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HIGH TEMPERATURE STRENGTH ANALYSIS OF LOW CARBON STEELS IN THE AS - CAST STATE

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Results of the study of the influence of chemical composition and microstructure on the strength values at high temperature tensile tests are described and discussed. By increasing the testing temperature, strength values in the low carbon steel slab continually decrease. Mathematical description of the temperature course and scatter zone of strength values was realized. Influences of the chemical composition and grain size on the strength values in a temperature interval from 900 to 1500 °C with a step of 100 or 50 °C was established by means of regression analyses. These influences are temperature-dependent. Strength values at 1400 °C, which chiefly depend on the effective grain size, were thoroughly analyzed.

***Key words**: cast low carbon steel, high temperature strength, high temperature fractures*

Niskougljični čelici u lijevanom stanju i analiza čvrstoće na visokim temperaturama. Opisani su i raspravljeni rezultati studije o utjecaju kemijskog sastava i mikrostrukture na čvrstoću pri ispitivanju na vlak na visokim temperaturama. Povećanjem ispitne temperature stalno se smanjuje čvrstoća u niskougljičnim čelicima. Realiziran je matematički opis toka temperature i zone rasipanja čvrstoće. Utjecaj kemijskih sastava i veličine zrna na čvrstoću unutar temperaturnog intervala od 900 do 1500 °C sa stopom od 100 ili 50 °C ustanovljen je pomoću regresivne analize. Ovi utjecaji su ovisni o temperaturi. U potpunosti je analizirana čvrstoća na 1400 °C koja uglavnom ovisi o učinkovitoj veličini zrna.

***Ključne riječi:** lijevani niskougljični čelik, čvrstoća na visokoj temperaturi, lomovi na visokim temperaturama*

INTRODUCTION

High-temperature properties of the continually cast low carbon steel slabs are tested on various equipments [1 - 7]. The high temperature tensile strength test is the most used one and the primary evaluated quantity, plasticity, is mostly assessed by reduction of area values.

Several heating techniques are used for high temperature tensile strength tests and the testing is performed at various deformation speeds. During testing the specimens are placed mostly in vacuum, or in a protecting, usually argon, atmosphere.

Specimens with circular cross-section are ordinarily used. Their diameter was from 5 to 20 mm and length between 15 - 200 mm. The testing itself can be realized after heating the specimens on temperatures under the solidus temperature or, if arrangement of the experiment enables it, after melting the specimens and then cooling them down to the testing temperature.

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Testing parameters, temperature cycles, dwelling times on individual temperatures, and heating, and/or cooling rates are variable. The dwelling times are from 30 s up to 15 min., the heating up rate is usually about 20 $°C \cdot s^{-1}$ and the cooling rates are mostly in an interval from 1 to 140 $°C \cdot s^{-1}$. Deformation rates differ in orders, from about $10^{-3} \cdot s^{-1}$ to about 1 s^{-1}.

The most frequently evaluated high temperature quantities as reduction of area and, possibly strength, have a conventional character. Therefore mutual comparisons of results found in the literature are, regarding to the different testing conditions, not unambiguous.

The main reason for high temperature properties testing is the study of plasticity and its correlation with susceptibility to surface defects on slabs. Less attention is given to other evaluated parameters. Therefore this contribution is addressed to investigation of strength values measured at high temperatures and their physical-metallurgical interpretation. The investigation is based on results of our high-temperature tests and on subsequent metallographic, fractographic, and statistical analyses.

