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THE INVESTIGATION OF APPLICABILITY OF THE HOLLOMON-JAFFE EQUATION ON TEMPERING THE HSLA STEEL

High strength low-alloyed (HSLA) Cr-Mn-Si steels belong to a group of steels that can reach their full mechanical properties after quenching and tempering. Those properties depend both on the temperature and time of tempering. Knowing the tempering parameters, it is possible to reach the desired properties of the treated steel. Some results on investigating the Hollomon-Jaffe equation (in parametric form) application for tempering of HSLA steel, are shown in this paper. The experiments were performed in real production conditions, using a standard material. The quenching was performed at 870 °C, the heating period was always 30 min, with subsequent cooling into the oil bath. The tempering was carried out in temperature range from 480 to 680 °C, while tempering time varied from 15 min to 24 h. The degree of tempering is referred through the hardness values changing. The experimental results have shown a pretty well agreement to tempering parameters, included in Hollomon--Jaffe equation, for this kind of HSLA steel.

Key words: HSLA steel; quenching/tempering; Hollomon-Jaffe equation.

Quenched steels, from a group of heat-treatable steels, always have high values of both hardness and strength, but pretty low values of impact properties. The residual stresses are also on a high level. So, any kind of tempering has to be done - depending of the steel type. However, the tempering [1-4] is provided in a wide temperature range (even up to Ac_1 point), and then a wide diapason of structures will appear: from the untransformed martensite (with different amounts of retained austenite) to the structure, which contains carbide globules into ferrite matrix.

Although the tempering temperature shows a dominant influence on the structure changes, the tempering time also has a strong influence but is usually less investigated. One more reason for investigating the tempering time is a fully diffusion character of all processes which are involved in tempering processes [1,4]. In relation with the processes mentioned, many efforts are still made to find out one proper parameter, which will include both the temperature and time of tempering. Only in that way, *i.e.*, on the equivalency of a simultaneous influence of tempering temperature

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and time, it can become an optimal solution even for industrial practice.

Here, an optimal tempering regime means first of all the spending energy needed for heating-up for a minimum of time.

At the same time, there is a tendency determining the proper equations that will closely define the relationships between the temperature and time, when quenched metal is further subjected to tempering. Some parametric equations in which the hardness values are expressed through the one parameter were developed [3].

Hollomon and coworkers have proposed the parametric equations in which, besides the temperature or time, the activation energy for the tempering process is included [5]. Craft and Lamont have proposed the so called "additive" method for hardness value determinations during tempering, in accordance with the chemical composition of steel and also from the kind of the structure obtained after quenching [5].

Hollomon-Jaffe approach

For determining the functional temperature (T) and time (τ) relationship during tempering, Hollomon--Jaffe proposed an equation in which the hardness (H) is changed in the manner of other diffusion processes [3,4], and that function is expressed as:

$$H = f_1(\tau \exp(-Q/RT)) \tag{1}$$

where Q is an activation energy for the tempering process, and R is universal gas constant.

The solution of Eq. (1) could also be written in the parametric expression:

$$p = H = f(T(c + \log \tau)) \qquad (2)$$

The value of the parameter c in this case depends upon the carbon content in steel and the former treatment. In the mathematical and physical manner, the value of parameter c also depends on the fact whether the time is expressed in s or in h. From the Eq. (2), it is possible to calculate the same tempering hardness value using adequately chosen pairs of tempering temperature and time. This further means that solutions of Eq. (2) are:

$$T_1(c + \log \tau_1) = T_2(c + \log \tau_2) \qquad (3)$$

From Eq. (3), the value of parameter c, which is a constant for each steel grade, could be easily calculated as:

$$c = \frac{T_2 \log \tau_2 - T_1 \log \tau_1}{T_1 - T_2} \qquad (4)$$

But, these equations still have no implication on the functional character of the hardness changes depending on the expression $T(c + \log \tau)$, as it could be seen from Eq. (2). It could just be said that there is a kind of relationship between hardness and the parameter. In other words, when the parameter c has one constant value, then the same value of hardness will be obtained: a) at higher temperature but lower time of tempering or b) at lower temperature but higher time of tempering.

