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End -quench Hardenability Test for Gas Quenched Steels

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Hardenability is usually characterized by the Jominy end-quenched test. For steel grades quenched in oil or water this test is enough selective, and for them a good fixed correlation between cooling time from 800 to 500 °C ($t_{8/5}$) and the distance from the quenched end can be established. For steel grades of high hardenability, the Jominy test is not enough selective and sensitive. To establish hardenability for these steels a new hardenability testing method with the modified Jominy test specimen has been proposed after initial investigations at Stiftung Institut für Werkstofftechnik at University of Bremen. The proposed method is based on the high pressure gas end-quenching of cylindrical specimen with variations of kind of gas, pressure and its velocity to achieve more gradual decrease of cooling rates along the specimen and to make the hardenability test more selective with a broader range of lower cooling rates. The conducted experiments and the heat transfer simulation of cooling curves at different locations in the end-quenched probe gives possibilities for determination of cooling time t8/5 at different distances from the quenched end, for set quenching conditions. In addition, from the conducted end-quenched tests and simulation results, the relation between hardness distribution and the cooling times t8/5 has been established for tested quench conditions.

Ispitivanje prokaljivosti čelika kaljivih u plinovima

Izvornoznanstveni članak

Prokaljivost čelika uobičajeno se ispituje Jominy pokusom čeonog gašenja. Za čelike kaljive u vodi ili ulju ovo ispitivanje je zadovoljavajuće selektivno te se za njih može postaviti točna i pouzdana i ovisnost vremena ohlađivanja od 800 do 500 °C ($t_{8/5}$) i udaljenosti od čela Jominy epruvete. Za dobro prokaljive čelike, Jominy pokus čeonog gašenja nije dovoljno selektivan niti osjetljiv. Nakon početnih ispitivanja provedenih u Stiftung Institut für Werkstofftechnik, Sveučilišta u Bremenu za ispitivanje prokaljivosti ovih čelika predložena je nova metoda s izmijenjenim mjerama Jominy epruvete. Predložena metoda temelji se na gašenju valjkastih ispitnih epruveta nastrujavanjem plina visokog tlaka na čelo epruvete, uz varijacije vrste plina, iznosa tlaka i brzine nastrujavanja, u svrhu postizanja polaganije promjene brzine ohlađivanja po visini epruvete. Time se povećava selektivnost ispitivanja prokaljivosti u području malih brzina ohlađivanja. Provedenim pokusima čeonog gašenja epruveta i računalnim simulacijama prijenosa topline određeno je vrijeme ohlađivanja t8/5 na nizu udaljenosti od čela uz ohlađivanje zadanim uvjetima gašenja. Iz provedenih pokusa čeonog gašenja i rezultata računalnih simulacija utvrđena je veza između iznosa tvrdoće i vremena ohlađivanja t8/5 za ispitane uvjete gašenja.

1. Introduction

Hardenability of steels is usually determined by the Jominy test. When a standard Jominy specimen is used (the quenched end is cooled by a stream of water), the cooling rate varies along the specimen's length, as shown in Figure 1. It is very high (270 K/s) at a distance of 1.6 mm from the quenched end. It decreases rapidly, but still at a distance of 80 mm is approximately 0.7 K/s (when the standard austenitization temperature 850 °C is used). The hardenability of all steel grades with the critical cooling rate greater then 0.7 K/s can be determined by the standard Jominy end-quench test, as a sufficient decrease in hardness will be obtained from increasing amounts of non martensite transformation products (bainite, pearlite, ferrite) (Figure 2). However, for steels with a critical cooling rate lower than 0.7 K/s, there will be no substantial change in the hardness curve, because martensite will be obtained at every distance along the Jominy specimen. This is the case with air hardening steels. So, for high alloyed steels having much lower critical cooling rates

Symbols/Oznake

$t_{8/5}$	- cooling time from 800 to 500 °C - vrijeme ohlađivanja s 800 na 500 °C	z	- distance from the quenched end - udaljenost od gašenog kraja
HPGQ	- High Pressure Gas Quenching - Visokotlačno plinsko gašenje	HRC	- Rockwell C hardness - tvrdoća po Rockwellu C
p	- pressure - tlak	CCT	- Continuous Cooling Transformation - Transformacija kontinuiranim ohlađivanjem
v	- velocity - brzina		

than 0.7 K/s the standard Jominy test, using a stream of water, is obviously to severe [1-3].

