STUDY CONCERNING THE IDENTIFICATION OF THE LAWS OF BEHAVIOR OF MATERIALS USED FOR THE RADIAL COLD ROLLING

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Abstract: An important objective of the process of volumetric deformation of materials is to obtain a flawless part with required qualities. Reaching this objective is possible through the simulation of the process, but we have to know the behaviour of the material during cold plastic deformation. From an elastic point of view the behaviour of the material is linear and can be expressed by Hoocke's law, while from a plastic point of view the relations used are combinations of exponential laws (relations Ludwick, Voce, Swift, Hollomon, Johnson-Cook etc). In this paper we propose a relation that combines the laws of Vocé, Hollomon and Johnson-Cook in order to characterize the plastic behaviour of materials OLC15, OLC35, 18MnCr11, 40Cr10; we also present the way to determine the coefficients using the compression test. To validate the laws, the experimental results were compared to the results obtained through the numerical simulation of compression using the ABAQUS/CAE program.

Keywords: mechanical behaviour, compression test, numerical modelling.

INTRODUCTION

The process of cold deformation of materials, such as rolling or other similar industrial processes, requires an improvement of the behavioural analysis of the material in order to describe correctly the flow of the material during the deformation process using numerical modelling.
The most frequently laws used for the analysis and simulation of metal deformation at ambient temperature when the effect of temperature rise caused by the flowing tension within the plastic deformation process can be neglected are Hollomon [8], Ludwik [10] and Ludwik-Hartley [6], [10], Swift [14], Krupkowski [5], Samanta [5] and Voce [15]. When this effect cannot be neglected we use Johnson-Cook's law [1], [17], [18].

Ludwik and Voce's laws are recommended for the study of processes with relatively high rate of deformation as they enable the determination of the coefficients [5]. The studies presented in this paper aimed at establishing a behavioural law for the cold plastic deformation of the following types of steel: OLC15, OLCC35, 18MnCr11 and 40Cr10, in order to be subsequently used for the processes of volumetric cold plastic deformation (rolling).

EXPERIMENTAL AND NUMERICAL PROCEDURE

Material

The chemical composition and the mechanical characteristics of the types of steel used for the experiments are presented in tables 1 and 2.

Table 1 Chemical composition of steel

Steel mark	Chemical composition, [%]							
	C	Mn	Cr	Si	S	Ni	Mo	Cu
OLC15	0.15	0.65	0.11	0.27	0.018	0.08	0.01	0.31
OLC35	0.37	0.56	0.15	0.26	0.034	0.18	0.03	0.34
18MnCr11	0.21	1.03	0.94	0.29	0.007	0.09	0.01	0.23
40Cr10	0.43	0.61	0.97	0.25	0.008	0.09	0.01	0.25

Table 2 Mechanical characteristics of steel

Steel mark	$Rp_{0,2,}$ [N/mm^2]	Rm, [N/mm^2]	A5, [%]
OLC 15	298	475	15
OLC 35	248	558	13
18MnCr11	309	776	10
40Cr10	396	837	7

Establishing the behaviour law

The compression tests were made at two speeds: 1.8 mm/min and 180 mm/min respectively, which correspond to deformation speeds of $10^{-3}s^{-1}$ and $10^{-1}s^{-1}$ respectively. They were marked with SS (low speed) and LS (high speed).

Johnson-Cook's law expresses the effects of cold straining, deformation speed and temperature as follows:

$$\sigma = \left[\sigma_0 + K\varepsilon^n\right]\cdot\left[1 + C\ln\left(\dot{\varepsilon}/\dot{\varepsilon}_0\right)\right]\cdot\left[1-\left(\frac{T-T_0}{T_m-T_0}\right)^m\right] \quad (1)$$

Where: σ_0, *K* and *n* are the cold straining parameters, "*C*" the sensitivity coefficient of deformation speed, $\dot{\varepsilon}_0$ is the initial deformation speed, T_0 the reference temperature, T_m the fusion temperature in the material and "*m*" a constant.

This law points out the dependence of the strain σ to: the plastic deformation ε represented by the first element of the relation (1); the plastic deformation speed $\dot{\varepsilon}$, the second element of the relation (1); the temperature T, the third element.

The cold straining coefficients σ_0, *K* and *n* correspond to Ludwik's law.