From careful analysis of Hollomon and Jaffe efforts, it becomes evident that they have made a lot of experiments using unalloyed steels. They also have broadened the same equation on some alloyed steels, but not for their own results - they used literature data. Some of these steels have had different amounts of retained austenite. Summarizing these facts, Hollomon and Jaffe have concluded that, for finding the true values for the tempering process, the exact experimental data are needed. The finding of these results for each type of steel is a tedious job.

The same question could be stated for the application of Hollomon-Jaffe equation on any of high strength low-alloyed steel. There is no better way than to make own experimental data, as we did for one of the HSLA steels. Optimal properties of the chosen steel are attainable after quenching and tempering. In a lot of literature sources [6-8], there were no fully systematized data on used steel, on its behavior after different regimes of tempering.

EXPERIMENTAL RESULTS

High-strength low-alloyed (HSLA) steel was used for investigations described in this paper. This steel belongs to a group of low-alloyed structural steels which attain their full advantages after quenching and tempering. The fact that this steel has a wide range of practical applications influenced this choice. A steel plate, 0.8 mm thick, was taken for the investigation directly from the production process. The chemical composition of used HSLA steel, in wt.%, is presented in Table 1.

Table 1. Chemical composition of used HSLA, %

Element	C	Si	Mn	Cr	S	P	Cu	Ni
Content	0.30	0.90	0.98	1.0	0.016	0.018	In traces	In traces

An initial heat treatment consisted of austenitizing in the vacuum furnace at 870 °C for 30 min, quenching into the oil, and then tempering.

Structure at the beginning

After providing an austenizing treatment, at the beginning of these experiments the structure consists of carbide globules in ferritic matrix, see Fig. 1.
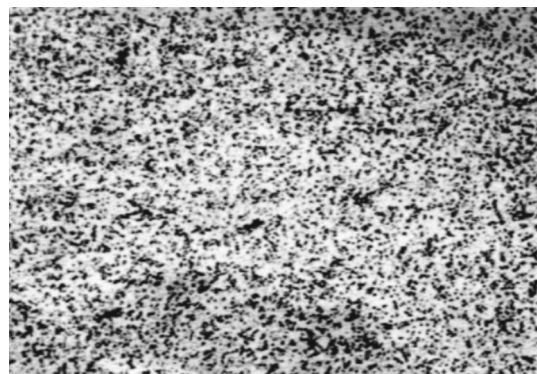

Figure 1. Microstructure of used HSLA steel at the beginning of experiments, 500×, nital etching.

In this state, the used steel has the following mechanical properties: R_m = 661.7 MPa, A = 23.8%, HV = 174 daN/mm^2.

Structure after quenching

The structure of quenched steel in oil, as stated above, consists of a mixture of massive and acilular martensite with retained austenite, Fig. 2.

Hardness after quenching was about 627 HV, and according to carbon content this is a maximal value that could be obtained in such steel. Such as high hardness value in this study could be explained by the fact that here a pretty thin sample, a relatively

high austenitizing temperature and a long time of soaking during an austenitizing process were used, and also through a high quenching rate.
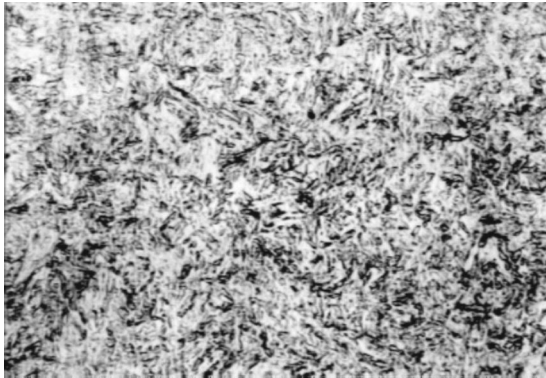

Figure 2. Microstructure of quenched HSLA steel, 500×, nital etching.

