Mathematical Modelling of the Stress-Strain Curve for 31VMn12 Ecological Steel

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In this paper, optimum hot formation processing parameters for 31VMn12 steel were established, the torsion deformation of 31VMn12 steel was investigated at temperatures from 900, 1000, 1100^{0}C and strain rates from 0.05 s^{-1} to 3 s.$^{-1}$. There were studied the structural aspects of materials, in microstructures by electronic microscopy. The stress level decreases with increasing deformation temperature and decreasing strain rate, which can be represented by a Zenner-Hollomon parameter. The mathematical model presented in the paper describes the relationship of tension strain, voltage and temperature coefficient 31VMn12 steel at high temperatures. The stress-strain curves determined by the torsion test allowed the calculation of the Zenner–Hollomon parameter corresponding to the maximum stress. By using this parameter has established a set of equations that reproduce completely stress-strain curve, including the hardening, the restoration and dynamic recrystallization area. Comparisons were made between the experimental results and the predicted and confirmed that constitutive equations developed can be used for mathematical modelling and other attempts (forging, compression) and other types of steel.

Keywords: flow stress, hot compression deformation, the Zener Hollomon parameter, constitutive equation, activation energy

The micro-alloyed steels are steels that contain besides C and Mn small quantities of elements such as Al, B, Nb, Ti, V [1, 6]. Recycling vanadium that is the use of very small amounts of V alloyed leads to eliminate expensive processes, energy-intensive and polluting obtaining vanadium, with direct implications on eliminating noxious substances.

Every year large quantities of vanadium are recycled from spent catalysts. This reduces the need to use vanadium mined, which reduces energy consumption and pollution generated by mining. The use of vanadium recycled also reduces the energy requirement normally associated with mineral processing, eliminating or reducing the need for land storage of such "waste" and ensuring the supply of vanadium to steel producers. When vanadium is used as an alloy in the steel making process requires less steel to meet the structural requirements same as in the standard C-Mn steel. This reduces the amount of energy required in production. There is also a fuel saving in the operation of vehicles that are lighter steel components micro-alloyed with vanadium. So, it is possible that by using alloyed with vanadium to use 30-40% less steel and engineering achieve the same objectives. As a consequence, there is also a smaller impact on the environment [6]. On the other hand, global steel production, based on current levels will find in a few years, demand for about two billion tons of steel per year. And thus, help reduce the waste to the environment [1, 2, 7].

The study of the micro-alloyed steels by help of torsion testing takes place in general by heating to a sufficiently high temperature in order to allow the precipitation process and then a cooling to the initial temperature of the test. The cooling rate to the testing temperature as well as the deformation speed are chosen in such a way so that to simulate to the highest degree, industrial shaping conditions [20, 23]. The most used elements in C-Mn steels microalloying are vanadium and niobium. Compared with niobium, vanadium steels offer some cost advantages in the process of continuous casting and hot rolling. In continuous casting of steel vanadium reduces the tendency to crack. In the hot rolling process as greater solubility vanadium carbo-nitrides means that lower reheating temperature before rolling can be used or forging, resulting in energy savings. Higher solubility vanadium carbo-nitrides also enables the practice of microalloyed steels deformation control with less wear V cylinders and lower power consumption [6].

The addition of vanadium in steel is designed to provide improved resistance compared to standard steels to ensure the requirements of ductility, weldability and toughness without increasing costs tremendously. Microalloyed vanadium steel has advantages: recovery of metals; good ability to be molded; high solubility during reheating; avoid large hot deformation force.

An attractive alternative is to obtain micro-alloy steel using recycled scrap. The main source of vanadium is the recovery of spent catalysts in petroleum refining operations.

These catalysts together with other *waste* of vanadium are subject to processing by recycling several companies developing Ferrovanadium supply type alloys. Environmental benefits of recycling vanadium are noteworthy. Microalloyed steels with V application is now supported for almost all complex metal structures: containers, bridges, construction equipment, machinery etc. This is confirmed by the use of largely high-strength steel micro-alloyed with vanadium [6]. Every year large

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quantities of vanadium are recycled from spent catalysts. This reduces the need to use vanadium extracted from minerals, which reduces energy consumption and pollution generated by mining [5]. Using recycled vanadium also reduce energy requirements normally associated with ore processing, eliminating or reducing the need for land disposal of these *waste* and ensuring the supply of vanadium for steel producers [17, 19].