According to the studies presented [11] we noticed that a three parameter law does not correctly represent the strain-deformation curve on the entire deformation domain. The laws we tested are Swift (2), Hollomon (3) and Vocé (4):

$$\sigma = K(\varepsilon_0 + \varepsilon)^n \quad (2)$$

$$\sigma = K\cdot\varepsilon^n \quad (3)$$

$$\sigma = S[1 - A\exp(-B\varepsilon)] \quad (4)$$

If we take into account the rapidity of the rolling process (the one we want to use for the simulation of behaviour laws), it is interesting to analyse a behaviour law that takes into consideration other parameters beside the cold straining ones. This is why we chose a five parameter law which combines Hollomon and Voce's laws and rewrote the law of thermo-viscoplastic behaviour as follows:

$$\sigma = \left[K\cdot\varepsilon^n + S(1 - A\cdot\exp(-B\cdot\varepsilon))\right]\cdot\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\cdot\left[1-\left(\frac{T-T_0}{T_m-T_0}\right)^m\right] \quad (5)$$

For the low speed test (SS), the process, deformation speed is equal to the speed used for the test $\dot{\varepsilon}$ =10^{-3} s^{-1}, and the reference temperature is the ambient temperature T=300K. Thus, the previous law becomes:

$$\sigma_{SS} = \left[K\varepsilon^n + S(1 - A\exp(-B\varepsilon))\right] \quad (6)$$

The high speed test, made at a speed 100 times higher, is described by:

$$\sigma_{LS} = \left[K\varepsilon^n + S(1 - A\exp(-B\varepsilon))\right] \cdot \left[1 + C\ln 100\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right] \quad (7)$$

For this law we will consider the same cold straining coefficients determined in the case of low speed compression (K, n, S, A and B) and we will only identify coefficients C and m. The heating $T - T_0$ under adiabatic conditions corresponds to fraction β of the plastic force that turns into heat. Under these conditions, the degree of temperature rise $\dot{T}$ is obtained with the equation:

$$\beta\sigma\dot{\varepsilon} = c\rho\dot{T} \quad (8)$$

where:

β is coefficient Taylor-Quinney [12], generally equal to 0.9, and represents the fraction of plastic force that turns into heat, C=0.460 J/gK is the caloric power specific to the material, $\rho = 7.8 * 10^6$ J/m^3K is the volumetric mass [12].

Thereby, we assume that the heating ($T - T_0$) is fraction α of the heating under adiabatic conditions, calculated with the equation (8) using the folders of the experimental points (σ, ε). To ensure a better coherence of the identification we set the same value for fraction α of the real temperature rise function of the temperature rise under adiabatic conditions for all materials. We chose a medium value of 0.7. Thus, we obtained a very good adjustment of the curves at high speed and the only parameters to be identified were the sensitivity coefficient *C* of deformation speed and the exponent *m* in the element of temperature sensitivity.

We will use the two laws, (6) and (7), as possibilities to describe the plastic behaviour of the material for the numerical simulations, assuming that their extrapolation to the entire domain of deformations that appear during the rolling process is valid.

Methods and experimental means

The compression test is better adapted to characterize the behaviour of the material since it allows us to reach high rates of deformation and the state of tension generated by the process of cold volumetric deformation is compression.

The compression tests were made on a Zwick traction-compression machine. The test was done at an ambient temperature on a blank of each type of material with identical dimensions (Ø20 x 30mm). The motion speed of the blades was of 1.8 mm/min ($\dot{\varepsilon}$ =10^{-3} s^{-1}) and 180 mm/min ($\dot{\varepsilon}$ =10^{-1} s^{-1}) respectively, the lubricant between the pressing blades and the blanks was vaseline. The values measured were the compression force (F) and the shortening of the blank (Δl). The identification of the 5 parameters (*K, n, S, A, B*) of the behaviour law was done through mathematical programming with the program FORTRAN on a LINUX operating system.

Simulating the test

In order to validate the laws determined we made numerical simulations of the test using the program ABAQUS/CAE. First we analyzed the results force (F) – movement (Δl) assuming that the state of deformations is homogeneous and we determined the behaviour laws. Then we made numerical simulations of the compression test using the laws determined and based on the simulated results F - Δl we determined the dependences (σ, ε).

During the simulation, the material of the blank was defined as follows:

- from an elastic point of view through Young's module E = 210 GPa and Poisson's coefficient ν = 0.3;
- from a plastic point of view through the values σ=f(ε) obtained with the behaviour law.

The analysis was made under dynamic conditions in a single step. The contact between the surfaces is “surface-to-surface”, the friction coefficient between the blades and the blank was of 0.3 and the movement imposed to the blade was of 18 mm.

