasing interest in the use of this traditional method, it is of interest to review the methods of experimentally determining H-Factors and the limitations of the information inherent in their use. These subjects will be addressed here.

DISCUSSION

1 Review of Classical Method of H-Factor Calculation

The actual attainable hardness of steel is primarily dependent on carbon content and is independent of the presence of alloying elements. To maximize hardness, it is usually desirable to maximize martensite content. There is an interrelationship between carbon content, amount of martensite and hardness. This is important in calculating the maximum attainable hardness for any steel grade up to approximately 0.6% carbon.

Hardenability refers to the ability of a steel to be hardened by the formation of martensite after quenching. Steels are not considered to have been effectively hardened if they contain less than 50% martensite.

The classical method of illustrating depth of hardening is to perform a Jominy end-quench test. In this test, a standard size cylindrical specimen (1 inch dia. x 4 inch long) is "flood quenched" at the end with a specified spray pressure. Specimen hardness will be greatest at one end where the quenchant spray impinges the specimen and will decrease with increasing distance from the quenched end. After quenching, the hardness of the bar is determined at 1/16 inch intervals (J-values) from the quenched end. This data is used to construct Jominy curves.

Examples of three Jominy curves representing high, intermediate and low alloy chemistry of AISI 4140 steel are shown in Figure 2. While experimental determination of Jominy curves is the best way of obtaining this data, excellent results can be obtained with various computerized Jominy curve generation programs ("predictors").

Ideal diameter (D_I) refers to the diameter of a bar that can be quenched to give 50% martensite in the center with an infinite quench (i.e. salt brine quench). An infinite quench is defined as a sufficiently severe quench so that the heat removal rate is controlled by the thermal diffusivity of the metal and not be the heat transfer rate from the steel to the quenchant. Typically, aqueous salt brine, either caustic or sodium chloride, is used to provide the infinite quench conditions.

D_I values may vary from less than one inch for difficult to harden, plain carbon steels such as AISI 1045 to values in excess of 10 inches for high hardenability steels such as AISI 4140. D_I values are an excellent means of comparing the relative hardenability of two steels. The use of D_I values are useful to determine if it is even possible to harden a particular cross-section size of a particular steel.

Ideal diameter is affected by the grain size of a steel. Grain size is defined by a standard ASTM number; the larger the number, the larger the grain size. In general, most steels have a grain size of at least 7-8. D_I values can be calculated from the use of alloy factors.

D_I values are dependent on the shape of the specimen being evaluated. For example, round bars, square bars and plates will have their own unique D_I values. The D_I values for different shapes can be interconverted with the appropriate nomogram. These interrelationships are linear since they are dependent on surface to volume ratios.

Table 1 shows the cooling rate at each Jominy position when the specimen is quenched in room temperature water. This data shows why section size has such a dramatic effect on as-quenched hardness.

As described previously,[1,9] the Jominy end-quench test is conducted by quenching an austenitized steel bar by spraying one end of the test specimen. However, most commercial quenching processes involve some variation of an

immersion quench. When a steel workpiece is quenched in this way, it is important to determine if the bar is adequately through-hardened, or to determine the depth of hardness.

Jominy data, obtained by experiment or computer calculation, can also be used to calculate the depth of hardness in standard workpieces that are immersion quenched. This is done by calculating the Jominy equivalent distance. This calculation assumes that cooling rates at two positions in the bar will exhibit the same hardness. In this case, the hardness at a subsurface value versus the same hardness at a known J-value on the Jominy bar, are the same.

To calculate the equivalent Jominy condition (J_{eq}), it is first necessary to introduce the **Grossman Quench Severity Factor (H)**. Typical values that have been traditionally used for water, oil, molten salt, brine and air are provided in Table 2. The water quenchant is assumed to be at 80°F. An H-Factor of 5.0 is about as high as is practically achievable and represents an "infinite quench".

A variation of the Jominy equivalence approach is to use the Lamont transform.[2] This transform allows the interrelationship of any Jominy position and equivalent bar diameter for different amounts of through-hardening if the H-Factor for the quenchant is known.

Although these approaches have served the industry well for many years, there are numerous problems with applying H-Factors, at least as shown, for predictive purposes. One of the difficulties, is the failure to adequately quantify agitation rates. There is no physical meaning to a value denoted as "mild", "violent", etc. Another problem is the way that agitation is applied. For example, with the exception of some induction hardening applications, flood quenching, such as that used for the end-quench test, is not used. Other difficulties have been reviewed by Murthy.[5]

Table 1. Cooling rate at each Jominy position for room temperature water.