Structure of tempered steel

Tempering parameters, temperature and time, were varied in a wide range. The tempering temperatures were: 400, 450, 500, 550, 600, 650 and 680 °C, while the tempering times were: 15 min, 1, 3, 6 and 24 h.

A detailed analysis of the investigated steel achieved hardness values, and the possibility to apply these results for verifying the suggested equation indicated that tempering of steel samples for above stated times did not enable collecting enough data, so for the tempering at higher temperatures, much shorter time periods had to be used. In this case, for tem-

pering at 550 °C the initial time was 2 min, and at 600 °C the tempering times were the following: 1, 2, 3, 4, 5, 6, 8 and 10 min; while for 680 °C the tempering times were varied in the range from 30 s to 5 min.

While varying one of the indicated parameters, the other parameters remained constant.

Since the metal surface layer can oxidize or decarbonize when the steel is quenched from the temperatures at which the furnace atmosphere reacts with the heated metal, the examined steel was austenitized in a vacuum furnace.

It can be observed that hardness curves have a similar tendency when the steel hardness dependence on the tempering time, at different temperatures, is plotted (Fig. 3). Hardness rapidly declines at the beginning of tempering, and the change is greater with a higher tempering temperature, for the same observing time. This behavior indicates that the obtained results are in accordance with a diffusion character of the complex steel tempering process.

Metallographic investigations indicated that the martensitic structure during tempering undergoes the transformation into a ferritic-carbide mixture with the retained martensitic morphology. This microstructure is obtained at lower tempering temperatures ($<$ 400 °C) even after tempering for 24 h (Fig. 4).

A uniform distribution of coagulated carbide particles in a ferritic matrix cannot be obtained until the highest tempering temperatures are used. For the examined steel, these temperatures were above 600 °C, and a microstructure can be seen in Fig. 5.
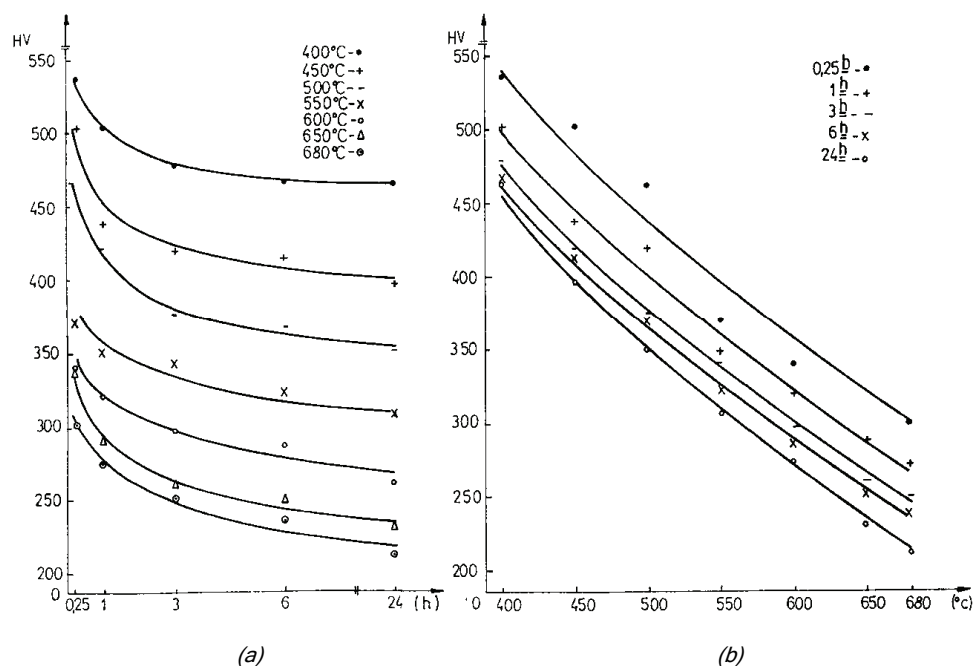