When vanadium is used as an alloy in steel making process requires less steel to meet the structural requirements same as for standard C-Mn steel. This reduces the amount of energy required in production. There is also a fuel-saving in the operation of vehicles that are lighter components micro-alloyed steel V. So, it is possible that using steel microalloyed with V to use 30-40% less steel and engineering achieve the same objectives. As a consequence, there is also less impact on the environment [15, 21]. It is useful to use environment-friendly materials to reduce pollution [3, 4,7-10, 12,14, 19, 21,22,27-30].

All this leads to a real opportunity for steel microalloyed with V under explosive worldwide demand for infrastructure incumbent need raw materials - steel, concrete and other resources - needed to support and infrastructure development. On the other hand, global steel production, relative to current levels will find it in a few years, the demand for approximately two billion tonnes of steel per year [1, 18]. This paper presents a mathematical model based on experimental curves of tension-torsion deformations obtained by seeking and relations based on mathematical literature [11, 13, 16, 18, 20, 23, 25-27].

Experimental part

Materials and methods

Studied the chemical composition of steel is shown in Table 1. In order to determine the specific values of the micro-allied steel, of the percents belonging to the mathematic model of the curve, a set of proofs from steel 31VMn12 (micro-allied with vanadium in table 1) was tested at torsion with speeds between 0.05 and 3 s^{-1}, at a temperature of 800, 900, 1000 and 1100 ^{0}C Celsius degrees.

Results and discussions

The results are shown in table 2.

The value of the activation energy (Q) was calculated according to [2, 11, 16, 18, 20]:

From the equation:

$$\dot{\varepsilon} = A \cdot \sigma^n e^{-\frac{Q}{RT}} \quad (1)$$

by setting the equation in logarithmic form:

$$\ln \dot{\varepsilon} = \ln A + n \ln \sigma - \frac{Q}{RT} \quad (2)$$

Table 1
CHEMICAL COMPOSITION OF THE STEEL TESTED IN TORSION

Steel	The elements from composition, %											
	C	Mn	Si	P	S	Cu	Cr	Ni	Mo	V	Al	N ppm	O ppm
31V Mn12	0.2 8	1.2 4	0.2 8	0.015	0.025	0.1 4	0.1 1	0.1 2	0.001	0.1 7	0.018	89	106

Table 2
MECHANICAL CHARACTERISTICS OF STEEL 31VMn12

T[^{0}C]	$\dot{\varepsilon}$ [sec^{-1}]	σ_{max} [daN/mm^2]	ε_{max} [%]	Z
800	0.05	156	0.681	2.59E+15
	0.1	180	0.708	5.18E+15
	3.0	206	0.732	1.55E+17
900	0.05	133	0.627	9.74E+13
	0.1	120	0.664	1.95E+14
	3.0	178	0.693	5.84E+15
1000	0.05	103,1	0.586	6.13E+12
	0.1	100	0.597	1.23E+13
	3.0	103	0.67	3.68E+14
1100	0.05	94	0.498	5.77E+11
	0.1	72	0.543	1.15E+12
	3.0	85	0.613	3.46E+13

in which:

$\dot{\varepsilon}$ - speed deformation [s^{-1}]; n - hardening coefficient; Q - the activation energy of the dynamic recrystallization [kJ/mole]; R - universal gas constant; T- the deformation temperature [K]; A -constant; where are variables: ε, Q, T and σ.

A constant value determined by different authors is not the same any material importance for the history of the same material deformation. Such values have been proposed: 0.67, 0.83, 0.86 [3,9,18,20]. We have statistically analyzed the obtained data by multiple regression with two variables and so the values of the coefficient and the constant of the equation have been calculated. Knowing the value of the gas constant R we have calculated the activation energy Q obtained was Q = 343.5 KJ / mol. By the following equation, one could calculate Z – H parameter [11]:

$$Z = \dot{\varepsilon} \cdot e^{\frac{Q}{RT}} \qquad (3)$$

The hardening area of the curve (σ = f(ε)) is characterized by a constant value of the strain-hardening coefficient and it can be expressed by the formula. The hardening area of the curve σ = f(ε) which can be characterized by a value of the hammering coefficient practically constant, can be expressed as following [18,20, 23]:

$$\sigma = B[1-e^{-C\varepsilon}]^n \qquad (4)$$

where the B and C coefficients depend on the Z parameter and *n* is practically equal to the strain hardening coefficient.

