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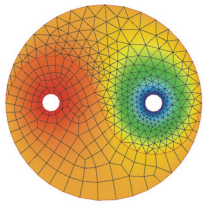

MATHEMATICAL MODELING OF STRUCTURE AND MECHANICAL PROPERTIES OF STEEL TUBES PRODUCTION

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Abstract

The article deals with FEM analysis, with mathematical modeling of structure evolution and with prediction of mechanical properties during hot rolling of seamless steel tubes.

There is a brief description of stretch-reducing mill in the introduction. It is a forming unit that reduces diameter of the tube semi-finished product and at the same time changes the thickness of the wall without inner tool. In this unit the tubes is achieving the final dimensions and after cooling process also the final mechanical properties.

Mathematical model of stretch-reducing mill of Železiarne Podbrezová, Inc. was created in Deform 3D software. Calibration sequence for rolling tube semi finished product diameter 144 mm and wall thickness 4,7 mm to diameter 88,9 mm and wall thickness 5 mm was chosen for creation of mathematical model of stretch-reducing mill. This calibration sequence consists of eleven rolling stands. Numerical simulation was created on mathematical model. By using the numerical simulation the values of thermo-mechanical parameters for each stand were gained. Time dependencies of strain, strain rate and rolling force were made from the obtained values.

The next part presents mathematical model describing the tube production for low carbon steels grade St52 on analyzed calibration sequence. Model is valid for range of rolling start temperatures 870–960°C and start rolling velocity 1,23 $m \cdot s^{-1}$.

Model includes:

- calculation of deformation temperature on each rolling stand in dependency on heating temperature,
- calculation of kinetics of static recrystallization in conditions of continual cooling,
- calculation of diameter of austenite grain after each deformation,
- calculation of Ar3 and Ar1 temperatures in dependency on chemical composition, austenite grain size, amount of residual deformation and cooling rate,
- calculation of austenite grain size after cooling to Ar3 temperature,
- calculation of ferrite grain size in dependency on chemical composition, austenite grain size, amount of residual deformation and cooling rate,
- calculation of structural fractions (ferrite, pearlite, bainite) in dependency on chemical composition, austenite grain size and cooling rate,
- calculation of yield and tensile strength in dependency of structural fractions and ferrite grain size,
- estimation of ductility for normalization conditions in dependency on chemical composition.

Numerical simulation and process condition statistic data were used for calculation of material temperature both during tube pass through stretch-reducing mill and during cooling. Values of strain and strain rate from numerical simulation were substituted into the mathematical models.

The calculated values were compared with experimental ones resulting from mechanical tests of industry rolled tubes of various chemical compositions. Good agreement of structural and mechanical properties was achieved for all chemical compositions and treatment conditions.

The conclusion deals with the possibilities of increasing the accuracy of presented mathematical model as well as the possibilities of extension dimension assortment and areas of applications of mathematical modeling of seamless steel tubes production.

Key words: stretch-reducing mill, tube, controlled forming, numerical simulation, static recrystallization, prediction of structure, prediction of mechanical properties

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1. INTRODUCTION

Seamless tubes are produced from tube semi-finished product (semi-tube) with one line of rolling stands in stretch-reducing mill. Semi-tube is produced from steel block with the sequence of forming operations. Semi-tube is reheated to rolling temperature in walking beam furnace before the reduction.

Hot forming without the usage of inner tool is present in the reducing mill. Gradual reduction of external diameter of tube is present. At the same time it is changing thickness of the tube wall. With induction of the longitudinal tensile stress on tube coarsening or thinning of the tube wall during the rolling process is achieved. Coarsening or thinning of the tube wall occurs according to induced strain in the direction of tube axis. Tensile stress is inducted with increasing of the working rolls rotation.

This forming unit allows reaching asked mechanical and structural parameters of materials straight ahead hot forming. It is possible to reach these properties without the need of heat treatment with the help of technologies of controlled forming and controlled cooling. (Kvačkaj, 1992)

Mathematical description of thermal, physico-metallurgical and mechanical processes is on such level that allows determining the optimal way of forming and cooling. Equations with some process variables and material constants are the most effective mathematical description of these processes. Databases of constants for numbers of materials are applicable. For new materials it is possible to obtain needed coefficients with material tests and consequently regression analyses.