Distance from water quenched end, 1/16 in.	Cooling Rate	
	°C/s	°F/s
1	270	490
2	170	305
3	110	195
4	70	125
5	43	77
6	31	56
7	23	42
8	18	33
9	14	26
10	11.9	21.4
12	9.1	6.3
14	6.9	12.4
16	5.6	10.0
18	4.6	8.3
20	3.9	7.0

Table 2. Approximate Grossman quenching severity factor of various media in the pearlite temperature range.

	Grossman quench severity factor, *H*			
Agitation	**Brine**	**Water**	**Oil & salt**	**Air**
None	2	0.9 - 1.0	0.25 - 0.30	0.02
Mild	2 - 2.2	1.0 - 1.1	0.30 - 0.35	. . .
Moderate	. . .	1.2 - 1.3	0.35 - 0.40	. . .
Good	. . .	1.4 - 1.5	0.40 - 0.50	. . .
Strong	. . .	1.6 - 2.0	0.50 - 0.80	. . .
Violent	5	4	0.80 - 1.10	. . .

2 Quantitative Experimental Determinations of H-Factors

Monroe and Bates have described the use of a cooling curve technique to estimate H-Factors.[6] In this work, analytical cooling curves were first calculated using a finite difference heat transfer program. Thermal properties of Type 304 stainless steel, the material used to construct the probe used for cooling curve measurement, were input into the program and specific quench severity values were imposed at the probe surface. Cooling curves were calculated for bars with 0.5, 1.0, 1.5 and 2.0 inch diameters and a length of at least four times the diameter which minimized end cooling effects.

The calculated time/temperature data were subsequently analyzed to determine the cooling rate at 1300° F (705°C) as a function of imposed quench severity and bar diameter. A temperature of 1300°F (705°C) was selected for cooling rate analysis since much of the metallurgical literature on steel transformations is related to cooling rate at this temperature. The calculation results are presented in Table 3.

A statistical model was developed to fit these data:[7]

$$H = (AX^C)\exp(BX^D)$$

where: H is the Grossman H-Factor, A is the cooling rate (°F/s) at 1300°F (705°C), A,B,C, and D are statistical model parameters from Table 4 (All probes were cylindrical and were constructed from AISI type 304 stainless steel with a Type K thermocouple inserted to the geometric center). As Figure 3 indicates, this model provides an excellent fit to the modeled data.

This approach was used to statistically model the effect of polymer quenchant concentration, agitation and bath temperature on H-factors for a PAG (polyalkylene glycol)[8] and a PVP (polyvinylpyrrolidone)[9] quenchant. The results are summarized in the contour plots shown in Figure 4.

These data show that both quenchants are capable of producing a broad range of H-Factors. However, a single H-Factor value provides no insight at all into the relative processing latitude of either quenchant.

Table 3. Cooling Rate at 1300º (ºF/s) versus H-factor

Probe Diameter (inches)				
0.5 Cooling Rate (°F/s)	1.0 Cooling Rate (°F/s)	1.5 Cooling Rate (°F/s)	2.0 Cooling Rate (°F/s)	Approx H-Factor
15.2	7.5	4.9	3.6	0.10
30.0	14.6	9.5	6.9	0.20
58.3	27.5	17.1	11.9	0.40
85.2	38.5	23.1	15.7	0.60
109.8	47.8	27.9	18.6	0.80
132.6	55.8	31.9	20.9	1.00
159.5	64.4	36.0	23.3	1.25
182.7	71.8	39.4	25.1	1.50
241.3	88.7	46.7	29.0	2.25
286.9	100.1	51.5	31.5	3.00
333.7	111.2	56.0	33.8	4.00
367.9	119.0	58.9	35.1	5.00
427.2	130.0	62.7	37.0	7.00
476.2	140.0	66.6	38.5	10.00

Table 4. Model Parameters for H-Factor Calculation (A, B, C, D = model parameters)

Probe Dia. (In.)	A	B	C	D
0.5	0.002802	0.1857×10^{-7}	1.201	2.846
1.0	0.002348	0.2564×10^{-9}	1.508	4.448
1.5	0.002309	0.5724×10^{-9}	1.749	5.076
2.0	0.003706	0.3546×10^{-10}	1.847	6.631

where:

$H = Ax^C exp(BX^D)$

H = Grossman H-Factor

X = CoolingRate a 1300 °F
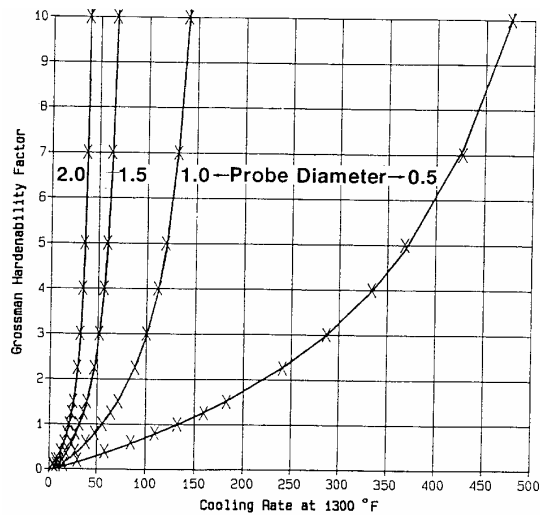
Figure 3. Grossman hardenability factor versus cooling rate at 1300°F.
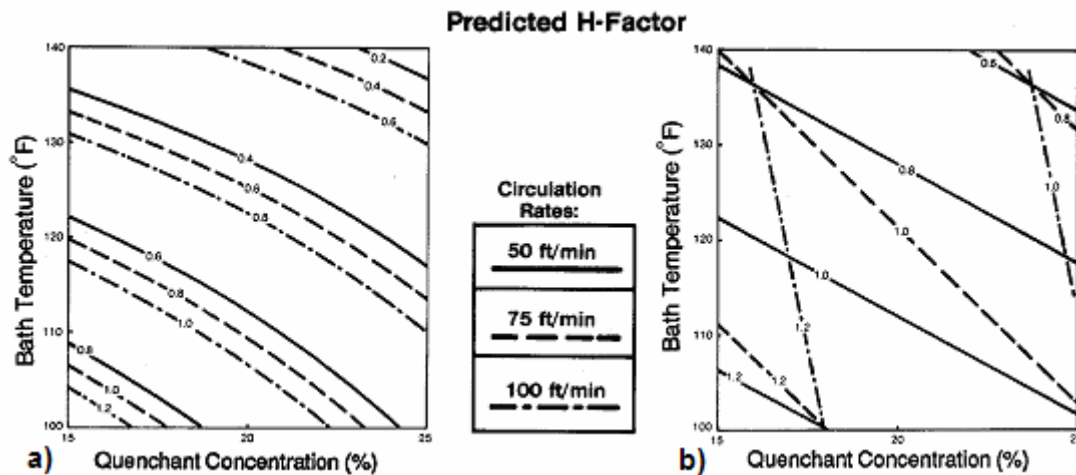
Predicted H-Factor

Figure 4. Grossman H-Factors for a PAG quenchant as a function of bath temperature, agitation rate and concentration for: a) PAG quenchant and b) PVP quenchant.

The Monroe and Bates calculation procedure does permit a good estimate of quenchant H-Factor for the quenching conditions of interest, however, there are a number of fundamental limitations of their use to compare various different quenchant media, including different quenchants, that cannot be overcome. These include:

1. Grossman H-Factors only reflect the ability to harden steel. They do not tell anything at all about steel cracking and deformation. For example, there are a number of recent references to the successful use of PAG polymer quenchants to quench 52100 bearing steel[10] and AISI H13 tool steel[11] which would not have been expected to be possible from the various polymer quenchant H-Factor plots such as Figure 1 that are currently available.

2. To estimate cracking propensity and even through-hardening hardness profiles, the total cooling process must be considered. H-Factors tell nothing about potential thermal and transformation stress generation during the quenching process.

3. Grossman H-Factors only refer to quench severity at a single very narrow temperature region (1300°F/705°C) of the steel transformation process. Although they are intended to indicate the ability of a quenchant to harden steel, they do not account for the cooling time required to achieve this process. To properly account for cooling time, a superposition of both the quenching cooling curve and the steel transformation curve must be performed.

3. Quench Factor Analysis

An excellent method of using a single number which will reflect this overall hardening process is the application of Quench Factor Analysis to steel hardening.[12] Quench factor analysis is based on the principle that steel hardening can be predicted by segmenting a cooling curve into discrete temperature-time increments and determining the ratio of time required to obtain a specific amount of transformation at that temperature. The sum of the incremental quench factors over the transformation range is equal to the quench factor (Q).

Quench factors are calculated from digital time-temperature (cooling curve) data and a C_T function describing the TTP (time-temperature-property) curve for the alloy of interest.

$$C_T = -K_1 K_2 \exp\left[\frac{K_3 K_4^2}{RT(K_4 - T)^2}\right]\exp\left[\frac{K_5}{RT}\right]$$

where:

C_T = critical time to form a constant amount of a new phase or educe the hardness by a specified amount. (The locus of the critical time values as a function of temperature forms the TTP curve.)

K_1 = constant which equals the natural logarithm of the fraction untransformed during quenching, i.e., the fraction defined by the TTP curve.

K_2 = constant related to the reciprocal of the number of nucleation sites.

K_3 = constant related to the energy required to form a nucleus.

K_4 = constant related to the solvus temperature.

K_5 = constant related to the activation energy for diffusion.

R = 8.3143 J/K mol.

T = temperature, K.

