EXPERIMENTAL STUDIES ON BULK TEMPERING OF 34CrNiMo6 STEEL

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The class of steels for hardening and tempering, alloyed with chrome, nickel and molybdenum, standardized in Europe (four steel grades), USA (10 grades) and Russia (9 grades) is highly diversified and is especially interesting in the production of machine parts having an extremely large range of dimensions. The heat treatment features of these steels are particularly attractive: high bainitic hardenability and a good temperability etc. The correlation between the hardness achieved after high tempering on products made from these steels, their equivalent diameter and the heat and time parameters of tempering can be explained by means or Jominy samples test for products with equivalent diameters equal to or less than 100 mm, or by the results obtained through the method of simulation of oil cooling (Pavaras-Gheller method) for products with equivalent diameters higher than 100 mm. In this paper, based on experimental results, these correlations are customized for a steel group representative as is 34CrNiMo6.

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INTRODUCTION

The studied 34CrNiMo6 steel [1] belongs to the class of steels for quenching and tempering, alloyed with 0.4–2% Cr, 0.5–4% Ni and 0.15%–0.5%Mo, with the carbon content within 0.3–0.45%, standardized in Europe (4 grades), U.S. (10 grades),and Russia (9 grades). These steels are widely used in industry for the manufacture of parts (machine parts) with very different thicknesses (D_{ech} = 15–200 mm). The main heat treatment features of these steels are low quenching temperature, high bainitic hardenability and good temperability, due to high proportions of martensite and bainite of the quenched structure. The standardized chemical composition of 34CrNiMo6 steel (SR EN 10083-1:1995) in weight % is :

C	Si	Mn	P	S	Cr	Ni	Mo
0.3–0.38	max 0.40	0.30–0.80	max 0.030	max 0.030	1.30–1.70	1.30–1.70	0.15–0.30

Fig. 1 presents the TRC chart and the hardenability band of the 34CrNiMo6 steel confirming its high bainitic hardenability.

MATERIAL AND RESEARCH METHODOLOGY

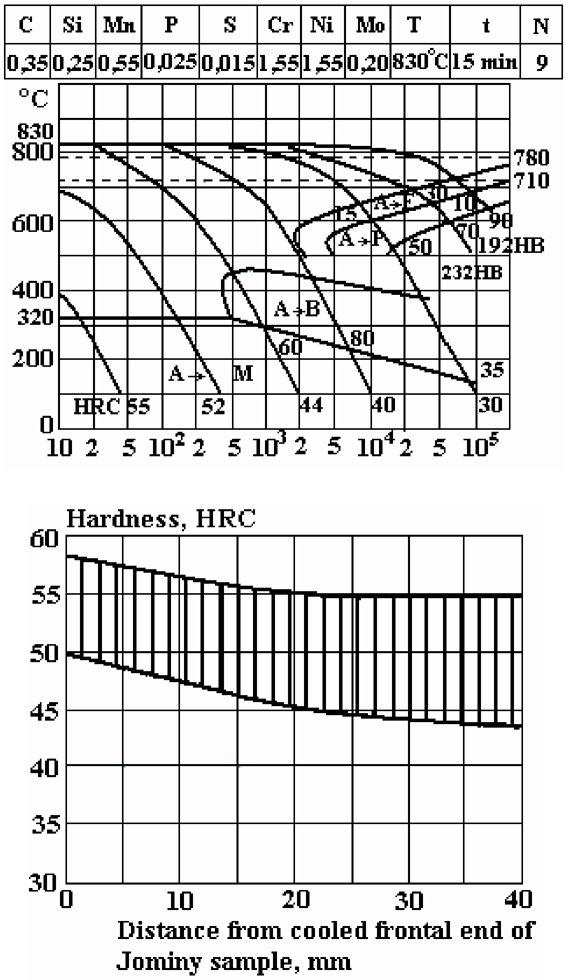
Samples taken from a Ø 40 mm bar, hot rolled and normalized, with the following chemical composition (in weight %) were used:

C	Si	Mn	P	S	Cr	Ni	Mo
0.35	0.31	0.65	0.018	0.022	1.40	1.50	0.16

For the parts with the equivalent diameter $D_{ech} \leq 100$ mm Jominy samples were used and for the parts with the equivalent diameter between 100 and 180 mm were used samples for oil cooling simulation of cylinders with the equivalent diameters D_{sim} = 60, 120 and 180 mm (fig. 2). The samples taken from the studied steel bars with square section, dimensions □ $20xR_{sim}$, packed in asbestos with h thickness, dependent on the simulated cylinder diameter, were used accordingly to the table shown below:

R_{sim},mm	30	60	90
h, mm	6	16	24

The asbestos layer is sealed with steel sheet having the thickness g = 2 mm.



C	Si	Mn	P	S	Cr	Ni	Mo	T	t	N
0,35	0,25	0,55	0,025	0,015	1,55	1,55	0,20	830°C	15 min	9

Fig. 1. TRC chart (up) and hardenability band (down) of 34CrNiMo6 steel

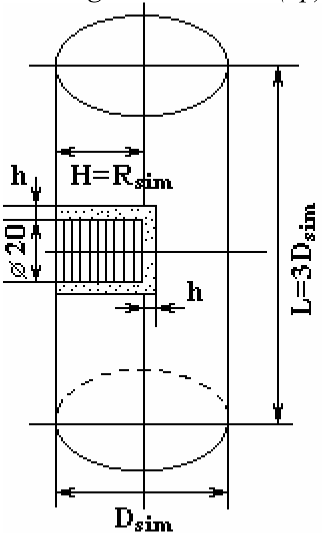


Fig. 2. Simulation of oil quenching of a cylinder with DsimxL dimensions by means of a square section sample with □20XH=R_{sim} dimensions, packed in an asbestos layer with h thickness (the Pavaras-Gheller method)

Jominy samples were austenitized at T_A = 830°C/t_A = 45 min and frontal quenched; the simulation samples of the cylinders with 60, 120 and 180 mm diameters were cooled in oil at 60°C, with moderate agitation (H_{rel} = 0.5). After the frontal quenching one Jominy sample was kept in as-quenched state and five samples were tempered at the temperatures and isothermal maintaining times listed in table 1.

Table 1. The tempering parameters of the frontal quenched Jominy samples

Tempering temperature, °C/K	500/773	550/823	600/873	650/923	700/973
Isothermal maintaining time, t_{iz}[h]	1.0	1.6	1.6	5.0	5.0
lgt_{iz}	0	0.2	0.2	0.7	0.7
P_{HJ}=T_{rev}(19+lgt_{iz})	14678	15800	16762	18183	19168

From the simulation samples quenched in oil, one was kept in the as-quenched state, and three samples were tempered according to the data shown below:

T_{temp},°C/K	500(773)	600(873)	700(973)
t_{iz} [h]	1	1.6	5.0
P_{HJ}	14678	16762	19168

Both for the quenched samples and quenched and tempered samples, the HRC hardness measurements were made. For the frontal quenched sample also a microstructural analysis was made.

EXPERIMENTAL RESULTS ON JOMINY SAMPLES

The hardnesses taken on length of Jominy samples are given in table 2.

Table 2. The hardnesses taken on length of quenched and tempered Jominy samples.

d_J, mm / Condition	1.5	3	6	9	12	18	27	36	45
Frontal quenched	55	54	53	52	51.5	50	49	48	47
Tempered 500°C/1h	46	45	44	42	40.5	39	34	31	28
Tempered 550°C/1,6h	41,5	40,5	39,5	38	37	35	31	28	25
Tempered 600°C/1,6h	38	37.5	36	35	34	32	29	26	24
Tempered 650°C/5h	34	33	32	31	30	28	25.5	23.5	22
Tempered 700°C/5h	30	29.5	29	28	27	25	23.5	22	21

The results shown in table 2 are also emphasized in fig. 3.