Side by side with development of computing numerical methods witch enable to simulate forming processes there is the opportunity to simply gain the process variables. In opposite to classic methods it is possible to obtain the process variables for new technologies without the need of mechanical tests realization. These process variables like strain, strain rate and temperature are needed for calculation of structure evolution.

Described combination of mathematical models of structure evolution and gaining the process variables from numerical simulation allows predicting structural and mechanical properties. This method can be used for already established technologies as well as for new ones.

2. MATERIAL AND EXPERIMENTAL METHODIC

2.1. Material

Material data for St52 steel were used for numerical simulation. For the experiment the seven chemical conceptions (S1-S7) of St52 steel with chemical composition were used (listed in Table 1). Tubes were rolled following standard technology each with different conditions.

Table 1. *Local chemical analysis of S1 – S7 steels.*

Steel	C [%]	Si [%]	Mn [%]	P [%]	S [%]
S1	0,19	0,27	0,70	0,010	0,016
S2	0,13	0,25	0,51	0,011	0,013
S3	0,09	0,21	0,41	0,009	0,008
S4	0,09	0,22	0,43	0,009	0,010
S5	0,09	0,22	0,43	0,009	0,010
S6	0,19	0,25	1,23	0,01	0,008
S7	0,19	0,22	1,15	0,01	0,008

From each tube three specimens were examined by static tensile test. One specimen from each tube was examined by metallographic analyses. Structure homogeneity, phase fraction and ASTM grain size were evaluated.

2.2. Experimental methodic

For computation behavior of steel tubes during and after reducing process with emphasis on structural and mechanical properties the FEM numerical simulation and mathematical modeling were used.

For creation of the mathematical model for specific rolling mill of stretch-reducing unit of Zeleziarne Podbrezova, Inc. Deform 3D software was used. Semi-tubes are reduced from diameter D=144 mm and thickness 4,7 mm to diameter D=88,9 mm and thickness 5 mm. FEM numerical simulation was run on the created mathematical model.

For computation of structural and mechanical properties from mathematical models following data are necessary:

- chemical composition,
- initial austenite grain size after heating in walking beam furnace,
- temperature-time dependency during reducing process,
- values of strain and strain rate for each stand,
- cooling rate in transformation area.

Temperature, strain and strain rate obtained from numerical simulation were used as an input data for

structure calculations. Other data were obtained form plant measurements.

Calculation of structure evolution

Equations proposed by authors (Anan at al., 1992; Nanba at al., 1992; Maccagno at al., 1996) were used for calculations of critical deformation needed for start of the dynamic recrystallization. In all the cases critical deformation was higher than deformations achieved in process (φ_c>0,35).

Main softening mechanism is static recrystallization. Structure evolution was calculated following to next equations:

$$d_{\gamma,SR} = D.d_{\gamma 0}^{D1}.\varphi^{D2}.Z^{D3} \qquad (1)$$

where: $d_{\gamma,SR}$ [μm] –austenite grain size after static recrystallization

$d_{\gamma 0}$ [μm] –austenite grain size before static recrystallization

φ [-] – logarithmic strain

Z [s^{-1}] – Zener-Hollomon parameter

D, D1, D2, D3 [-] – material constants (Kvačkaj, 2004)

$$t_{0,5=SR} = F.d_{\gamma 0}^{F1}.\varphi^{F2}.\exp\left(\frac{Q_d}{RT}\right).Z^{F3} \qquad (2)$$

where: $t_{0,5\text{-}SR}$ [s] – time needed for 50% of static recrystallization

Q_d [kJ] – activation energy for deformation

R [kJ/mol.K] – gas constant (R=8,314.10^{-3} kJ/mol.K)

T [K] – thermo-dynamical temperature

F, F1, F2, F3 [-] – material constants (Kvačkaj, 2004)

Given kinetic is valid for isothermic conditions of static recrystallization course. For continual cooling conditions it is necessary to calculate temperature compensated time.