MATERIAL AND EXPERIMENTS

The experimental material consists of 24 commercial produced steels. These were made in oxygen converters and electric furnaces and continually cast. The specimens were taken longitudinally from the cast segments. Basic chemical composition of the steels is presented in the Figure 1. The characteristic temperatures of plasticity degra-

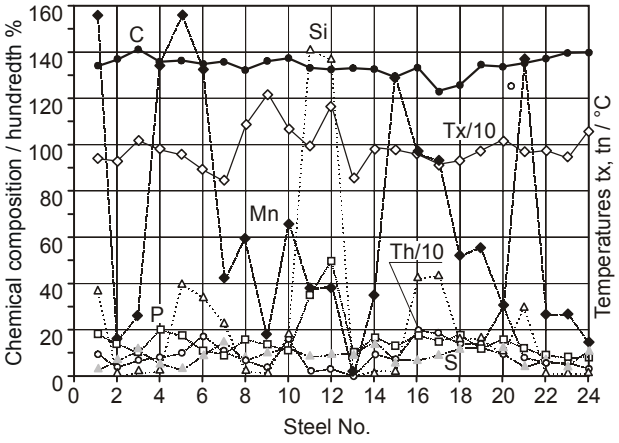

Figure 1. **Graphical presentation of the chemical composition**
Slika 1. **Grafički prikaz kemijskog sastava**

dation *tx* and *th* are also plotted in Figure 1. The chemical analyses of Al, N, V, Ti, Nb, Cu, Cr, Ni, As, Sn, Sb, and B were at our disposal, too.

Tensile tests were realized on specimens with a diameter of 5 - 6 mm in protecting atmosphere of argon. Specimens were high-frequency heated.

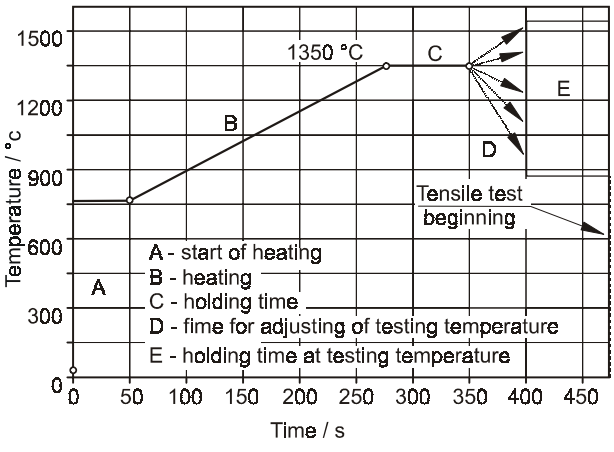

Figure 2. **Temperature-time testing cycle**
Slika 2. **Ispitni ciklus ovisan o vremenu održavanja određene temperature**

The deformation rate of $4{,}7 \cdot 10^{-2}$ s^{-1} and a common heating technique for specimens was used, Figure 2. Tests were made on smooth rods after heating them up. A more detailed description of the equipment and testing conditions can be found, in [8 - 10].

For designation of strength values symbol *Rht* [MPa] was used, because this is not a normalized test.

HIGH TEMPERATURE PLASTICITY

Course of the high-temperature plasticity is schematically presented in Figure 3. The material has mostly high

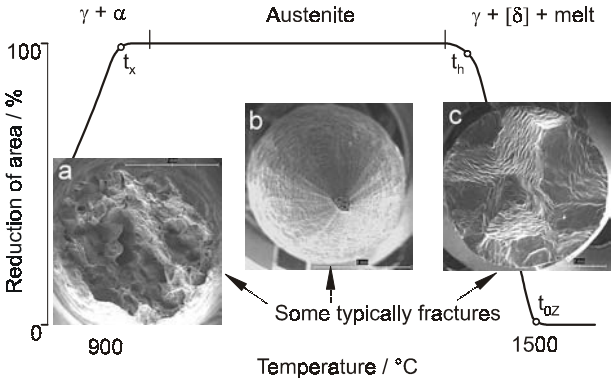

Figure 3. **Scheme of the reduction of area vs. temperature course and some typical fractures**
Slka 3. **Shema redukcije područja sukladno tijeku temperature i nekim tipičnim prijelomima**

reduction of area values in the austenite region, sometimes very near to 100 %, Figure 3., fracture b. At lower testing temperatures, below the temperature *tx* a drop of plastic-