Today high alloyed steels are hardened primarily by gas quenching in vacuum furnaces (the High Pressure Gas Quenching – HPGQ). In order to differentiate and determine their hardenability when gas quenched, a new Jominy like test method is necessary. This method should be less severe i.e. start with lower cooling rates at quenched end and extend the range of cooling rates enough below the critical cooling rates of those steels. The details of design of modified end-quenched specimen for testing hardenability in gas stream is described in [4-6]. In this paper the details for performing this test are investigated together with definition of corresponding transfer parameter which have the same value on test specimens and on the cross-section of a real workpiece after HPGQ process.

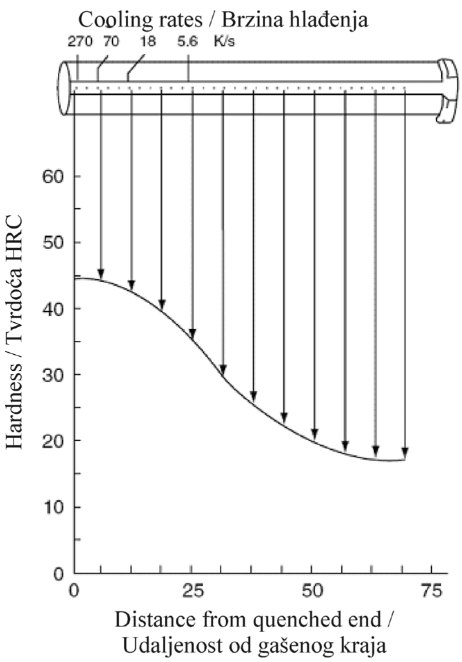

Figure 1. Measuring hardness and cooling rates on the standard Jominy specimen and plotting the Jominy hardenability curve [1]

Slika 1. Ispitana tvrdoća i brzine ohlađivanja normiranog Jominy ispitnog uzorka i prikaz Jominy krivulje prokaljivosti [1]

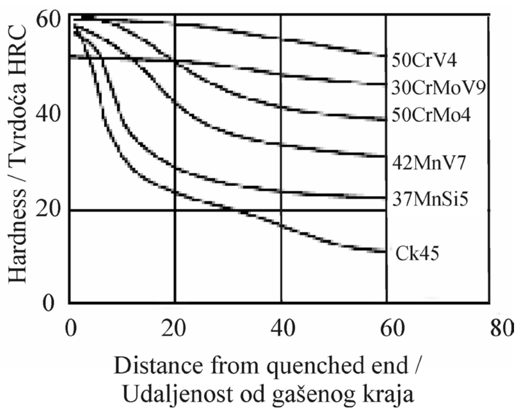

Figure 2. Jominy hardenability curves (average values) for selected steel grades (designations according to German DIN standard) [2]

Slika 2. Jominy krivulje prokalivosti (srednje vrijednosti) izabranih čelika (označenih prema DIN) [2]

2. Description of performed tests

Based on the already done investigation at the Stiftung Institut für Werkstofftechnik, the University of Bremen, Germany [4, 5], a modified Jominy specimen (Figure 3), to be used in a special gas end-quenching facility (Figure 4) is shown. The modified Jominy specimen is austenitized by induction heating and then it is end-quenched in a stream of pressurized gas (Figure 5). A tool steel grade EN-90MnCrV8 has been chosen for this investigation. It is a medium-alloyed cold work steel with high hardening capacity and limited through hardenability. Table 1 gives the chemical composition of the testing specimens. For recording the time-temperature curves during heating and cooling phases three thermocouples (TC1, TC2 and TC3) are mounted as shown in Figure 3. The first one is placed at the centre axis of the specimen 0.3 mm below the quenched end. The others two: "TC2" and "TC3" are mounted at 50 mm, and 90 mm from the quenched end, respectively (at the depth of 3 mm below the cylindrical surface of the specimen).