$$W_i = \int_0^{\Delta t_i} exp\left(-Q_r/(T-\dot{w}.\Delta t_i)\right).dt \qquad (3)$$

where: Δt_i [s] – time between two consecutive deformations

Temperature compensated time for 50% of static recrystallization after i-deformation was calculated by equation:

$$W_{0,5;i} = \int_0^{t_{0,5;ii}} exp\left(-Q_r/(T-\dot{w}.t_{0,5;i})\right).dt \qquad (4)$$

Fraction of static recrystallized volume was calculated by equation:

$$X_i = 1-\exp\left(-0,693.(W_i/W_{0,5;i})^2\right).dt$$

Investigated process is defined with sequence of eleven consequential small deformations Δφ=(0,01-0,15). Time between the deformations is very short Δt=(0,16-0,25) s. Small values of strain and short times does not allow complete static recrystallization between particular deformations. According to this fact in equation (1) retained logarithmic strain instead of logarithmic strain was used. Retained logarithmic strain after i-deformation is described by equation:

$$\varphi_{re,i} = \varphi_i + (1-X_{SR,i-1}).\varphi_{re,i-1} \qquad (5)$$

where: $\varphi_{re,i}$ [-] – retained logarithmic strain after i-deformation

$X_{SR,i-1}$ [-] – part of static recrystallized material after i-1 deformation

There will be both recrystallized and non recrystallized grains in material due to incomplete static recrystallization. Such constitution is most properly described with modified austenite grain size that includes both recrystallized and non recrystallized grains. Modified austenite grain size after i-deformation is described by equation:

$$d_{\gamma,\mathrm{mod},i} = d_{\gamma,SR,i}.X_{SR,i} + d_{\gamma,\mathrm{mod},i-1}.(1-X_{SR,i}) \qquad (6)$$

where: $d_{\gamma,\mathrm{mod},i}$ [μm] – modified austenite grain size after i-deformation

Before computation of final ferrite grain size is necessary to know temperatures of both beginning and end of transformation and calculate austenite grain size at the beginning of transformation. These calculations were realized following methodic given in (Zemko, 2006).

During continuous cooling the ferrite nucleation and growth exists. The ferrite grain size $d_{\alpha 0}$ can be expressed as a function of the primary austenite grain size and the retained strain. There is a relationship between the ferrite grain size and the carbon equivalent. A modified equation (Zhang at al., 2002) originally proposed by Sellars and Beynon (Sellars at al., 1985) is given as follows:

$$d_{\alpha 01} = (-0,4+6,4C_{eq}) + (24,2-59,0C_{eq})\dot{w}^{-0,5} + (22,01-\exp(-0,015d_\gamma)) \qquad (7)$$

where: $d_{\alpha 01}$ [μm] – ferrite grain size in the absence of retained strain

C_{eq} – carbon equivalent (C_{eq}=C+Mn/6)

$\dot{w}$ [K/s] – cooling rate

d_γ [μm] – austenite grain size

Any retained strain present in the austenite at transformation will refine the grain size. The model by Sellars and Beynon (Sellars at al., 1985) is also used as follows:

$$d_{\alpha 0} = d_{\alpha 01}\left(1-0,45\sqrt{\varepsilon_{re}}\right) \qquad (8)$$

where: $d_{\alpha 0}$ [μm] – ferrite grain size taking into account retained strain
ε_{re} [-] – retained strain
Calculation of phase fractions and mechanical properties

Anisothermic austenite decomposition was taken into consideration during calculation of ferrite, pearlite and bainite fractions. Transformed fraction of ferrite, pearlite and bainite for different temperatures and times during transformation was calculated by isothermic model as follows (Kvačkaj, 2004):

$$X = 1 - \exp\left\{-\exp\left[\left(-4{,}6 + \ln t_n\right) * \left(1 + \left(\frac{T - T_n}{T_0 - T_n}\right)^2\right)\right] t^n\right\} \tag{9}$$

where: X [-] – transformed fraction
T [K] – temperature of transformation
T_n [K] – temperature of "nose C-curve"
T_0 [K] – equilibrium temperature
t [s] – time of transformation
t_n [s] – incubation time by temperature T_n

Final transformation course is summation of fractions of isothermic transformation (Figure 1).

Values of yield stress R_e and tensile stress R_m were calculated following the methodic given by (Saito at al., 1980).