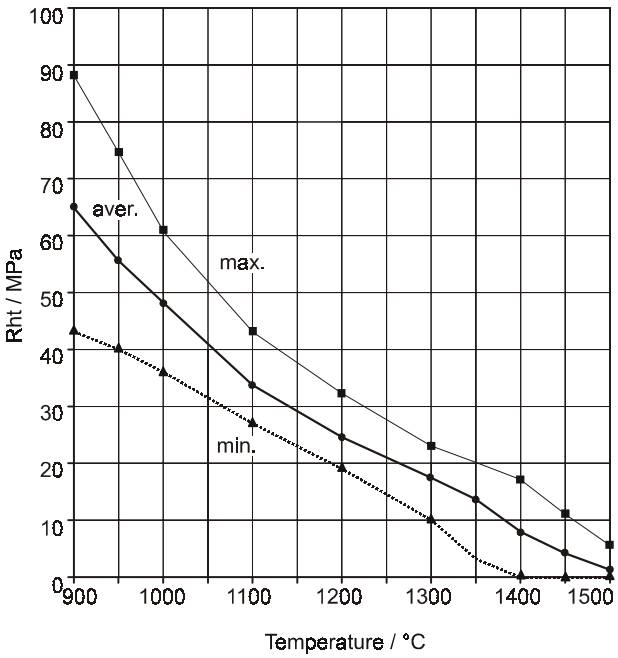

Figure 4. **Dependence of the strength values on temperature**
Slika 4. **Ovisnost čvrstoće o temperaturi**

ity takes place as a consequence of ferrite presence on the austenite grain boundaries [11 - 15], possibly as a result of grain boundary strength degradation by some trace elements [4, 16 - 21].

Fractures with higher or lower portion of intercrystallinity were formed at these temperatures, Figure 3., fracture a. Thermal degradation of the grain boundary strength is taking place at the highest testing temperatures and above the t_h temperature the reduction of area value decreases. The reduction of area drop is accompanied by intercrystalline fractures with various morphologies as, Figure 3., fracture *c*.

HIGH TEMPERATURE STRENGTH

In the temperature interval between 900 and 1500 °C the strength values continuously decrease. The maximal and minimal strength values in the set of experimental states together with the average value shown in Figure 4. The drop of the *Rht* strength values with temperature can be, in the above mentioned temperature interval, described by this type of equations: $Rht_i = A_i + B_i \cdot t^{-1}$, Figures 5. - 7.

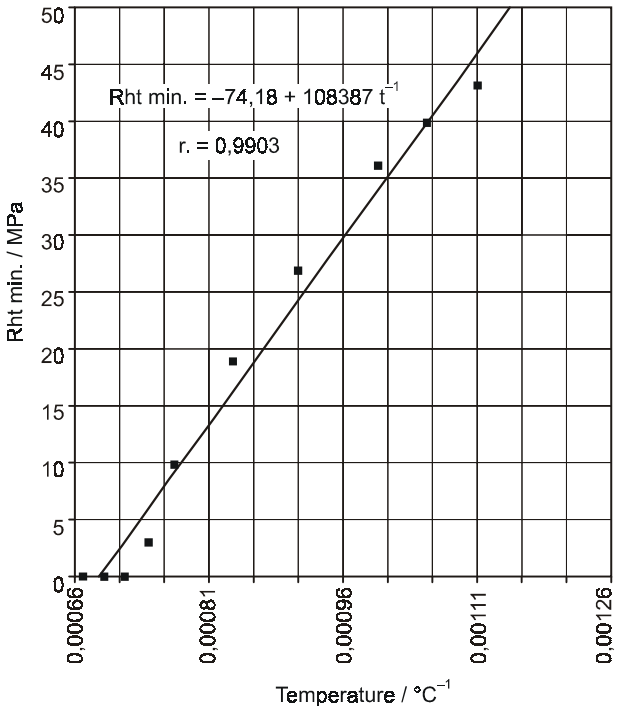

Figure 5. **Regression analysis of the minimal strength values**
Slika 5. **Regresivna analiza minimalnih vrijednosti čvrstoće**

The accuracy of these equations is excellent, the correlation coefficient exceeds in all cases the value 0,99.