The strain hardening coefficient can be obtained from the following relationship that characterize the stress-strain curve in the torsion test:

$$\varepsilon = \frac{2\pi RN}{\sqrt{3}L} \quad [11] \qquad (5)$$

$$\sigma = \frac{\sqrt{3}C}{2\pi R^3}(3+m+n) \qquad (6)$$

where:

- *n* represents the strain hardening coefficient [23]

$$n = \frac{\partial \ln C}{\partial \ln N} \qquad (7)$$

- *m* represents the viscous-plastic coefficient [18]

$$m = \frac{\partial \ln C}{\partial \ln \dot{N}} \qquad (8)$$

- N represents the number of rotations
- C represents the torsion moment

The *n* coefficient has an important role in developing the mathematical model allowing the separation of the hardening area from the restoring area [23].

The number (5) equation is valid, as we have previously shown, only for the strain hardening area. For bigger deformations, for which the restoration process begins, the equation changes and it becomes [23]:

$$\Delta\sigma = B'\left\{1 - e^{-k\left(\frac{\varepsilon - a\cdot\varepsilon_p}{\varepsilon_p}\right)^n}\right\} \qquad (9)$$

where B' coefficient and the ε_p deformation (corresponding to the maximum stress) depend on Z parameter. In the restoration area (at bigger deformations) the function Δσ takes values with a trend towards B'. It allows also the modelling of this area. The product a x ε_p must be equal to the deformation that marks the beginning of the dynamic restoring process (in the restoring area $\varepsilon > \varepsilon_p$, and before the restoring process $\varepsilon < \varepsilon_p$).

where the B' coefficient and ε_p deformation that corresponds to the maximum tension, depend upon Z parameter. In the restoring area (at bigger deformations) the function Δσ takes values that tend towards B' which allows the modelling of this area also [13,18,20,23]. The result of a x ε_p must be equal to the deformation that marks the beginning of the dynamic restoring process (in the restoring area $\varepsilon > \varepsilon_p$, and before the restoring process $\varepsilon < \varepsilon_p$).

Formula number (9) is an Avrami type equation and it is valid for deformations bigger than a x ε_p. For deformations with values close to a x ε_p product, Δσ has lower values and its derivative is lower as compared to equation number (5) which allows the modelling of the restoring area.

On the other hand, the inflexion point calculated by using the equation [23]:

$$\varepsilon = \varepsilon_p[a + (\frac{n'-1}{kn'})^{1/n'}] \qquad (10)$$

is relatively close to the maximum stress and it allows the calculation of the transition area, meaning the area between the beginning of the dynamic recrystallization up to the complete recrystallization.

The criteria for the derivative of the σ and Δσ functions were established starting from the value of deformation ε_0 determined through the continuity of the derivatives.

The deformation curve σ = f(ε) is given by the difference between equation number 5 and equation number 10, all coefficients depending mainly on *Z* parameter [23].

The resulted values for coefficients and for the mathematic model of the curve σ = f(ε), are valid for the complete dissolution of the vanadium nitrides before the deformation, the test tubes being heated up to 1150^{0}C for 30 min and then added particles (nitrides, carbonitrides) area not put in solution at high temperature, their presence during deformation process changes the needed deformation for the dynamic recrystallization, and, consequently, all the values obtained are changed.

Based on obtained results we have calculated by regression coefficients B, C, B', ε_{max}, ε_p. These coefficients represent independent variables in those two equations.

Figures 1 to 6 presents the dependence of these coefficients on Z parameter.

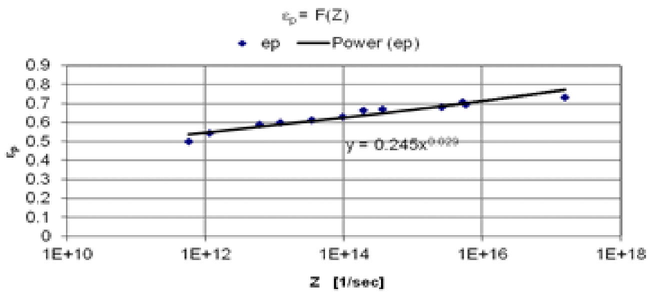


Fig. 1 The variation of the deformation ε_p depending on the Zenner Hollomon (Z) parameter