3. NUMERICAL SIMULATION OF STRETCH-REDUCING MILL

3.1. Mathematical model of stretch-reducing mill

Rolling mill consists of eleven stands. Each stand is formed with three rolls which axis contains angle of 120° (Figure 2) Each stand has its own individual drive. Rotation speed of rolls is expanding with the tube diameter reduction. Consecutive stands are slewed by angle of 60°. Tube is not spinning around during the pass through the mill.

Rolls geometry was created in SolidWorks 2004 CAD system. Mathematical model of stretch-reducing mill was created in Deform 3D FEM software (Figure 3).

Model was created for simplification of the geometric conditions. Shorted length (1 m) of semi-tube was used. Real lengths of semi-tubes are (15-20) m. This geometric simplification is sufficient for an acquirement of process variables progress. It is not sufficient for an acquirement of real geometric shape of the tube after rolling mill pass. This state is approximate to conditions both on the beginning and on the end of tube, where the crop-ends originate.

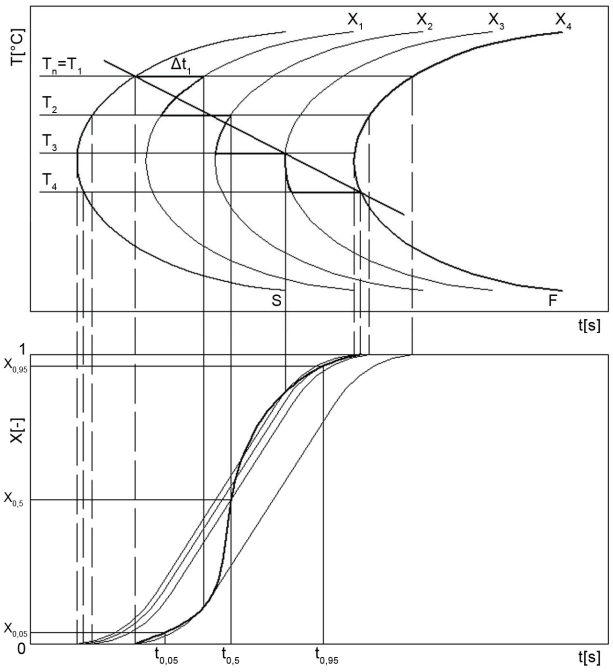

Fig. 1. *Transformation course.*

Introduced geometric simplification was essential for the sufficient density of elements guarantee. For achievement of min. four elements following the wall thickness has been necessary to use 200.000 elements.

First contact temperature of semi-tube with rolls was defined as 920°C, rolls temperature was 50°C and environment temperature was 23°C.

Fig. 2. *Stand of stretch - reducing mill.*

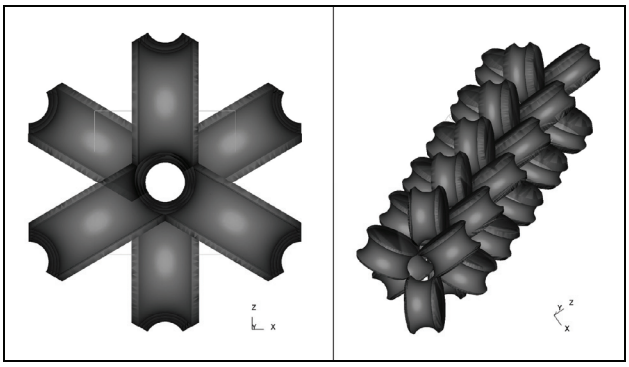

Fig. 3. Geometric model of stretch - reducing mill.

3.2. Numerical simulation

FEM numerical simulation was run on the mathematical model. Computational time step was determined as t=0,001 s. Rear part o tube was out of mill after 2.700 steps. It emerges that whole process duration was less than 3 s. For computation more than 150 h of computer time was necessary. Computation has passed without problems.

Values of parameters were obtained from numerical simulation after each deformation as is presented in Table 2.

Table 2. Values of chosen parameters after each deformation.