RESULTS

The state of deformations at the compression test is inhomogeneous because of the frictions between the blank and the blades of the machine; the blank takes the shape of a barrel, fig. 1. This shape is obtained both experimentally and through numerical simulation.

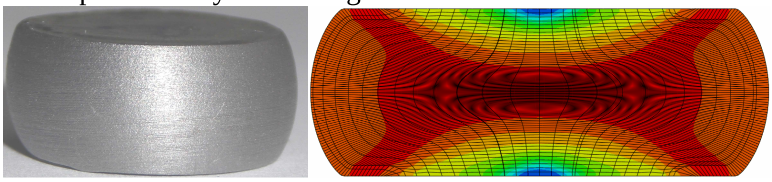

Fig. 1 Shape of the workpiece after the test

The real strains and deformations were calculated, (σ - ε, fig.3), starting from the dimensions measured experimentally (F-Δl, figure 2).

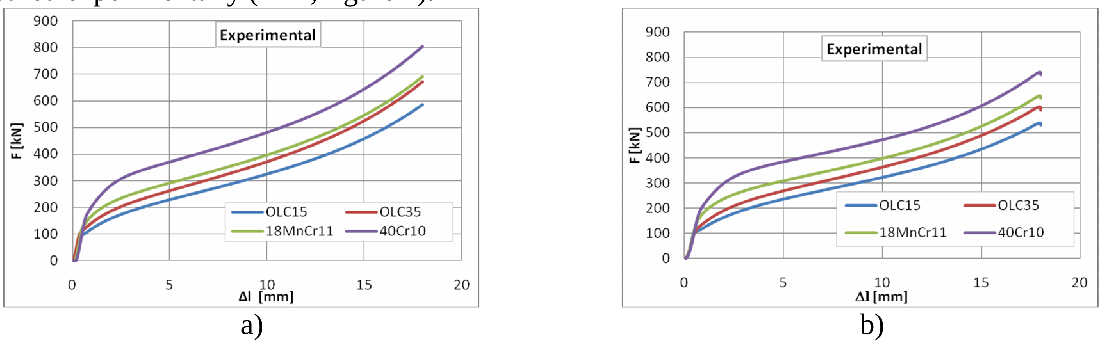

Fig. 2 Force-motion curves experimentally obtained: a) low speed(ss), b) high speed(ls)

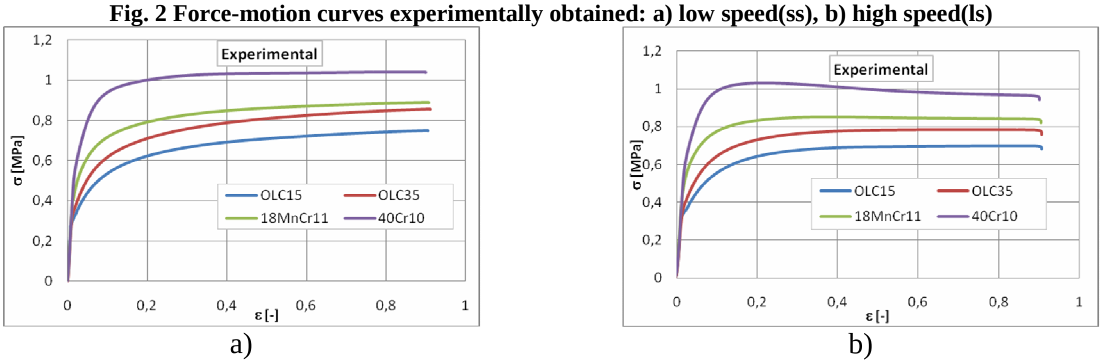

Fig. 3 Strain – deformation curves obtained through experimental data: a) low speed(SS), b) high speed(LS)

By applying the processes presented at establishing the behaviour law, we obtained the coefficients of the behaviour laws, table 3 for the low speed test and table 4 for the high speed test.

Table 3 Coefficients of the behaviour law at low speed (SS)

Material	*K* (MPa)	*n*	*S* (MPa)	*A*	*B*
OLC15	542.5	0.135	217.6	0.99	9.91
OLC35	645.2	0.134	224.0	0.99	9.93
18MnCr11	710.5	0.104	216.5	0.99	13.53
40Cr10	673.8	0.022	371.8	0.99	15.61

Table 4 Coefficients specific to the behaviour law at high speed (LS)

Material	*C*	*m*
OLC15	0.0125	0.78
OLC35	0.0164	0.71
18MnCr11	0.0213	0.70
40Cr10	0.0119	0.87

The compression test was simulated and the results obtained were compared to the experimental ones. The comparisons force movement (F-Δl) obtained through experiments and simulation are presented in figure 4, the comparisons strain deformation (σ-ε) are presented in figure 5.