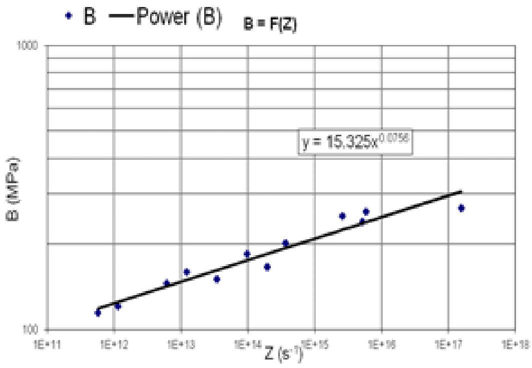


Fig. 2. The variation of B coefficient depending on Zenner-Hollomon

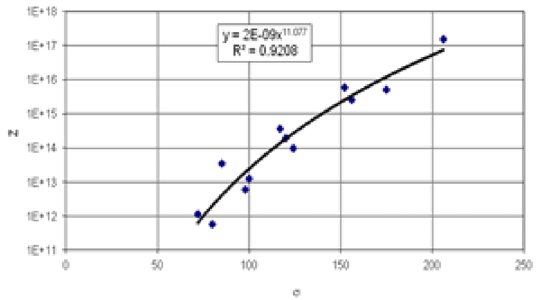


Fig. 5. The Zenner-Hollomon depending on the Stress-strain σ

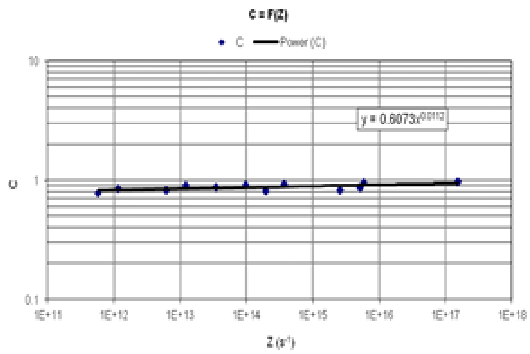


Fig. 3. The variation of the C coefficient depending on Zenner-Hollomon

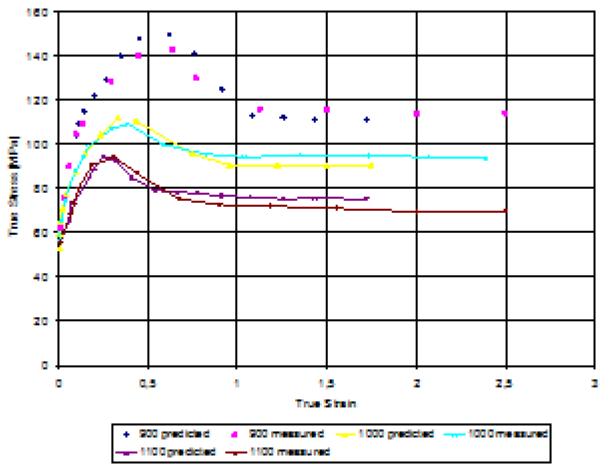


Fig. 6. The Stress-strain curves s, depending on the deformation ^o_e determined for 0,05 s^{-1} and 900, 1000, 1100^{0}C

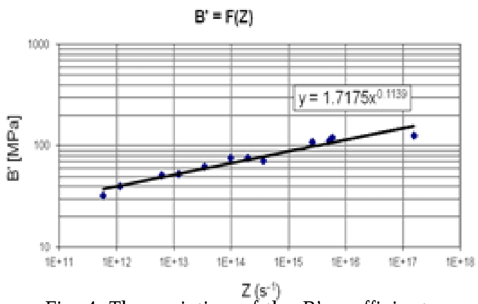
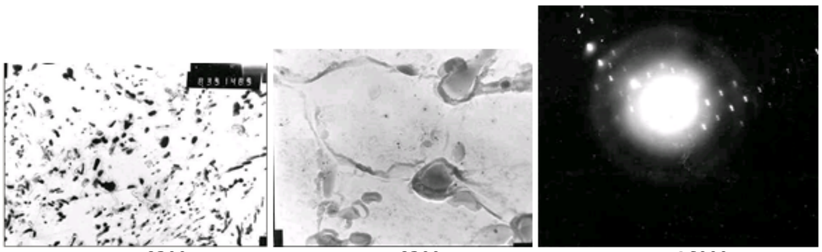


Fig. 4. The variation of the B' coefficient depending on Zenner-Hollomon



x 8300 x 8300 x 26000

Fig. 7 The distribution of vanadium precipitates mainly on particles limits (and sublimits) from micro-alloyed steel, deformed at 900^{0}C with a 3 s^{-1} speed.