The scatter zone of the strength for individual testing temperatures can be graphically described, e.g., in relation to the mean strength, as it is depicted in Figure 8. It follows from the Figure 8. that the relative scatter of the measured

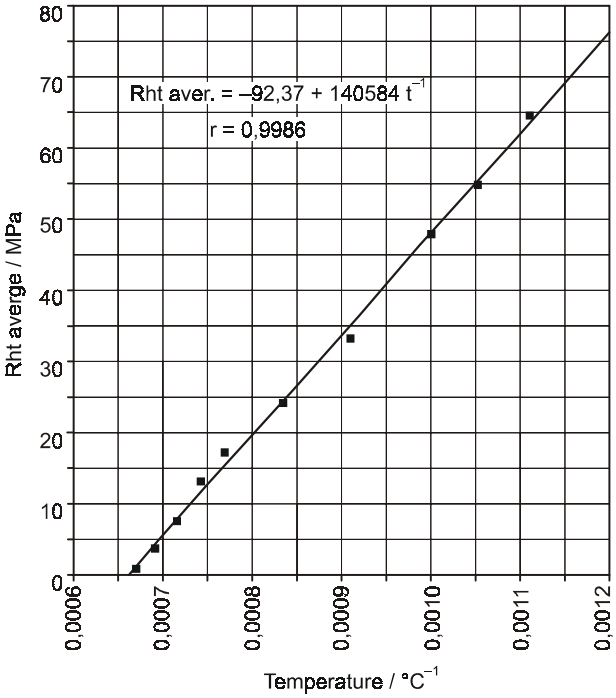

Figure 6. **Regression analysis of the mean strength values**
Slika 6. **Regresivna analiza srednjih vrijednosti čvrstoće**

values rapidly increases above the temperature approx. 1350 °C. The higher scatter can also be influenced by the fact that the strength values are very low, therefore the accuracy of the load readings at the moment of cracking is small.

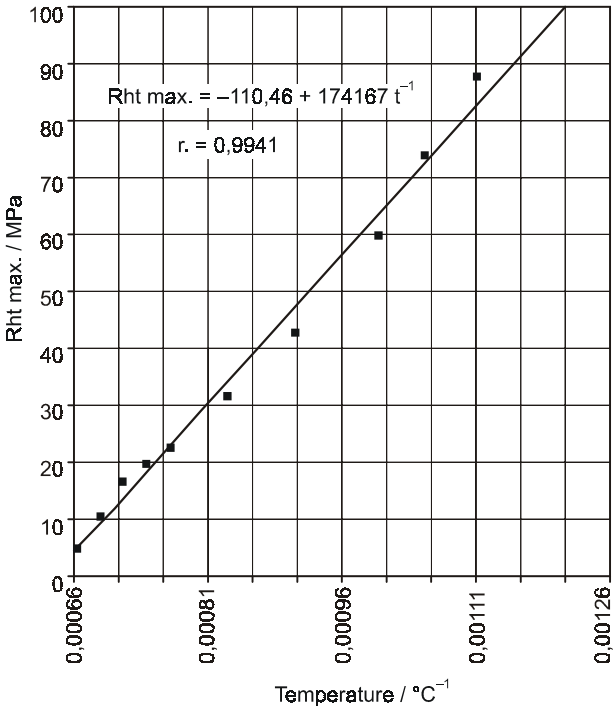

Figure 7. **Regression analysis of the maximal strength values**
Slika 7. **Regresivna analiza maksimalnih vrijednosti čvrstoće**