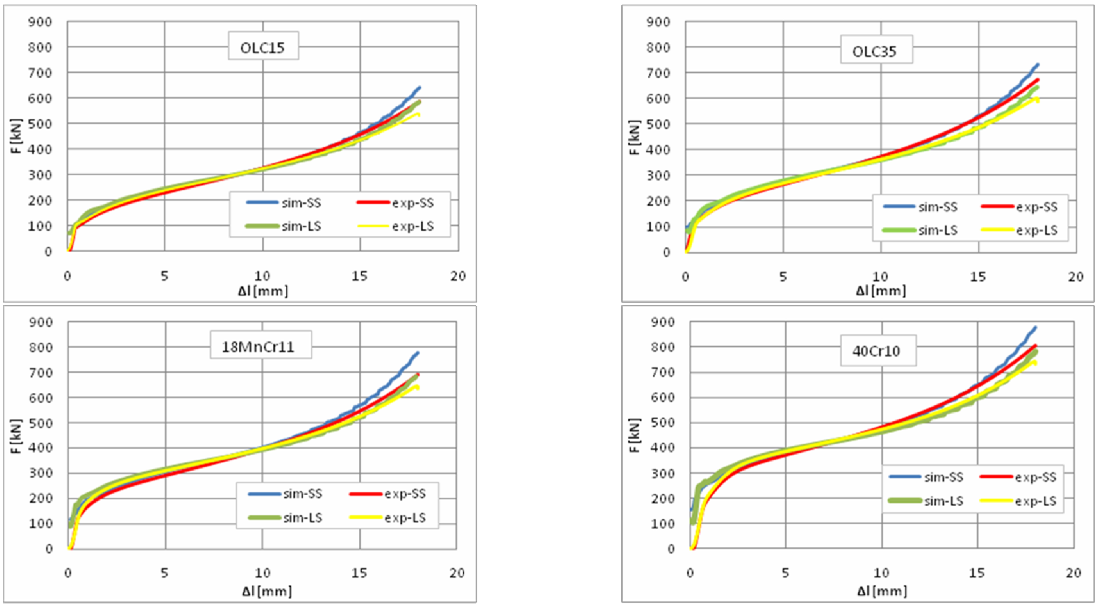

Fig. 4. Force-motion curves for the four materials

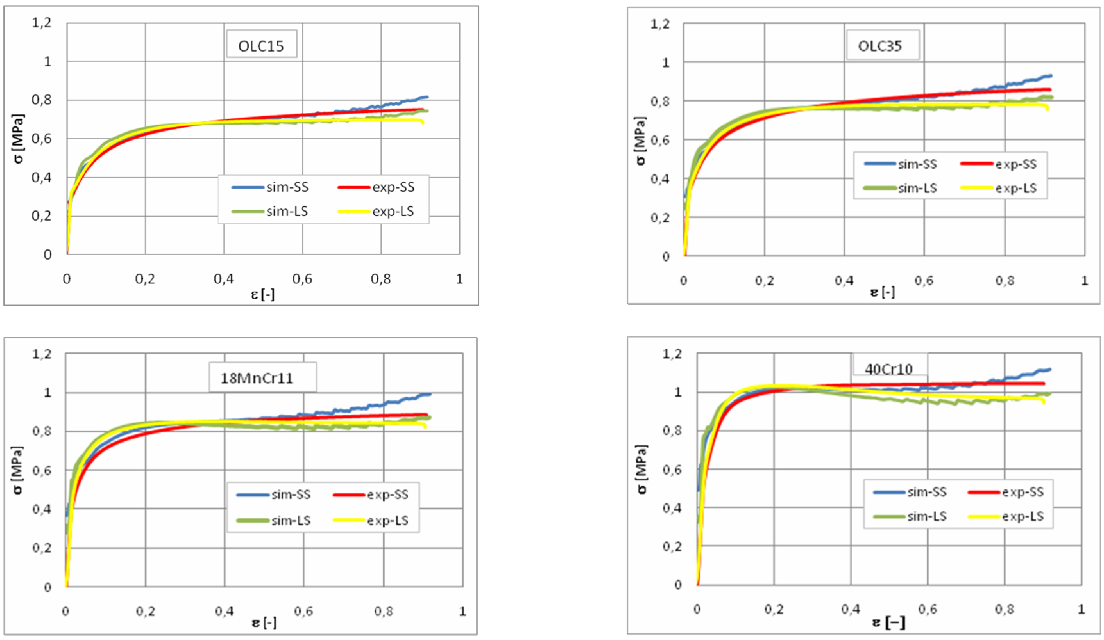

Fig.5 Strain – deformation curves for the four materials

After analyzing these graphs we may notice that:

- the curves have the same relative positions for all the materials: the high speed curve is situated slightly above the low speed curve, then goes underneath the latter (at high degrees of deformation).
- in the case of the laws determined based on the low speed test the simulated curves overlap the experimental ones, both for the force-deformation dependences and for the strain-deformation dependences, but only for a deformation rate under 0.6. For deformation values over 0.6, the values of the force and of the tension obtained through simulation are slightly higher than those determined experimentally, the difference between them increases along with the increase of the rate of deformation.
- in the case o the laws determined based on the low speed test we notice that the simulated curves overlap those obtained experimentally, both for the force-deformation dependences and for the strain-deformation dependences, for the entire domain of experimental values of the degree of deformation.

CONCLUSIONS

In the study we took into consideration a law combining Hollomon and Voce's laws and the thermo-viscoplastic behaviour (5) in order to characterize the behaviour of the material at plastic deformation. This law was adapted function of the conditions imposed by the compression tests: low speed deformation ($10^{-3}\ s^{-1}$ and $10^{-1}\ s^{-1}$), thus obtaining laws (6) and (7). The laws determined were used for the numerical simulation of the compression tests of the four materials analyzed.