Table 1. Chemical composition of the tested tool steel grade EN-90MnCrV8

Tablica 1. Kemijski sastav ispitivanog čelika EN-90MnCrV8

% C	% Mn	% Cr	% V	% Si	% S	% P
0.86	2.06	0.28	0.079	0.24	0.010	0.023

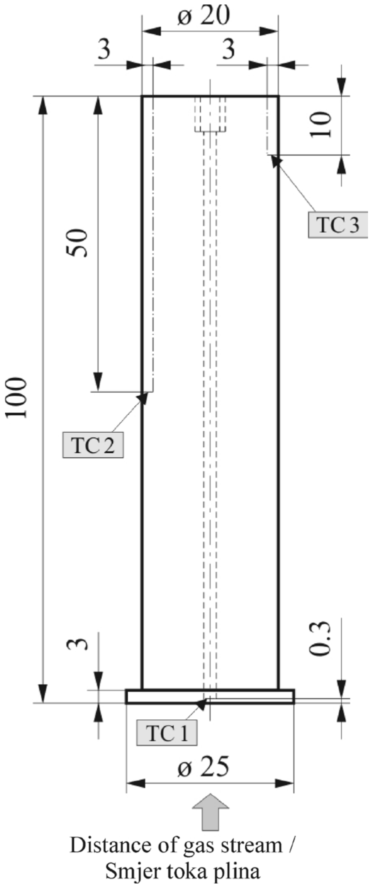

Figure. 3. The test specimen developed for gas end-quench hardenability testing [6]

Slika 3. Ispitni uzoraka razvijen za ispitivanja prokaljivosti u plinovima pokusom čeonog gašenja [6]

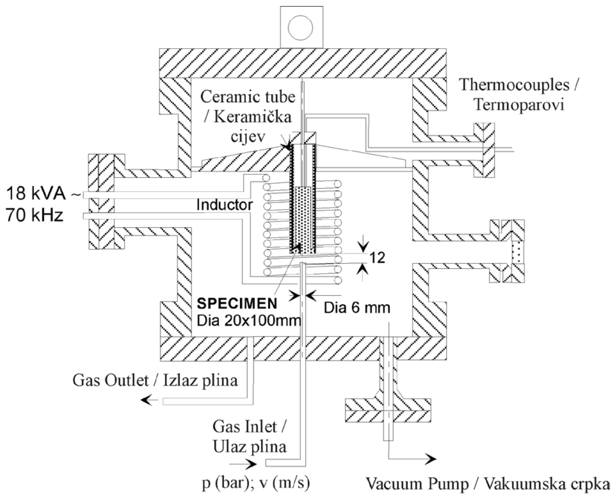

Figure. 4. The proprietary facility for end quench testing by a stream of pressurized gas developed at Stiftung Institut für Werkstofftechnik, University of Bremen; Germany [6]

Slika 4. Vlastiti uređaj za pokus čeonog gašenja u stlačenim plinovima razvijen na Stiftung Institut für Werkstofftechnik, University of Bremen; Germany [6]

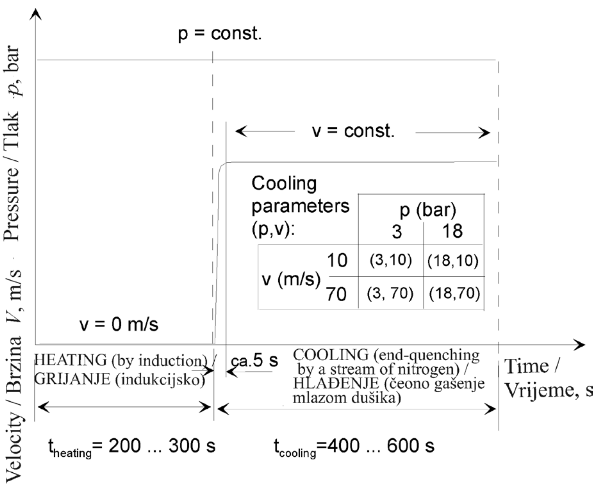

Figure 5. Diagram of the process parameters during gas end-quenched tests

Slika 5. Dijagram promjene radnih parametara tijekom pokusa čeonog gašenja u plinu

Figure 5 shows the investigated range of pressure and cooling conditions obtained with nitrogen as cooling gas. The specimens are induction heated to the austenitizing temperature between 790 and 820 ^{o}C for 3 to 5 minutes. Nitrogen has been used as cooling gas under constant pressure 3 or 18 bar with gas velocity 10 or 70 m/s, as shown in Figure 5. The facility needed less than 5 seconds for establishing stationary cooling conditions. Cooling times varied between 7 to 10 minutes. In addition, the standard Jominy test has been carried out with test specimens produced from the same cold rolled bar as specimens used in gas end-quenched test. After quenching hardness testing is performed at different distances from the quenched end for all tests.

