Non Destructive Determination of Mechanical Properties of Hot Rolled Steel Strips

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Abstract
Automatic prediction of mechanical properties immediately after hot rolling is becoming a standard feature of modern rolling train. Prediction can be interpreted as the non-destructive testing of mechanical properties and it can be used as a substitution of typical destructive tensile test for issuing non specific inspection of the type 2.1 and 2.2. Preparing of test specimen is time and material consuming. Average material loss in testing of coils is about 130 kg and time delay in standard conditions is at least about two days. Although there are several commercially available prediction models available on the market, U. S. Steel Košice, s.r.o. (USSK) has developed its own prediction system. The main aim of USSK’s model is quality control warning as well as a possibility to use predicted values of mechanical properties for issuing non specific inspection documents.

Keywords: modeling, simulation, steel plant, material characterization, mechanical properties, hot rolling, quality control

1. Introduction

A need for quick gathering of information on strip quality motivates steel strip producers to develop facilities enabling prediction of mechanical properties immediately after hot rolling. Several approaches for describing the relation between chemical composition, process parameters and final mechanical properties can be applied, for instance physical and/or empirical description of metallurgy phenomena, statistical approach and methods such as neural networks etc. The physical-metallurgical approach is favorable now probably because of its proclaimed flexibility. The statistical approach can lead to more accurate results, but is not as flexible as the physical-metallurgy approach. Especially in case of a new grade and/or first use of nonstandard process parameters the statistical approach can’t be used due to lack of data.

There are several commercially available prediction models on the market, for instance Danieli's Coil Quality Estimator (CQE), Siemens’ SIROLL MSM etc. USSK has developed its own simple model optimized for USSK’s conditions.
2. **USSK Hot rolling mill and brief characteristic of USSK’s model**

USSK hot rolling train consists of roughing mill and finishing mill. Rougher consists of vertical and horizontal scale breaker and five reduction mill stands, four of them are universal stands, containing in addition to vertical rolls also the prepositioned edger (vertical rolls). The finishing train consists of seven mill stands, working in tandem (i.e. strip is in one moment under reduction by each mill). After finishing of rolling the strip is cooled by water on run-out table and wrapped into coils on coiler. The schema of strip mill is shown in Figure 1.

![Figure 1. Schema of USSK hot strip mill. Key: Push Furnaces, Vertical Scale Breaker (VSB), Horizontal Scale Breaker (HSB), Roughing Mill Stands (R1-R5), Flying Shear (FCS), Finishing Mill Stands (F1-F7), Cooling section and Coiler](nanx5301942369767898755824025173714700627010885735013148518110645796732928)

USSK model for prediction of mechanical properties of hot rolled strips has been developed on the basis or basic ideas of INTEG process group’s offline model named “Hot strip model v 6.0”. INTEG enhanced and validated the technology developed by the University of British Columbia (UBC) and the National Institute of Standards and Technology (NIST). USSK model has some simplification in comparison with INTEG model - there is no material categorization. Instead of material grade groups characterized by several material constants, USSK model calculates necessary material parameters (constants) applying interpolation and/or extrapolation methods.

The main aim of USSK’s model development was application in quality control with warning in the case when calculated values are out of order limit, as well as possibility to use predicted values of mechanical properties for issuing non specific inspection documents.

USSK’s model contains description of austenite microstructure evaluation, sub-model of austenite to ferrite transformation and sub-model describing relation between final microstructure and achieved mechanical properties including effect of precipitation strengthening. Model calculates average mechanical properties (exactly expressed mechanical properties characterized by average input process parameters) as well as mechanical properties along entire strip length.
3. Metallurgical phenomena description

Metallurgical phenomena used in models contain empirical and physical description of microstructural phenomena, such as grain growth, recrystallization, phase transformation etc. Consequently semi-empirical relations between final microstructure and mechanical properties are used to predict mechanical properties. Several papers about simple “Spreadsheet model” are available in [1]. Some models are very complex and some are relatively simplified. Anyhow, a detailed model must not lead in fact to better results. The reason can be found in several round robin tests of tensile tests which revealed the fact, that differences between labs are so significant that verification of prediction model by comparison of predicted values with mechanical test results would not be insufficient. The really perfect verification requires comparison of thousand results of model prediction with test results performed by several labs while this issue is discussed herein below.

3.1 Austenite grain size evolution

Each model calculates evolution of austenite grain size during hot rolling. The grain size is calculated after each reduction. The first step is determination of critical deformation to determine which kind of recrystallization will occur after reduction pass. Frequently used formula used also in USSK model is as follows:

$$
\varepsilon_c = 5.6 \times 10^{-4} d_0^{0.3} Z^{0.17}
$$

where $Z$ is the temperature corrected strain rate (Zener-Hollomon parameter), $d_0$ is austenite grain size. Fraction of recrystallized grain is calculated by Avrami form formula. If there is a sufficient time for complete recrystallization, then the size of newly recrystallized grain can be expressed e.g. by the following equation:

$$
d_{\text{rex}}^{\text{SRX}} = 89 d_0^{0.37} \varepsilon^{-0.37} e^{\frac{28000}{RT}}
$$

$$
d_{\text{rex}}^{\text{MRX}} = 26000 Z^{-0.23}
$$

where $d_{\text{rex}}$ is the recrystallized grain size (after static recrystallization-SRX, or metadynamic recrystallization-MRX) and $\varepsilon$ is the true strain. Time $t_{0.5}$ required for 50% recrystallization is:

$$
t_{0.5}^{\text{SRX}} = 8.3 \times 10^{-15} d_0 e^{-0.8-3.78 C} e^{-0.33} e^{\frac{255000}{RT}}
$$

$$
t_{0.5}^{\text{MRX}} = 2 \times 10^{-6} e^{-0.75} e^{\frac{124000+60000 C}{RT}}
$$