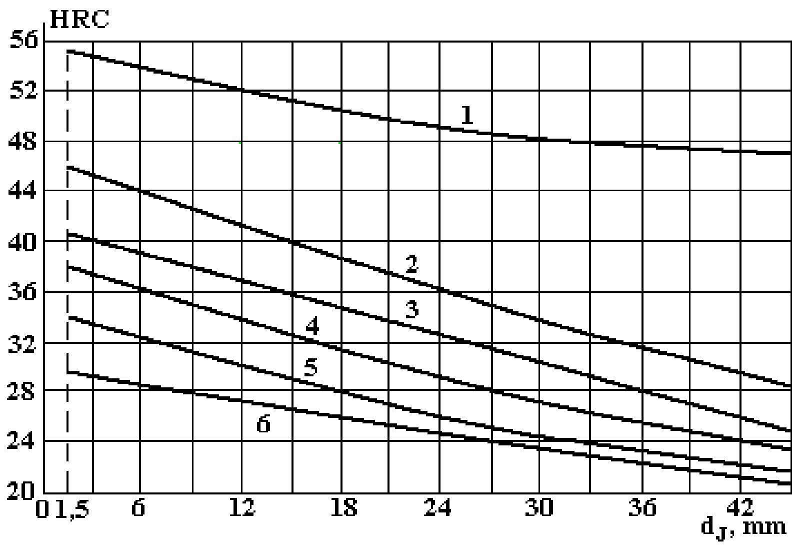


Fig. 3. Hardness variations in the frontal quenched Jominy samples, respectively in the frontal quenched and tempered Jominy samples. 1 – frontal quenched; 2 – tempered 500°C/1h; 3 – tempered 550°C/1,6h; 4 – tempered 600°C/1,6h; 5 – tempered 650°C/ h; 6 – tempered 700°C/5h

Fig. 4 shows the microstructures obtained at few distances from the cooled end of a Jominy sample and the corresponding hardnesses of these microstructures, which are in accordance with the bainitic hardenability specific to steel.

EXPERIMENTAL RESULTS OF THE SIMULATING QUENCHING AND TEMPERING ON SAMPLES WITH SIMULATING DIAMETERS OF 60, 120 AND 180 mm

These results have been obtained through determining the hardness on simulating samples, that had allowed the graphical representation of hardness variation in the cross section of parts with the given diameters (fig. 5).

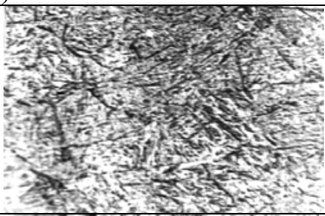
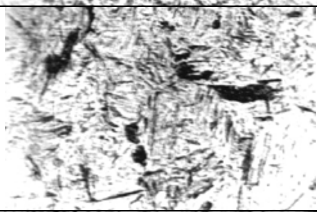
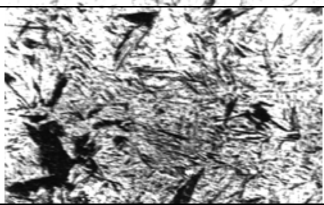
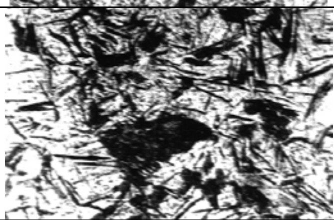
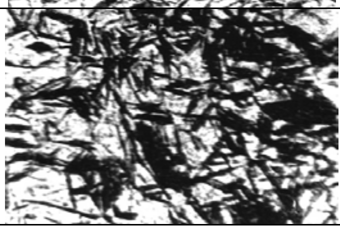
	d_J = 2.5 mm	98%M+2%B	54HRC
	d_J = 5 mm	96%M+4%B	53HRC
	d_J = 12.5 mm	92%M+8%B	51HRC
	d_J = 30 mm	75%M+25%B	48HRC
	d_J = 45 mm	50%M+50%B	47HRC