3. Results and discussion

3.1. Simulation of gas end-quench cooling

For simulation of cooling by gas end-quenching a FEM model has been developed. The details about this model have been described in reference [6]. It is an unsteady and nonlinear 2-D axially symmetrical heat transfer model with a system consisting of a specimen, specimen holder, ceramic tube and a stream of gaseous nitrogen (Figure 6): Stream of nitrogen blows from a nozzle at distance 12 mm from the lower end of test specimen. The boundary conditions and steel properties have been taken as temperature dependent. The temperature distribution achieved after induction heating within the observed thermodynamic system is taken as the start condition for cooling simulation. The simulation task consisted of two parts.

The first part was searching the boundary conditions for which a good coincidence is achieved between calculated cooling curves at distances from the quenched end: 0.3 mm, 50 mm and 90 mm respectively, compared with experimentally recorded curves at the same distances. For each tested combination of pressure and gas velocity (Figure 5) used in end quenching, cooling curves at three locations in the specimen have been recorded (Figure 3). The recorded curves served as verification curves for testing of FEM simulations.

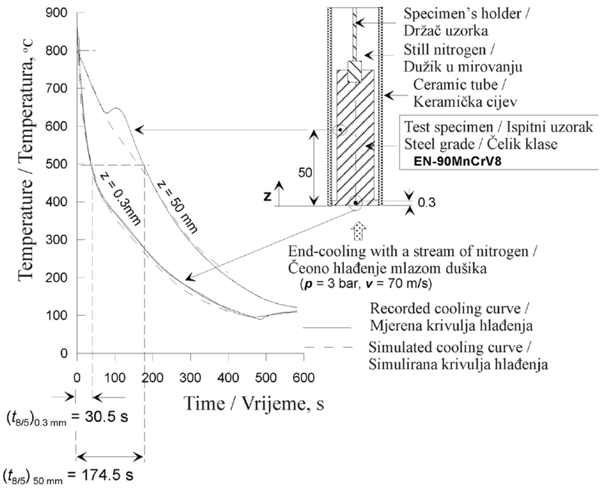

Figure 6. Geometry domains of the thermodynamic FEM model with calculated and recorded cooling curves and times $t_{8/5}$ at 0.3 mm and 50 mm from the specimen's quenched end

Slika 6. Geometrijske domene termodinamičkog FEM modela s izračunatim i snimljenim krivuljama ohlađivanja i vremenima ohlađivanja $t_{8/5}$ na udaljenostima 0.3 mm i 50 mm od gašenog čela ispitnog uzorka

The second task of FEM simulations was calculation of cooling times $t_{8/5}$ at different distances from the quenched end. The Figure 6 shows an example of achieved coincidence between the simulated and recorded curves at 0.3 mm and 50 mm from the quenched end, and determination of cooling time $t_{8/5}$ at the same distances from the quenched end.

3.2. Hardenability curves and cooling time $t_{8/5}$

Figure 7.a represents the hardenability curves for steel grade EN-90MnCrV8 after end-quenching tests using cooling parameters according to Figure 5. From these curves it is evident the increase of hardenability compared to standard Jominy hardenability at higher Jominy distances, when more intensive gas cooling is applied (e.g. with p = 18 bar and v = 70 m/s). Figure 7.b represents the dependence of hardness from cooling time $t_{8/5}$ observed after the same gas end-quenching experiments. From the curves at Figure 7.b it can be seen that gas end-quenching gives considerable longer cooling times $t_{8/5}$ compared to standard Jominy end-quench test (except in case of the most intensive gas cooling with 18 bar and 70 m/s) for the same value of hardness. From Figure 7.b follows that it is possible to produce a great influence on cooling time $t_{8/5}$ and hardness distribution along the modified end-quenched specimen by changing the impinging gas pressure The hardness value after cooling with a specified cooling curve depends from its shape and the position, due to temperatures of start and