The constants K_1, K_2, K_3, K_4, and K_5 define the shape of the TTP curve shown in Figure 5.
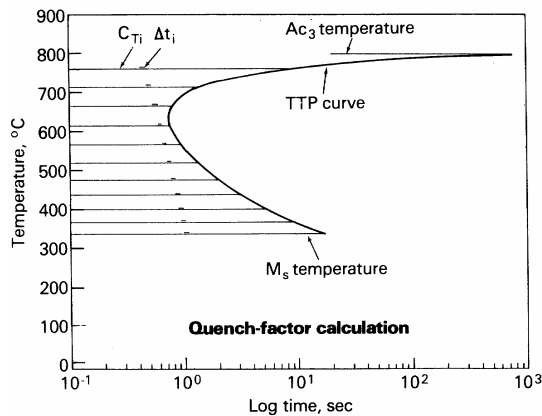

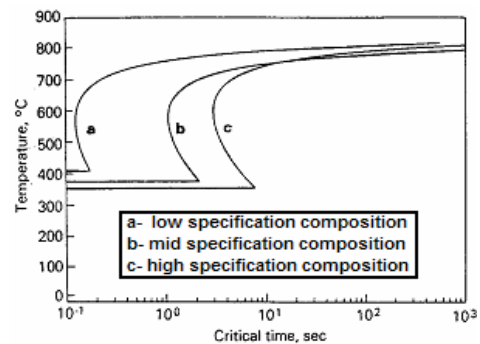**Figure 5**. Illustration of quench factor calculation from a TTP curve.

Figure 6. Curves for cast 4130 steel.

The incremental quench factor (q) for each time step in the cooling curve is calculated from: q = $\Delta t/C_T$ where: Δt is the time step used for cooling curve data acquisition. The incremental quench factor (q) represents the ratio of time that the alloy is at a particular temperature divided by the time required for transformation to begin at that temperature. The incremental quench factors are summed over the entire transformation range to produce the cumulative quench factor (Q) according to:

$$q = \Sigma q = \Sigma_{T=Ar_3}^{T=Ms}\frac{\Delta t}{C_T}$$

The cumulative quench factor reflects the heat-removal characteristics of the quenchant as indicated by the cooling curve. It also includes section thickness effects because these influence the cooling curve. Transformation kinetics of the alloy are reflected because the calculation involves the ratio of time the metal was at a particular temperature by the amount of time for transformation to begin at this temperature, i.e., the position of the TTP curve in time as indicated for three hardenability bands of AISO 4130 indicated in Figure 6.

The calculated quench factor can be used to predict the as-quenched hardness in steel using the following equation:

$$P_P = P_{min} + (P_{max} - P_{min})\exp(K_1 Q)$$

where:

    P_P = predicted property,
    P_{min} = minimum property for the alloy,
    P_{max} = maximum property for the alloy,
    exp = base of the natural logarithm,
    K_1 = ln(0.995) = -0.00501,
    Q = quench factor.

The solid line in Figure 7 represents the predicted hardness as a function of quench factor and the data points represent measured hardness values at locations in the quenched part where cooling curves were available. These data show a good correlation between predicted and obtained hardness.

The cumulative quench factor under particular quench conditions reflects the heat-extraction characteristics of the quenchant, as modeled by the cooling curve over the transformation range of the alloy, section thickness of the part and transformation kinetics of the alloy. An alloy with a low rate of heat transfer will produce a lower Q-Factor under given cooling conditions compared to an alloy with a high transformation rate.
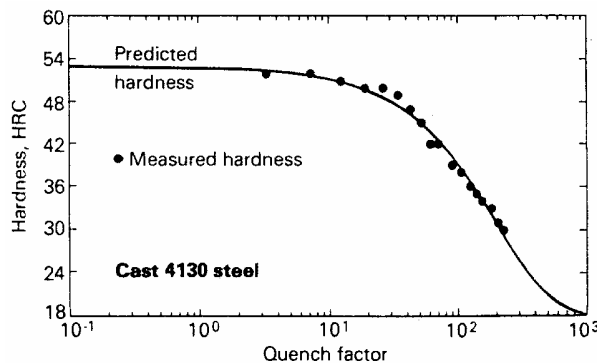

Figure 7. Illustration of the correlation between predicted and measured hardness of cast 4130 steel as a function of quench factor.

CONCLUSIONS

The data presented here show that although the classical approach of using Grossman H-Factors to estimate the quench severity necessary to harden steel, they have a number of deficiencies. Some of these can be overcome by experimental determination from cooling curves. However, a better approach to estimate as-quenched properties such as hardness is the use of Quench Factor Analysis. In general, it is not a recommended practice to select quenchants, especially polymer quenchants, from a graphical representation similar to Figure 1.

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