Fig. 4. Microstructures (nital 2%) and hardnesses in the frontal quenched Jominy sample

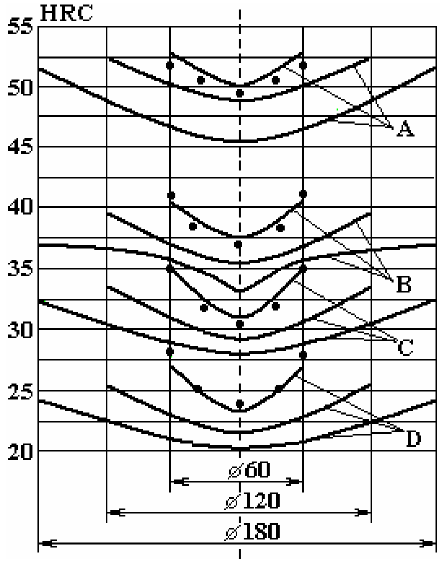


Fig. 5. Hardness variations in the cross-section in the samples of 60, 120 and 180 mm simulation diameters. A – oil quenched; B – quenched and tempered 500^{o}C/1h; C – quenched and tempered 600^{o}C/1,6h; D – quenched and tempered 700^{o}C/5h; ● – experimental data in Jominy samples for D = 60 mm

Note. Fig. 5 also gives the hardness values (black circles) in *S*; 3/4*R*;1/2*R* and *C* points in the sample with D_{sim} = 60 mm, taken from the diagram that show the connection between these points from the cross section with the distance in the Jominy sample d_J (fig. 6). These values are close or similar to those experimentally determined on the simulating sample, therefore the simulating method used in this work is available also for diameters larger than 100 mm.

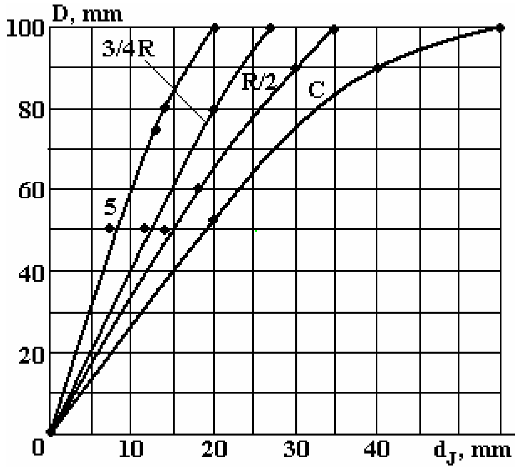


Fig. 6. Correlation between the diameter of the piece, D, and distance d_J from the end of Jominy sample, cooled to quench the piece in oil 60^{o}C with moderate agitation (H = 0.5)

PROCESSING, DISCUSSION AND INTERPRETATION OF EXPERIMENTAL RESULTS DETERMINED ON JOMINY SAMPLES

The experimental results presented in table 2 and illustrated in fig. 3 demonstrate that hardness decreases after tempering with the increase of the tempered parameter P_{HJ} and the distance from the cooled end of the Jominy sample d_J. To process this dependence and determine the mathematical expression of the correlation $HRC_{rev} = f(P_{HJ}; d_J)$, in fig. 7 were plotted $HRC_{rev} = f(P_{HJ})$ curves at some significant distance from the Jominy sample (d_J = 9, 18, 27, 36 and 45 mm). It is evident from fig. 7 that these curves are straight lines, in fact, the straight lines having the following general equation:

$$HRC_{Rev} = HRCo - m\,(P_{HJ} - 14700) \quad (1)$$

in which both the ordinate at the origin (HRCo),and the straight lines slope (*m*) decrease when increasing distance d_J. Further mathematical processing has shown that both HRCo and *m* are linearly dependent on distance d_J (fig. 8), having concrete equations, as below:

$$HRCo = 45.5 - 0.39d_J \quad (2)$$

respectively:

$$m = 0.0035 - 0.000043d_J \quad (3)$$

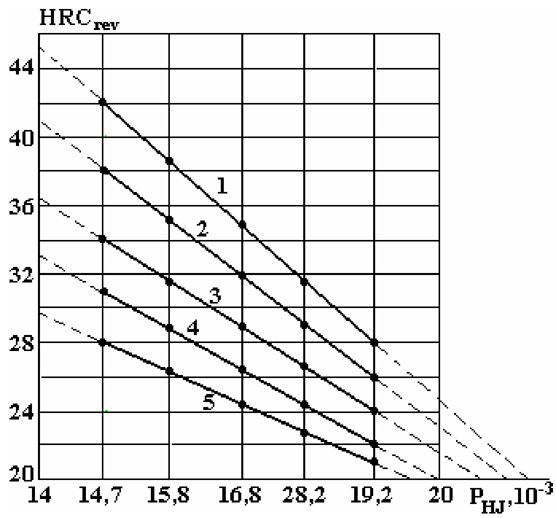


Fig. 7. Variations of hardness after tempering, with the tempered parameter, P_{HJ} and distance from the end of the cooled Jominy sample d_J mm: 1 – 9; 2 – 18; 3 – 27; 4 – 36; 5 – 45

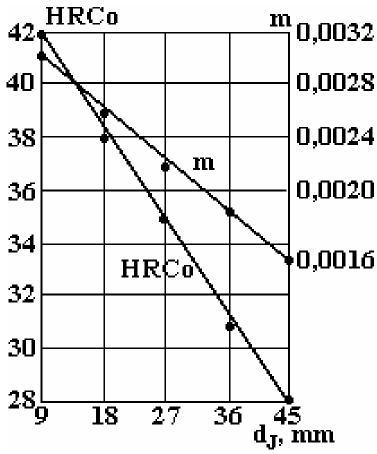


Fig. 8. Dependence of the ordinate at the origin (HRCo) and slope (m) of the straight lines $HRC_{rev}=HRC_o-m\ (P_{HJ}-14700)$

With these explanations, the general equation (1) has the form:

$$HRC_{rev}=(45.5-0.39d_J)-(0.0035-0.000043d_J)(P_{HJ}-14700) \quad (4)$$

which can be written in an explicit polynomial form:

$$HRC_{rev}=97-0.0035P_{HJ}-1.022d_J+0.000043P_{HJ}.d_J. \quad (5)$$

From the equation (5) results that the hardness of steel 34CrNiMo6 after tempering decreases more rapidly with P_{HJ} tempering parameter, more slowly with the d_J distance and slightly increases with $P_{HJ}\text{x}d_J$ product. That product is the result of ongoing changes in the conditions of decomposition reactions of structure hardening during the tempering stage IV, in the sense that the longer the d_J distance, the lower the proportion of martensite, and simultaneously the higher the proportion of bainite (fig. 9) will be. This phenomenon has two significant effects, respectively:

a) a decrease of the initial hardness HRCo (fig. 8, derived from data in fig. 4);

b) a decrease of the softening rate, respectively of the slope *m* of the straight lines from fig. 8, because bainite softens more slowly than martensite.