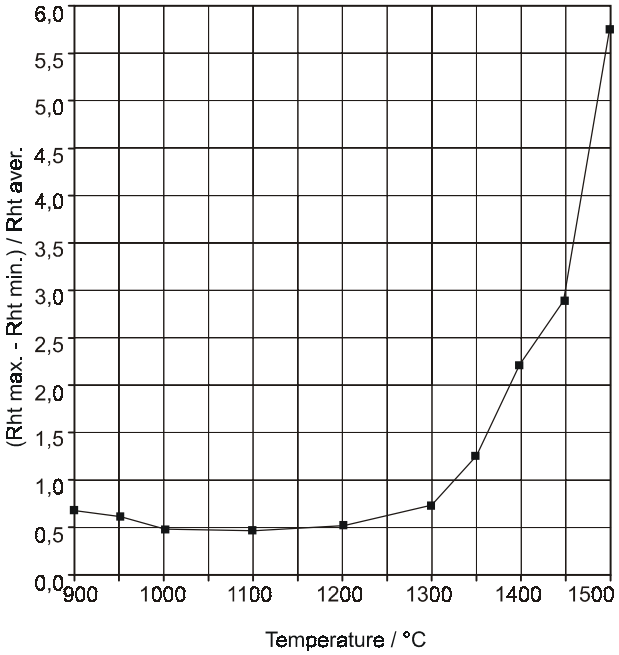

Figure 8. **Scatter zone of the strength - temperature course**
Slika 8. **Zona rasipanja čvrstoće - tok temperature**

Mathematical description of the strength scatter zone in the form of $A + B \cdot t^{-2}$ gives a good correlation, $r = 0{,}9104$ and it is depicted in Figure 9.

At the highest temperatures various structure of phases exist in the examined low carbon steels with C content up

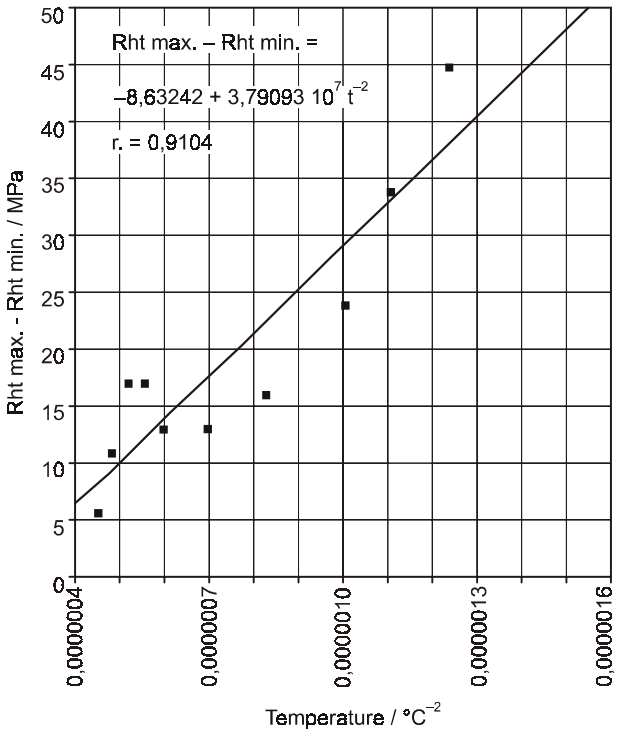

Figure 9. **Regression analysis of the strength scatter zone**
Slika 9. **Regresivna analiza zone rasipanja čvrstoće**

to 0,20 %. Dependent on the temperature and chemical composition of the steel these steels can be formed of austenite, austenite and δ ferrite or, in case of steels containing less then about 0,095 C, of δ ferrite, only. But the process of $\gamma - \delta$ recrystallization influences the high temperature properties of the steel.

Temperature at which grain boundary strength degradation takes place depends beside other factors also on the melting temperature of the steel, and this is dependenz on its chemical composition. The temperatures at which the ductility value was zero, t_{0Z}, Figure 3., were in our set of experimental states between 1390 and 1520 °C. The theoretical maximal temperatures of solid phase existence were between 1487 and 1537 °C.