The comparison between the experimental results and those obtained through simulation shows that the behaviour law established based on the low speed compression test leads to results which are very close to those obtained experimentally, but only for a rate of deformation under 0.6. This is why it can only be used for the simulation of cold plastic deformation with values under 0.6. In exchange the law established based on the high speed compression test leads to results close to the experimental ones for the entire experimental domain. This fact proves that it can be used to describe the behaviour of materials for high rates of deformation. The laws, adapted for each one of the four materials, are as follows:

- OLC15: $\sigma_{SS} = [542.5\cdot\varepsilon^{0.135}+217.6\cdot(1-0.99\exp(-9.91\cdot\varepsilon))]$;

$\sigma_{LS} = [542.5\cdot\varepsilon^{0.135}+217.6\cdot(1-0.99\exp(-9.91\cdot\varepsilon))]\cdot[1+0.0125\ln100]\cdot[1-((T-T_0)/(T_M-T_0))^{0,78}]$;

- OLC35: $\sigma_{SS} = [645.2\cdot\varepsilon^{0.134}+224\cdot(1-0.99\exp(-9.93\cdot\varepsilon))]$;

$\sigma_{LS} = [645.2\cdot\varepsilon^{0.134}+224\cdot(1-0.99\exp(-9.93\cdot\varepsilon))]\cdot[1+0.0164\ln100]\cdot[1-((T-T_0)/(T_M-T_0))^{0,71}]$;

- 18MnCr11: $\sigma_{SS} = [710.5\cdot\varepsilon^{0.104}+216.5\cdot(1-0.99\exp(-13.53\cdot\varepsilon))]$;

$\sigma_{SS} = [710.5\cdot\varepsilon^{0.104}+216.5\cdot(1-0.99\exp(-13.53\cdot\varepsilon))]\cdot[1+0.0213\ln100]\cdot[1-((T-T_0)/(T_M-T_0))^{0,70}]$;

- 40Cr10: $\sigma_{SS} = [673.8\cdot\varepsilon^{0.022}+371.8\cdot(1-0.99\exp(-15.61\cdot\varepsilon))]$.

$\sigma_{SS} = [673.8\cdot\varepsilon^{0.022}+371.8\cdot(1-0.99\exp(-15.61\cdot\varepsilon))]\cdot[1+0.0119\ln100]\cdot[1-((T-T_0)/(T_M-T_0))^{0,87}]$.

The study can be continued by analyzing the influence of the use of the determined laws on the results of the numerical simulation of some processes of volumetric cold plastic deformation, such as: thread rolling, tool rack rolling, intermittent rolling.

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