When time between passes is shorter than time required for perfect recrystallization, the final structure consists from both recrystallized and non recrystallized grains – in that case an adequate mixture model shall be used. After full recrystallization the growth of austenite grains starts. The growth of austenite grain can be described by the following relation:
\[ d_y = \left( d_y^2(t_0) + 3b^2(0.8 - 0.35 C^{0.68}) \int_{t_0}^{t_s} \frac{8.9 \cdot 10^{-5} e^{-\frac{q}{kT(t)}}}{kT(t)} \, dt \right)^{\frac{1}{2}} \tag{4} \]

where \( d_y \) is the austenite grain size, \( t \) is the time, \( b \) is the Burgers’ vector and \( k \) is the Boltzmann constant.

### 3.2 Transformation of Austenite to Ferrite

The austenite grain refined or with retained deformation, will start to transform into ferrite on the run-out table. In plain carbon steel the size of ferrite grain is the most important parameter determining strength properties. Therefore, the calculation of ferrite grain size plays an important role in prediction model. The ferrite grain size is determined by the nucleation process at the beginning of transformation. The grain size can be expressed as a function of initial transformation temperature \( T_s \) i.e. temperature when 5% of austenite is decomposed. This approach is used in paper [2]. Other models use the cooling rate for description of resulting ferrite grain size [3]. USSK model uses the first mentioned approach. The final ferrite grain size \( d_\alpha \) can be predicted by the following formula:

\[ d_\alpha = \left( F_\alpha e^{(50.05+13C)d_y^{(0.0222+0.036C)-\frac{51000}{T_s}}} \right)^{\frac{1}{3}} \tag{5} \]

where \( F_\alpha \) is the ferrite portion and \( d_y \) is the austenite grain size before decomposition. USSK model gives the relation between transformation start temperature, temperature of ferrite grain nucleation and cooling rate by formula \( T_s = T_n - 0.8 \text{ cooling rate} \).

### 3.3 Properties model

The relation between mechanical properties on the one hand and final microstructure characteristics, chemical composition, ferrite volume fraction and particle size of precipitation shall be used. The relationship can be semi-empirical but also a neural network or statistical approach can be used. The modification of Institut de Recherche de la Sidérurgie (IRSID) model is used in USSK’s model. Mechanical properties (7, 8) are affected mainly by the ferrite grain size \( d_\alpha \) and the ferrite ratio \( F_\alpha \). The final properties (yield strength \( YS \) and ultimate tensile strength \( UTS \)) are superposition of IRSID properties and precipitation strengthening (\( UTS_{ppt}, YS_{ppt} \)) derived by Shercliff-Ashby model as it is described in [4].

\[ UTS_{IRSID} = 237 + 29Mn + 80Si + 7.24(1 - F_\alpha)d_\alpha^{-0.5} + 500(1 - F_\alpha) \]

\[ UTS = UTS_{IRSID} + UTS_{ppt} \tag{6} \]

\[ YS_{IRSID} = 63 + 23Mn + 53Si + \left( 15.4 - 30C + \frac{6.094}{0.8 + Mn} \right)(1 - F_\alpha)d_\alpha^{-0.5} + (360 + 2600C^2)(1 - F_\alpha) \]

\[ YS = YS_{IRSID} + YS_{ppt} \tag{7} \]
4. Achieved accuracy and limits of prediction

The comparison of calculated values with values measured by tensile test is graphically presented in the Figure 2. The whole 40 days production of USSK Hot Strip Mill is involved in the graphs.

Figure 2. Comparison of measured and calculated values of mechanical properties
The best correlation between measured and calculated values was observed in case of tensile strength. The yield strength is more sensitive to process parameters as well as to sample taking (especially the rough specimen cutting and the test pieces preparation). The prediction of elongation is more difficult because it is significantly influenced by the steel cleanliness which can’t be detected only from chemistry – it depends also on processing by the Steel Shop. Another problem is the automatic evaluation of elongation by extensometer - e.g. the usual asymmetry of fracture (different distance between fracture line and extensometer’s clips) is not included into test result. The statistical evaluation of accuracy of mechanical properties production obtained by evaluation of the difference between measured and calculated values is set forth in Table 1.