Stand	1	2	3	4	5	6	7	8	9	10	11
φ [-]	0,1	0,2	0,3	0,46	0,59	0,68	0,76	0,8	0,83	0,86	0,88
Δφ [-]	0,1	0,1	0,1	0,16	0,13	0,09	0,08	0,04	0,03	0,03	0,02
T [K]	920	901	885	870	857	846	836	827	819	812	805
t [s]	0	0,25	0,49	0,72	0,94	1,14	1,33	1,51	1,68	1,85	2,01
Δt [s]	0,25	0,24	0,23	0,22	0,2	0,19	0,18	0,17	0,17	0,16	99
$\dot{\varphi}$ [s^{-1}]	10	10	12	15	15	10	8	6	6	5	5

Table 3. Rolling conditions and final mechanical and structural properties.

Steel	T_{vst} [°C]	T_{dov} [°C]	d_α ASTM [μm]	R_e [MPa]	R_m [MPa]	A [%]
S1	957	832	8,1	398	496	28
S2	957	832	9,3	341	420	31
S3	947	825	11,1	346	424	42
S4	927	810	9,6	365	455	38
S5	930	801	9,3	399	471	35
S6	942	816	5,9	500	855	11
S7	945	814	6,6	497	810	12

Table 4. Comparison of calculated and measured structural and mechanical properties of steels S1-S7.

Steel	$d\alpha_{calc}$ [μm]	$d\alpha_{meas}$ [μm]	difference [%]	Re_{calc} [MPa]	Re_{meas} [MPa]	difference [%]	Rm_{calc} [MPa]	Rm_{meas} [MPa]	difference [%]
S1	8,4	8,1	4	443	398	11	557	496	12
S2	10	9,3	8	384	341	13	455	420	8
S3	10,7	11,1	4	369	346	7	419	424	1
S4	10	9,6	4	396	365	8	431	455	5
S5	10,1	9,3	9	390	399	2	428	471	9
S6	6,6	5,9	11	562	500	12	786	855	8
S7	6,9	6,6	5	539	497	8	745	810	8

Time dependencies of chosen parameters are presented in Figure 4.

4. RESULTS AND DISCUSSION

Results from experimental rolling of seven tubes are listed in Table 3. Final structure of rolled tubes was heterogeneous near the surface. Values of grain size in Table 3 are from middle of the tube wall. Values of mechanical properties are average value from three tensile tests.

Computations of static recrystallization, austenite and ferrite grain size and mechanical properties for steels S1-S7 were realized following the methodic listed in *Chapter 2.2*.

Comparison between calculated and measured results is given in Table 4.

Difference between measured and calculated values is in range 1-13%.

Obtained values could by affected by:

- interval of validity of used material constants,
- evaluation methodic of ferrite grain size,
- factors with influence on tensile test (local temperature and structure heterogeneities),
- incomplete static recrystallization between stands (Figure 5).