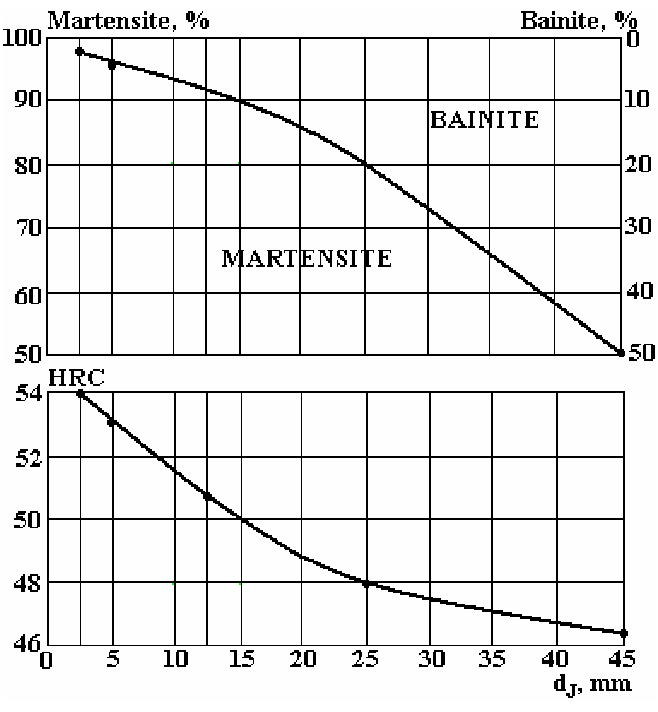


Fig. 9. Variations of the proportions of martensite and bainite (up), hardness (down,) with the distance d_J of Jominy samples of front quenched 34CrNiMo6 steel

On the other hand, the tempering parameter directly influences the kinetics of the softening process through high tempering, because the tempering temperature leads to the exponential increase of the softening process rate and the increase of the isothermal tempering time also leads to the parabolic increase of the softening process rate.

PROCESSING AND DISCUSSION OF EXPERIMENTAL RESULTS OBTAINED BY THE METHOD OF SIMULATION OF PARTS WITH THE EQUIVALENT DIAMETER GREATER THAN 100 mm

In the mathematical processing the experimental results obtained on simulation diameters 60, 120 and 180 mm, in the main points of the cross section (*C*, *R*/2 and *S*), in the three values of parameter of tempering (P_{HJ} = 14700, 16800, and 19200) were used. First, the results plotted as shown in fig. 10, demonstrate that hardness linearly varies with the tempering parameter and evidenciate that the straight lines slopes are much smaller at larger diameter , and that the points in the cross section are deeper placed from the surface, so the structure contains less martensite.

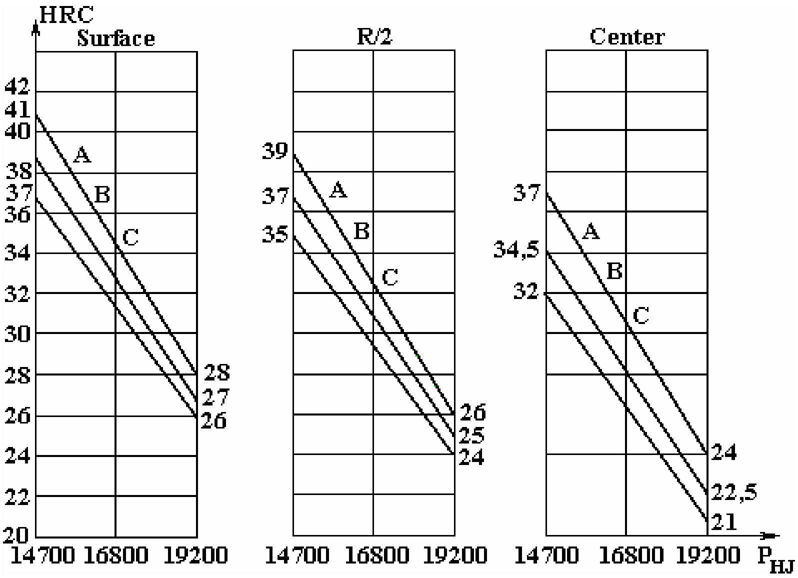


Fig. 10. Variation of hardness after tempering, with the tempered parameter and the diameter of the piece, in the main points of the cross section: A:D = 60 mm; B:D = 120 mm; C:D = 180 mm

As the second step the results were mathematically processed, and finally the equation of straight line was determined: HRC= HRCo – mP_{HJ}, which has the general expression:

$$HRC = [76-0.1D+ (25-0.001P_{HJ})\, r/R]-(0.003-0.000004D)P_{HJ}. \quad (6)$$

where: r/R is the coordinate point of the cross section of a machine part with the equivalent diameter $D = 2R$ From equation (6) it is found that after tempering hardness is even lower, as the tempered parameter and the part diameter are larger and the corresponding point is placed deeper from the surface (as in fig. 10).