Figure 7 shows the evolution of the s and Ds functions depending on the deformation it is noticed that σ - Δσ curves have exactly the some shape curves σ = f(ε) obtained by the experimental determination of the steel deformability.

In figure 6 shows the stress - strain curves for strain 0.05 s^{-1} and temperatures 900, 1000, 1100^{0}C.

The analysis at the electronic microscope on extraction retorts of the tested proofs in each variant of temperature and speed of deformation emphasized, on steel 31VMn12 deformed at a 3 s^{-1} speed and 900^{0}C temperature, the presence of some precipitation on grain limits and sublimities The analysis of the diffraction image indicates the fact that the precipitation network is cubic (fig. 7). From the calculus of the interplanar distances resulted that the values corresponding to de carbonide of vanadium, results confirmed by the network type also.

The presence of the vanadium nitride in the deformed proof at 900^{0}C (steel 31VMn12) along with the beginning of the appearance of small recrystallized grains close to prolonged, hammered grains leads to the idea that the dynamic precipitation. The hypothesis of the existence of the dynamic precipitation in the 900^{0}C deformed proof is confirmed by the small size of the precipitates in (below 10 μ); if the vanadium nitride particles had not dissolved at warmth for deformation, their and would have been bigger, because they would have appeared at warmth and would have traversed the whole germination, growth and coalescence domain (from the documentary study, these processes begin at 700^{0}C and end at 950-1000^{0}C – the proofs have been austenitized at 1000^{0}C, when practically the whole amount of precipitates is in solution.

Conclusions

The established model allows a complete formulation of the stress-strain curve; all the functions of the model depend on a single parameter (Z); the mathematic expression of the model is relatively simple. The value of the resistance to deformation, for each rolling step, can be calculated by an analytical method.

The deformation characteristic of 31VMn 12 steel have been investigated by means of the torsion test in the interval 800...1200^{0}C, these charge being twisted at deformation rates between 0.5 and 3 s^{-1} was observed appearance of small recrystallized grains steel microalloyed studied due to plastic deformation induced precipitation temperature of 900^{0}C hot and 3 s^{-1} by: metallographic analysis showing the boundaries of new grains grains harden; electron microscopy analysis, highlighting V particles precipitated under these conditions.

The presence of the vanadium nitride in the deformed proof at 900^0C (steel 31VMn12) along with the beginning of the appearance of small recrystallized grains close to prolonged, hammered grains leads to the idea that the dynamic precipitation. The hypothesis of the existence of the dynamic precipitation in the 900^0C deformed proof is confirmed by the small size of the precipitates in (below 10 μ); if the vanadium nitride particles had not dissolved at warmth for deformation, their and would have been bigger, because they would have appeared at warmth and would have traversed the whole germination, growth and coalescence domain.

Based on experimental stress-strain data, a revised constitutive equation incorporating the effects of temperature, strain rate and work-hardening rate of the material is derived by compensation of strain and strain rate. Comparisons between the experimental and predicted the proposed model well agree with experimental results, which confirmed that the revised deformation equation gives an accurate and precise estimate for the flow stress of 31VMn12 steel. For all samples, we have processed the recorded quantities and we equated them to values of tension and deformation specific to the hot torsion testing: σ_{max} has an increasing tendency with an increase of e and a decreasing one when T_0 is increasing.

References

1.RUSANESCU, C. O., RUSANESCU, M., ANGHELINA, F. V., J. Optoelectron. Adv. Mater. 15(7-8), **724** (2013)

2. SCHMITT, J. , FABREGUE, P., THOMAS, B., J. Phys. IV, 1995, **05** (C3), pp.C3-153-C3-163.

3. DURBACA, I., STEFANESCU M.FL., SPOREA, N., Buletinul Universitatii Petrol-Gaze din Ploiesti, Seria Tehnica, Vol. LXV, No.1/ 2013, p. 64-70

4. ENESCU, M.C., POPESCU, I.N., ZAMFIR, R., MOLAGIC, A., BRATU, V., International Journal of Energy and Environment, **4** (4) (2010)122-130.