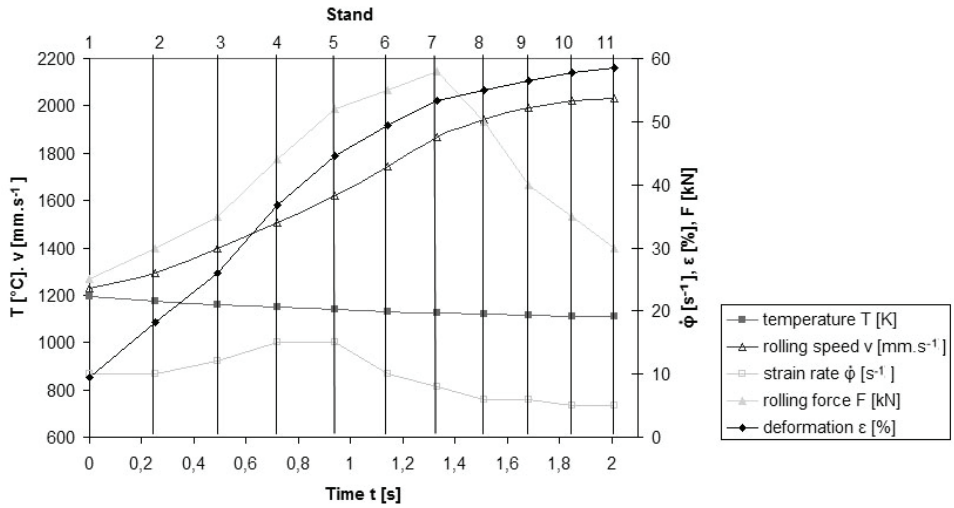

Fig. 4. *Influence of chosen parameters on time after each deformation.*

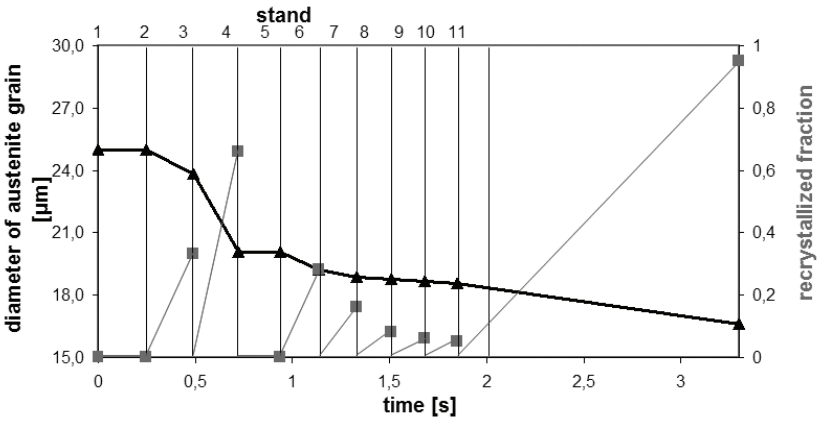

Fig. 5. *Example of austenite grain size and recrystallized part during and after the reducing process.*

Main softening mechanism is dynamic recovery and static recrystallization. There is no complete static recrystallization course between the two deformations in any case. Complete course of static recrystallization is not allowed because of small deformations and short times.

Transformation begins immediately after the finish of recrystallization initiated by last deformation. Cooling air passes with cooling rate of $\dot{w} = 9\,°C/s$.

Mechanical tests show heterogeneity of the results. Air-cooling is characteristic with different cooling rates for different finish temperatures.

5. CONCLUSION

Mathematical model of structure and mechanical properties was applied on tube hot rolling. Numerical simulation for specific rolling mill reducing the tubes of diameter of D=88,9 mm and thickness of 5 mm production was realized. Calculated results were compared with measured ones for seven chemical conceptions of St52 steel.

From results analyses ensue:

- Main softening mechanisms are dynamic recovery and static recrystallization.
- Complete static recrystallization occurs only after last stand.
- Proposed offline model has shown the ability to predict the final size of ferrite grain size and mechanical properties for the range of chemical composition C-Mn steels: C ~(0,09-0,2), Mn (0,41-1,23). For carbon content C ~0,1 and manganese content Mn ~0,45, was the dispersion of results ~5 %. For higher carbon contents it was ~10 %.
- It is possible to improve the accuracy of the model with introducing the material constants for more specific types of steels or with the creation of adaptive indicators from production statistics that will allow better convergence of measured and calculated results.
- Introduced methodic can be used for prediction of final structure and mechanical properties also for new steel grades and dimension assortment of hot rolled tubes.
- Proposed offline model could be modified into online model with adaptive principles of feedback.

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MODEL MATEMATYCZNY STRUKTURY I WŁASNOŚCI MECHANICZNYCH RUR BEZ SZWU WALCOWANYCH NA GORĄCO

Streszczenie

Symulacje numeryczne z wykorzystaniem MES w połączeniu z modelowaniem matematycznym rozwoju struktury oraz opisem własności mechanicznych podczas walcowania na gorąco rur bez szwu jest tematem niniejszej pracy. Model matematyczny reduktora pracującego z naciągiem w Železiarne Podbrezová, Inc. został stworzony w programie Deform 3D. Do obliczeń pola temperatur podczas przejścia rury przez reduktor oraz późniejszego chłodzenia wykorzystano modelowanie numeryczne i dane statystyczne z rzeczywistego procesu. Uzyskane z symulacji wartości odkształceń i prędkości odkształcenia przeniesiono do modelu matematycznego. W pracy porównano wyniki symulacji z wynikami doświadczalnymi otrzymanymi dla różnych składów chemicznych materiału. Porównanie to wykazało dobrą zgodności struktury oraz własności mechanicznych dla wszystkich badanych składów chemicznych i warunków procesu.

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