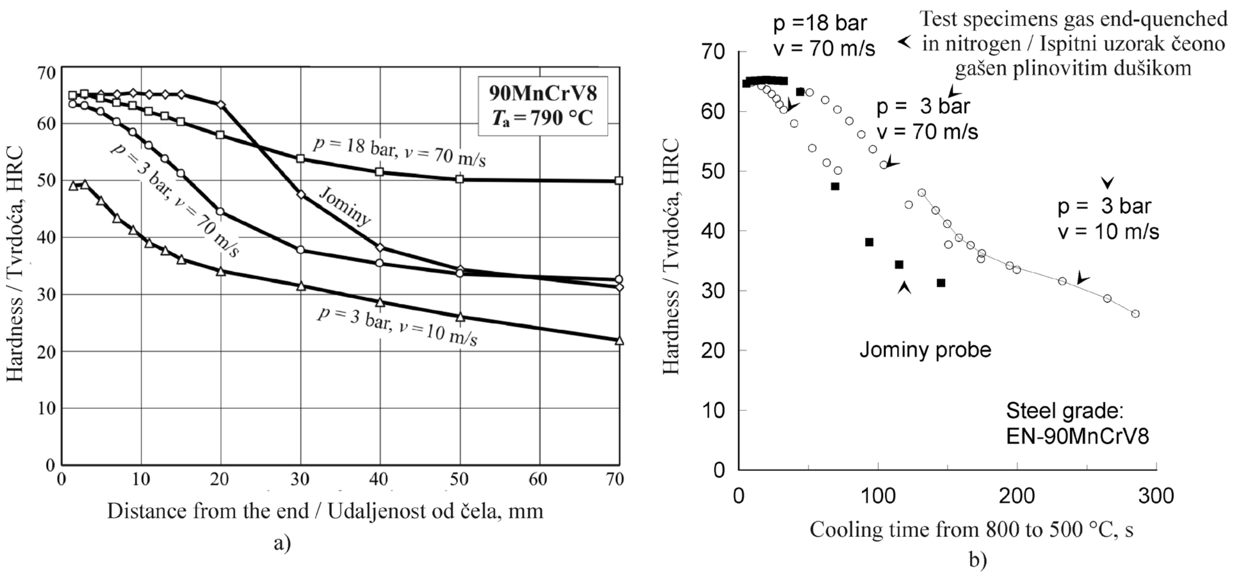

Figure 7. Hardenability curves for steel grade EN-90MnCrV8 after gas end quenching (with different cooling parameters) and standard Jominy testing with distribution of: a) hardness vs. distance from the quenched end [6]; b) hardness vs. cooling time $t_{8/5}$

Slika 7. Krivulje prokaljivosti čelika EN-90MnCrV8 nakon pokusa čeonog gašenja u plinu (s različitim parametrima gašenja) i normiranog Jominy pokusa s raspodijelom: a) tvrdoće zavisne od udaljenosti od gašenog čela [6]; b) tvrdoće zavisne od vremena ohlađivanja $t_{8/5}$

finish of phase transformations in the corresponding CCT diagram of selected steel grade. It is always, possible to have a few cooling curves with the same cooling time $t_{8/5}$ that will give a different value of hardness, and phase compositions after cooling. So, using the cooling time $t_{8/5}$ at some distance from the end-quenched specimen as the only one criterion for transmissions of hardness results from hardenability curve to a real workpiece quenched within a batch in vacuum furnace, has a limited feasibility. This prediction of hardness distribution is proved for quenching in liquid quenchants with continuous cooling [7], but it is necessary to be tested in cases of gas quenching. It seems that in cases of gas quenching it is necessary to perform the gas end-quenching experiments with the similar values of the average heat transfer coefficient at quenched end together with the cooling dynamic similar to that which will be produced in industrial conditions. In this case the same family of cooling curves $\vartheta = f(t)$ (with the similar shape) would be produced, and the equal function of hardness dependent of cooling time $t_{8/5}$ would be possible. This can be seen from Figure 7.b for cases of gas end-quenching with the following parameters: (p = 3 bar, v = 10 m/s), (p = 3 bar, v = 70 m/s) and (p = 18 bar, v = 10 m/s). Further simulations and experiments have to confirm this transfer of results or to indicate some other more adequate parameters.

4. Conclusion

There is a fixed relation between the cooling time 800-500 °C and the distance from the quenched end of the Jominy specimen, valid for all kinds of steel, because the Jominy test is always performed under same strictly specified conditions. For high pressure gas quenching the conditions vary in respect of: kind of gas, pressure and velocity of gas flow. Therefore for each combination of these parameters different relations between the $t_{8/5}$ and the distance from the quenched end of the specimen has to be established. Without having established those correlation for the real case, there is no possibility to accurately predict the hardness distribution after quenching, using the $t_{8/5}$ criterion.

The effect of gas pressure and velocity on the cooling time $t_{8/5}$ and on hardenability of the tool steel EN-90MnCrV8 is tested and validated. It is also shown experimentally that using extreme gas cooling conditions (N_2, p = 18 bar, v = 70 m/s) the same steel shows a higher hardenability at distances greater than 25 mm from the quenched end, compared to the standard Jominy test.

Further investigations will be directed towards development of a simulation algorithm for prediction of hardness distribution at the section of real workpieces quenched in a batch by high pressure gas quenching with different quenching parameters, in industrial vacuum furnaces.

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