Figure 3. Hardness-tempering time dependence at a) constant temperature and b) constant time.
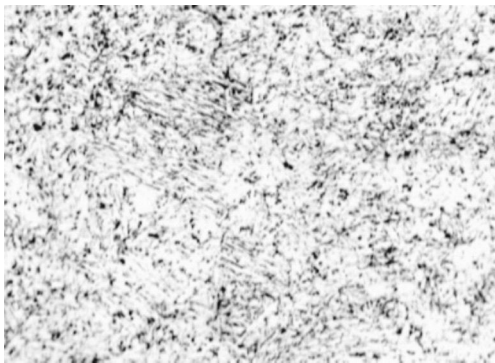
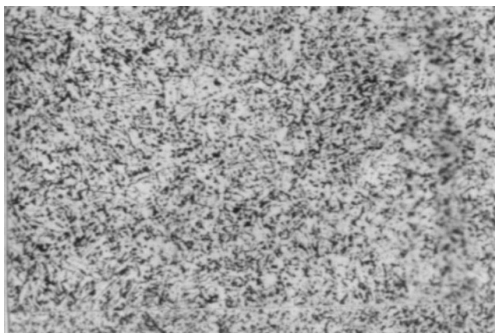*Figure 4. Microstructure of tempered HSLA steel; 400 °C; 24 h; 500×, nital etching.*

Figure 5. Microstructure of tempered HSLA steel; 680 °C; 24 h; 500×, nital etching.

RESULTS ACCORDING TO HOLLOMON-JAFFE EQUATION

The validity of Hollomon-Jaffe equation for chosen HSLA steel is tested after obtaining the experimental data [5]. The parameter of tempering, $p = T(\log \tau + c)$, which is proposed by the mentioned authors, is calculated for two different values of constant c to be 20 and 15.96, if tempering time is expressed in hours and seconds, respectively.

Some obtained results are presented in Tables 2 and 3. It could be noticed that, for the examined steel, with increasing the values of parameter p, the hardness is continuously decreasing.

It was found that the equivalent hardness values, obtained after tempering at different conditions, corresponded closely to the values of parameter p, even for the calculations with different values of constant c, for adequate experimental conditions. For example, when the hardness value is 370 HV after tempering for 6 h at 500 °C or after tempering for 15 min at 550 °C, the parameter p has matching values of 15.69 and 15.57; or values of 16.06 and 15.96 (Table 2).

Similarly, when tempering is carried out at 600 °C for 24 h, the hardness of 262 HV is achieved, and the same hardness is obtained when tempering is carried out at 650 °C for 3 h; accordingly, parameter p has also comparable values of 18.24 and 18.44 (Table 3).

Table 2. Hardness values vs. parameter p, given at different tempering times, calculated for c = 15.96

T / K	τ / s									
	900		3600		10800		21600		86400	
	HV	p	HV	p	HV	p	HV	p	HV	p
673	536	12.73	503	13.13	478	13.46	468	13.66	464	14.06
723	503	13.67	437	14.11	421	14.46	417	14.67	397	15.11
773	464	14.62	421	15.09	376	15.45	370	15.69	351	16.15
823	370	15.57	348	16.06	342	16.46	324	16.70	308	17.20
873	340	16.51	321	17.04	297	17.29	287	17.72	262	18.24
923	339	17.46	289	18.01	262	18.44	254	18.73	232	19.29
973	302	18.02	274	18.60	253	19.05	238	19.34	212	19.91

Table 3. Hardness values vs. parameter p, given at different tempering times, calculated for c = 20

T / K	τ / h									
	0.25		1		3		6		24	
	HV	p	HV	p	HV	p	HV	p	HV	p
673	536	13.05	503	13.46	478	13.78	468	13.98	464	14.39
723	503	14.02	437	14.46	421	14.80	417	15.02	397	15.46
773	464	14.99	421	15.46	376	15.83	370	16.06	351	16.53
823	370	15.96	348	16.46	342	16.86	324	17.09	308	17.60
873	340	16.93	321	17.46	297	17.71	287	18.14	262	18.66
923	339	17.90	289	18.46	262	18.89	254	19.18	232	19.37
973	302	18.49	274	18.06	253	19.51	238	19.80	212	20.38

Through a careful analysis of the data from Tables 2 and 3, it could be stated that values of constant *c* practically have no qualitative different influence on the correlation character: hardness - parameter *c*. That is the reason for the change of tensile properties (R_p -yield strength, R_m -tensile strength, *A*- elongation) according to the parameter *p* for the whole range of applied temperatures, as it can be seen in Fig. 6.