DISCUSSION

Temperature course of strength values in a set of 24 grades of low carbon steels was mathematically described in the previous chapter. But its more detailed physical and mathematical interpretation is difficult for various reasons. Possibilities of the metallographic study are limited because of microstructure changes during cooling down of specimens from the testing temperature. Based on metallographic observation of fracture lines it can be assumed that in the case of intercrystalline fractures at the testing temperatures microstructure changes did not occur during fracturing process, while ductile fracture was probably accompanied by dynamic recrystallization [20].

Stressing of specimens at high temperature tests, when the fracture is formed in the course of a few seconds, differs considerably from the creep stress. Applying classical models according to Hall-Petch or Langford-Cohen, which were derived for room temperature and for the yield strength values, is also questionable. The investigated low carbon steels represent from the point of view of chemical composition multicomponent systems and the influence of individual chemical elements is evidently temperature dependent. Beside these, there exist further problems, e.g., with the accuracy of chemical analysis of trace elements, or with grain size determination. An estimation of the grain sizes was used in this paper, therefore it is necessary to expect a higher inaccuracy of in such a way the values determined [21 - 23].

In respect to the outlined problems, in this phase of solution we confined ourselves to the investigation of the influence of grain size and chemical composition on the high temperature strength. In respect to the dwelling temperature prior to testing, 1350 °C we assume that the grain sizes at the temperatures between about 900 to 1350 °C were approximately equal. The grain sizes were evaluated from the intercrystalline fractures at the lower testing temperatures in REM and from metallographic cross sections through the fracture surfaces. The values of such a way es-

timated grain sizes were between 0,12 and 1 mm. The grain sizes for the temperature 1400 °C were estimated the same way, these were in a range from 0,08 to 3 mm. In view of the grain size estimation method, this parameter should be taken for the „effective the grain size", i.e., a microstructure formation which is relevant for the process of fracturing.

The estimated grain size for 1400 °C was in some cases lower then for 900 °C. This was repeatedly examined and experimentally confirmed. It follows from the fractographic study that characters of the intercrystalline fractures at lower and at the highest temperatures were different, see Figure 10. Even if $\gamma - \delta$ recrystallization does not take place at the temperature 1400 °C, it can be assumed that

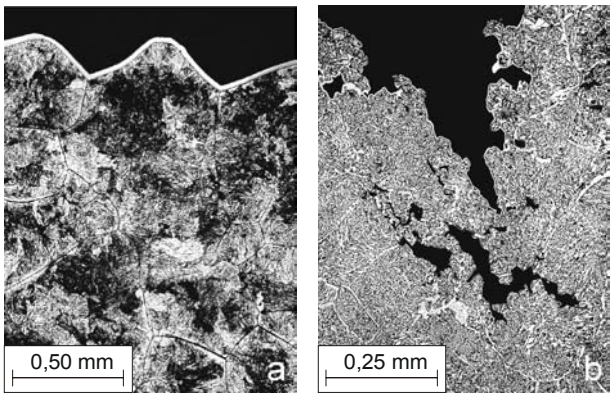

Figure 10. **Intercrystalline fractures at the temperatures 900 a) and 1375 °C b), metallographic cros sections**
Slika 10. **Međukristalni lomovi na temperaturama od 900 a) i 1375 °C b), međukristalni presjeci**

there exists a marked thermal movement of the austenite grain boundaries and subgrain dismemberment. The established „effective" grain size asserts itself in the fracturing process. Morphology of the fractures arising at the highest investigated temperatures is varied and almost each of the investigated steels shows smaller or larger particularities. The problem is under investigation at present.

High-temperature strength of the former defined set of independent variables was analyzed by mean of multiple regression analysis with selection of the regression model regime. The analyses were realized for temperatures 900, 950, 1000, 1100, 1200, 1300, 1350, 1400, 1450, and 1500 °C. The regression coefficients r were mostly about 0,6, in some cases, particularly at lower testing temperatures, they had a higher value. The results are schematically represented in Figure 11. It is obvious that various independent variables are confirmed at different testing temperatures. It is interesting that a correlation between strength and estimated grain size was not found at lower testing temperatures, but the influence of grain size on the high temperature plasticity was very strong, [9, 24, 25]. The influence of the grain size was determined only for the highest testing temperatures, Figure 11.