Table 1. Difference between measured and calculated values

<table>
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<tr>
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<th>Number of records</th>
<th>Average</th>
<th>Standard deviation</th>
<th>Median</th>
<th>5th Percentile</th>
<th>95th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>YS [MPa]</td>
<td>1470</td>
<td>-5.54</td>
<td>19.86</td>
<td>-6.50</td>
<td>-35.85</td>
<td>27.40</td>
</tr>
<tr>
<td>TS [MPa]</td>
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<td>13.80</td>
<td>-5.95</td>
<td>-25.61</td>
<td>20.37</td>
</tr>
<tr>
<td>EL [%]</td>
<td>1148</td>
<td>0.07</td>
<td>3.35</td>
<td>0.05</td>
<td>-5.5</td>
<td>5.1</td>
</tr>
</tbody>
</table>

The statistical processing of huge data set containing results of mechanical test gathered during more than 10 years enables to derive variation of mechanical properties when the same technical parameters including chemistry were used. The standard deviations of analyzed results are: 14 MPa for yield strength and 10 MPa for tensile strength. This variation in results can be explained by differences between individual lab, in accuracy of technical parameters determination, in handling with samples and test specimens before testing, etc. Non explainable inherent variability also plays certain role.

It cannot be expected that standard deviation of difference between calculated and measured values could be lower than standard deviation of measured values. So, it can be stated, that it is impossible to make the model, which doesn’t contain at least 5% values of differences between calculated and measured value greater than 20 MPa for tensile strength and 28 MPa in the case of yield strength.

The reproducibility by comparison of results of mechanical tests performed on 2 machines (73 couples of test pieces) was evaluated in [3]. The standard deviation of difference between two machines was 11 MPa for YS and 7 MPa for UTS [3]. Andorfer interpreted these results by the statement, “accuracy of prediction is comparable with reproducibility of measured results”. Anyhow, when long time accuracy is evaluated by comparison of predicted properties with the measured ones (and each measurement is performed only on one randomly selected machine) then the standard deviation of this difference must be equal or greater than reproducibility of measurement.

USSK’s model standard deviation of results of mechanical test performed on strips prepared with the same parameters corresponds well with Andorfer’s results. The standard deviation of 14 MPa can be superposition of 11 MPa representing the difference between machines, operators, etc. (i.e. measurement reproducibility) and partially of other parameters (neglected technology parameters affecting mechanical properties, sample handling, etc.).
The standard deviation of yield strength prediction (approx. 19 MPa) consists of standard deviation of the reproducibility of the production parameters’ consequence in same measured results of tensile test (contribution 14 MPa) and standard deviation of model accuracy (contribution 13 MPa). The standard deviation of test results in case of same production parameters (14 MPa) consists of the actual standard deviation of measurement (contribution is about 11 MPa [3]) and the real deviation of mechanical properties in test specimen (calculated contribution is about 9 MPa). In calculation of standard deviation contribution, the squares of standard deviations shall be summed.

5. Prediction model verification issue

Typically the accuracy of model is evaluated by comparison of predicted values of mechanical properties with values achieved via tensile test performed by steel producer lab. The aim of all tests - including prediction tests - is to determine the objective and trustworthy quantity of mechanical properties. Therefore, in case when significant difference between labs exists, the verification of model performed by comparison of predicted values with results of tensile test, carried out by only one lab is not objective. Sometimes the prediction models are verified by including results from more companies. However, it also does not guarantee objectiveness, because each producer may have tuned the model according his own test results. The prediction accuracy is rarely related to reproducibility, for example [3].

The difference between labs can be more important than the difference between machines in one company (especially when test procedure is carefully controlled). The available information concerning round robin test reveals the fact that the difference between labs can be about 7% in case of yield strength. For example, in case of mild strength steel the test results are within the range 147.15-158.45 MPa and in case of DP 590 steel they are within the range 376.5-402.6 MPa [5].

Of course, certain variation is present in individual lab results, too. In addition to the already mentioned difference between machines, the other sources of variability exist. For instance the inaccuracy 0.01 mm in thickness measurement can influence both the yield and the tensile strength by about 1% when 1 mm thick test sample is used. The difference along the sample length can be more than 0.02 mm. So, only the effect of irregular thickness can affect the tensile properties by several MPa.

6. Application of prediction model

The estimation of mechanical properties from USSK model is available via company SCADA system (supervisory control and data acquisition) along with mechanical properties, strip length, evaluation of austenite grain size during rolling, deformation in pass, mean flow stress in particular stand etc. The users can observe the currently rolled strip as well as a strip from archive. An example of SCADA screen is shown in Figure 3. The predicted data are used also by another IT control system, which compares predicted mechanical properties with order requirements. When predicted properties are not in conformity with an order, the system generates a warning.
The strictness of warning generation can be managed by narrowing or widening of an interval of mechanical properties given by the order specification.

Figure 3. SCADA system, mechanical properties prediction along strip length

7. Conclusion

The developed system of mechanical properties prediction comprehensively describes evaluation of microstructure and its effect on as hot-rolled properties of strips made of plain as well as microalloyed steels. This system is regularly in use to appraise fulfillment of required mechanical properties. Another intended application of the model is issuing of inspection documents based on non specific tests and inspection.

References

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