For example, after tempering at 450 °C for 2 h, when parameter *p* has value of 15.11, such treated steel has R_m = 1240 MPa, R_p = 1129 MPa and *A* = = 11.80%.

steel. It implies than in a particular case, the most economical treatment (temperature and duration of the process) could be applied.

The provided analysis approved the expectations for the applicability of the Hollomon-Jaffe equation on the used steel.

Nomenclature

HSLA　High strength low-alloyed
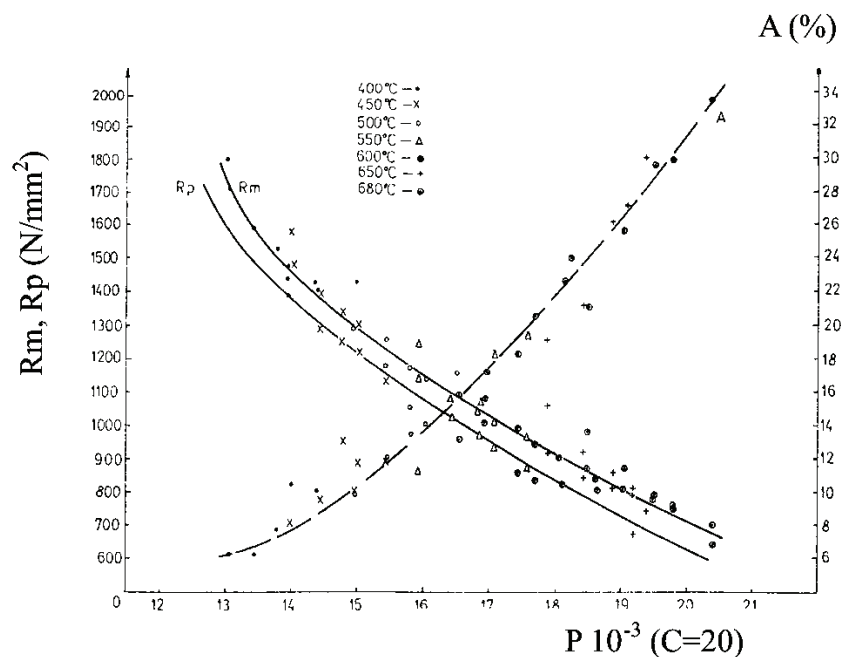*H*　　　Hardness
T　　　Temperature
Q　　　Activation energy

Figure 6. Changes of R_p, R_m and A vs. parameter p.

But, tempering at 500 °C for 1h gives similar results: R_m = 1256 MPa, R_p = 1180 MPa and *A* = = 12.00 %. This implies that applied tempering regimes with similar values of parameter *p*, will provide almost identical values of mechanical properties.

CONCLUSION

Based on the obtained experimental results and literature overview [1-7], for the used high-strength low-alloyed steel (0.30% C, 0.90% Si, 0.98% Mn and 1.0% Cr; Ni and Cu content in traces) it could be concluded that Hollomon-Jaffe parametric equation, $p = T(\log \tau + c)$ describes the changing of both hardness and mechanical properties depending on an unique parameter *p* relatively well.

It was stated that close values of hardness correspond to the close values of parameter *p*, which can be obtained by different regime of tempering the used

R　　　Universal gas constant
τ　　　Time
p　　　Hollomon-Jaffe parameter
c　　　Constant
R_p　　Yield strength
R_m　　Tensile strength
A　　　Elongation

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