5. RUSANESCU C. O., RUSÃNESCU M. J. Min. Metall. Sect. B-Metall. **49** (3) B (2013) 353 – 356;

6. RUSÃNESCU C.O., JINESCU C., PARASCHIV G., BIRIS S. ‘T., RUSANESCU M., GHERMEC O., Rev. Chim. (Bucharest), **66**, no. 5 2015, p. 754

7. GHITA, C., POPESCU, IL. N.Computational Materials Science Volume: 64 Pages: 136-140, 2012

8. DURBACÃ, I.,Mat. Plast.,**52**, no. 1, 2015, p. 43

9. ENESCU, M.C., POPESCU, I.N., ZAMFIR, R., MOLAGIC, A., BRATU, V., Proc. 2nd International Conference on Manufacturing Engineering, Electrical and Computer Engineering (2010) 212-216.

10. BEGEA, M., STROIA, I., BOCA, E., VLADESCU, M., BEGEA, P., J. Environ. Protection Ecology, **8**, no. 2, 2007, p. 380

11. C. ROSSARD, Proc. ICSMA 3, vol.11 (1973) 175

12. RIZESCU, CR. Z., BACINSCHI, Z., STOIAN, EL. VA., POINESCU, A. A., Proceedings of the 4 th WSEAS International Conference on Waste Management, (WWAI 10), p.139-143, 2010,

13. LIN Y.C., MING – SONG CHEN, JUE ZHONG Computational Materials Science **42** (2008) 470-477

14. POPESCU, I.N., ENESCU, M.C., BRATU, V., ZAMFIR, R.I., STOIAN, E.V., Advanced Materials Research, Trans Tech Publ. **1114** (2015), 239-244.

15. RUSANESCU, C.O., RUSANESCU, M., ANGHELINA FL. V., Optoelectronics and advanced materials Rapid communications, **7**, 11-12, 2013, p. 947-951

16. MEDINA, S.F., LOPEZ V., ISIJ International, **33**(1993), No. 5, pp. 605-614

17.POPESCU, I.N., BRATU, V., ENESCU, M.C., AEE ’10: Proceedings of the 9th WSEAS Int. Conference On Applications of Electrical Engineering, Recent Advances in Electrical Engineering, (2010) 225-232.

18. MEDINA , S.F., MANCILLA J. E. , ISIJ International, **36** (1996), No. 8, pp. 1077-1083

19. STOIAN, E. V., RIZESCU, C. Z., CHITANU ELENA, ANGHELINA, V., POINESCU, A. A., EMESEG 2010, WORLDGEO 2010, p.130-135,

20. MEDINA, S.F., FABREGUE, P., J. Mat. Sci., 26 (1991), 5427

21. STOIAN, E. V., RIZESCU, C. Z., PINTEA, J., UNGUREANU, D. N., FLUIERARU, C. P., International Journal of Geology, Issue 3, **3** (2009), p.70-78,

22. POPA, N., CARDEI, P., VOICU, GH., MINCIUNA, V. ST., DONCEA, S.M., DINCA, M., DURBACA, I., Mat. Plast., **52**, no. 2, 2015, p. 144

23. MEDINA, S.F., HERNANDEZ, C. A., Memoires et Etudes Scientifiques Revue de Metallurgie – 1992(**4**);

24.SIMA, T.,Rev. Chim. (Bucuresti), **61**, no. 1, 2010, p. 8

25. PAPADATU, C. P., SANDU, A. V., BORDEI, M., SANDU, I. G., Rev. Chim.(Bucharest), **67**, no. 11, 2016, p. 2306

26. BUCUR, L., BUCUR, G., MOISE, A. G., POPESCU, C., Rev. Chim.(Bucharest), **67**, no.1, 2016, p. 87

27.CARDEI, P., POPA, N., VOICU, GH., MINCIUNA , V. ST., DONCEA, S.M., DURBACÃ, A.C., DURBACA, I., DINCA, M., Mat. Plast., **52**, no. 3, 2015, p. 345

28. PETRE, I., STOIAN, E.V., ENESCU M.C, Scientific Bulletin of Valahia University-Materials and Mechanics, 14 (2016), (**11**), 35-40, ISSN 2537-3161/ pp.35-40

29. STOIAN, E.V., BRATU, V., ANGHELINA, F. V., ENESCU, M.C., The Scientific Bulletin of Valahia University - Materials and Mechanics, 10 (13) 2015

30. DURBACA, I., POPA, N., VOICU, GH., DURBACA, A.C., Mat. Plast., **52**, no. 4, 2015, p. 464

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