The determined relation between the high temperature strength at 1400 °C and the grain size is, alternatively:

$$Rht_{1400} = 4{,}12 + 0{,}95 \cdot f_{1400}^{-1} \; r = 0{,}7213,$$

or:

$$Rht_{1400} = 0{,}53 + 4{,}95 \cdot f_{1400}^{-0{,}5} \; r = 0{,}7511,$$

where f_{1400} is the estimation of effective grain size at 1400 °C [mm], has relatively good correlation coefficients, which are approximately on the level we have found earlier when we have analyzed a limited set of experimental states; these results are published in [10]. A better correlation coefficient was determined for the exponent – 0,5. At 1400 °C the grain size f_{1400} has primary effect on the strength values. After including all other detected influences, Figure 11. and their possible mathematical adjustments, the correlation coefficient *r* increased to about 0,85 - 0,86.

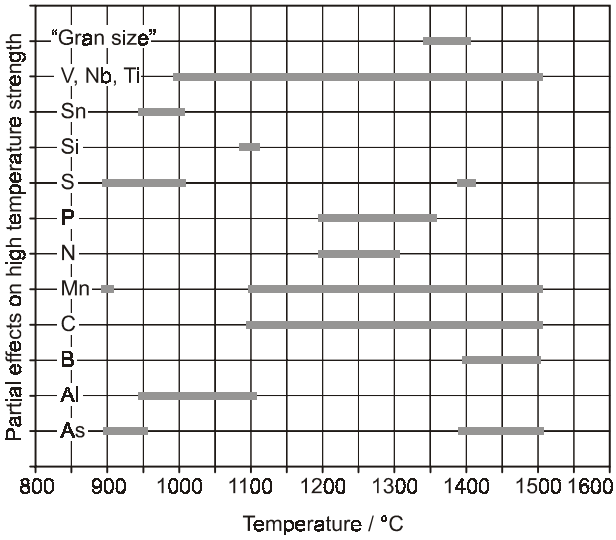

Figure 11. **Schematic presentation of the influence of chemical composition and grain size on the high temperature strength**
Slika 11. **Shematski prikaz utjecaja kemijskog sastava i veličine zrna na čvrstoću na visokoj temperaturi**

In case of the discussed regression analyses, with respect to inaccuracy at determining of parameters, it is generally not possible to anticipate high accuracy of models. The achieved results can be distorted by randomly formed bonds between some independent variables. On the other hand, as indicated in the followed statistical analyses, the accuracy of prediction models can be often increased by mathematical optimization of variables. The presented results enable to make basic mathematic description of high temperature strength values and point out some specific influences on them. From the realized experiments and their analyses it is obvious that the high temperature strength depends on chemical composition and grain size. In the fol-

lowing phase of investigation it would be useful to specify the existing results and verify the possible influence of secondary phases on the high temperature strength.

CONCLUSIONS

1. The temperature course of minimal, maximal, and mean strength values in an interval from 900 to 1500 °C for the set of investigated steels can be generally described as:

   $Rht_i = A_i + B_i \cdot t^{-1}$, Rht_i /MPa, t /°C

   The mathematical description has high correlation coefficients, more then $r = 0{,}99$.

2. By means of regression analyses in the regression model selection regime for temperatures 900, 950, 1000, 1100, 1200, 1300, 1350, 1400, 1450 and 1500 °C the influences of chemical composition and the effective grain size on strength values were estimated. These results were submitted graphically and they are of a qualitative character.

3. The strength value at 1400 °C is primarily controlled by the effective grain size:

   $Rht_{1400} = -0{,}53 + 4{,}13 \cdot f_{1400}^{-0.5}$ $r = 0{,}7511$,

   where f_{1400} is the estimated effective grain size at 1400 °C [mm].

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