At the end of this section it should be noted that the results obtained by applying relation (6) lead to linear changes in hardness in the cross section of the part and, as a result, to deviations of up to ±2.5 HRC against to the real situations in which hardness variation in cross-section occurs in accordance with curves having the minimum in the centre section (fig. 5). With this specification, the simulation method can be applied with satisfactory results in the case of parts with diameters larger than 100 mm, and for the parts with diameters up to 100 mm the method of Jominy samples can be applied.

CONCLUSION

The experimental research into the bulk tempering of steel 34CrNiMo6 was performed on Jominy and simulation samples. It resulted in the production of two general relationships for the dependence of hardness after tempering on the Hollomon-Jaffe parameter, namely:

$$HRC = 97-d_J-0.0035P_{HJ}+ 0.000043P_{HJ}d_J \quad (5)$$

applicable to parts with $D_{ech} \leq 100$ mm, with an accuracy of ± 1HRC, also:

$$HRC = [76\text{-}0.1D+(25\text{-}0.001P_{HJ})r/R]\text{-}(0.003 - 0.00000\ D)\ P_{HJ} \qquad (6)$$

applicable to parts $100 < D_{ech} \leq 180$ mm, with precision ± 2.5 HRC.

Equation (5) is more accurate and leads to graphical presentation of straight beam lines, converging at the point of coordinates (P_{HJ} = 23 000; HRC = 16), as can be seen from fig. 11. This graphical result evidences that the point of convergence would be the highest tempering at the softest structure, consisting of polyhedral ferrite and globular carbides with a very small degree of dispersion.

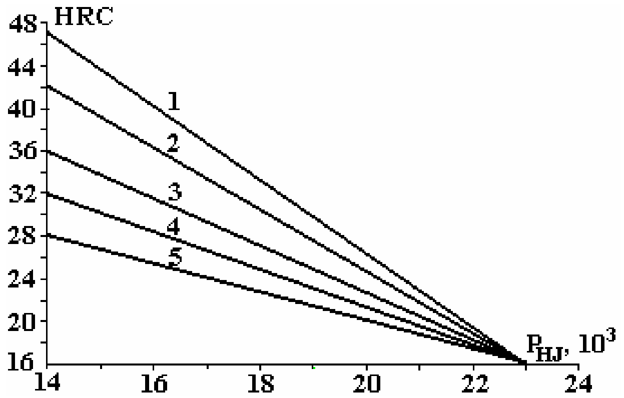


Fig. 11. The dependence of hardness on the P_{HJ} tempering parameter and d_J distance from the end of front quenched Jominy samples of 34CrNiMo6 steel. d_J, mm: 1 – 2; 2 – 20; 3 – 30; 4 – 40; 5 – 50

REFERENCES

1. Standard of steel SR EN 10083-1:1995.

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Реферат

Номенклатура сталей, подвергаемых закалке и отпуску, легированных хромом, никелем, и молибденом, имеющих аналоги в Европе (4 марки), в США (10 марок), и России (9 марок), довольно обширна. Такие стали представляют особый интерес при производстве деталей машин и механизмов различных размеров. Наиболее привлекательны характеристики жаропрочности таких сталей, а именно высокая способность к закаливанию (в случае бейнитной стали), хороший отпуск и др. Корреляции между твердостью деталей из такий сталей, полученных путем высокого отпуска, их эквивалентным диаметром и режимом отпуска (температурой и временем выдержки) можно определить с помощью теста Джомини для деталей с эквивалентным диаметром ≤ 100 мм, либо с помощью моделирования охлаждения в масле (метод Павараса-Геллера) для деталей с эквивалентным диаметром > 100 мм. В представленной работе на основе данных, полученных экспериментально, указанные корреляции описаны на примере такой распространенной марки стали как 34CrNiMo6.