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Development of Usage of Brinell Hardness Test Method for Flow Stress Definition during Cold Deformation

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In this article a method of construction of ferrous metals flow curve for flow stress definition with Brinell hardness tester is represented. The flow curve is approximated with a power function by P. Ludwig. Equations relating hardness by Brinell and the flow curve are obtained by finite element method simulation. According to the method it is necessary to make two measurements of hardness at loads of 29.43 kN and 2.453 kN on ball indenter with a diameter of 0.010 m. The unknown coefficients are hardening and strength coefficients, which are found by solving a system of nonlinear equations.

Keywords: FLOW CURVE, POWER FUNCTION, HARDNESS, BALL INDENTATION, BRINELL, FINITE ELEMENT METHOD

In the process of plastic forming of metal the change of reformation resistance is observed. In this simple and complex monotonic loading most metals in the cold condition show the property of hardening, as a result of which strength characteristics increase and ductility characteristics reduce. In the plasticity theory Odqvist parameter (true strain) is taken as a strengthening means. It is put into one-to-one dependence under with monotone deformation with the intensity of the normal stresses (true stress), regardless of the state of stress condition (Nadai-Lode parameter) and loading history. Functional relationship between the true stress and strain is called the flow curve, which is the main characteristic of the metal hardenability in cold condition during for quasi-static deformation [1-3].

For convenience's sake, the flow curves are usually approximated by different functions, depending on the peculiarities of the material behaviour. From our point of view, P. Ludwig approximation gives sufficient accuracy for most quasi-monotone processes of metal forming both in the experimental and theoretical, and numerical calculations under deformations, which substantially exceed the yield point [1, 2, 4-6].

$$\sigma_i = Ae_i^n, \qquad (1)$$

where A and n (empirical coefficients) are a module and indicator of material hardening; σ_i, e_i are intensity of normal stress and deformation.

In the technological processes of metal forming, cutting, a complex parameter is often used which is responsible for the mechanical properties of the material, particularly, for its hardness [3, 7-9]. Hardness value correlates with yield and break points, the Hall-Petch coefficients, and also can also be used for metal microstructure study [8, 9]. However, in practice, the materials having the same hardness may behave differently in identical conditions of pressure treatment [3, 5]. This is due to the fact that hardness is an integral characteristic of the metal in the form of contact stresses averaging. It and depends on the method and the experimental conditions. However, the simplicity of the method and its accessibility make it extremely attractive for the study of the metal flow curve.

In this study [5], using the finite element method (FEM) the empirical relationship of the flow curve is obtained in the form (1) with the Brinell hardness in the implementation of the steel ball diameter of 0.010 m with a force of 29.43 kN (3000 kgf), which will be denoted as HB_{3000}. The dependence is the following:

$$HB_{3000} = -82{,}61 + 98{,}45n^{0.349} + 1{,}942A^{0.798} - 1{,}989n^{0.349}A^{0.798} \qquad (2)$$

and allows determining hardness value HB_{3000} with an error less than 2%.

Yield point of material in the simulation and obtaining the expression (2) was set approximately as the intersection of straight elastic plot,

set by Young modulus with power function. This is acceptable when considering the processes in which deformations are rather higher than yield strain [5]

$$\sigma_y = A\left(\frac{E}{A}\right)^{\frac{n}{n-1}}.$$

As an additional condition for determining of coefficients approximation of expression (1) by hardness HB_{3000} it is suggested in the study [6] to use the relationship of n and A on the basis of the empirical dependence of break and hardness point [7]. It should be noted that this relation is valid for non-heat-treated, non-hardened metals within the limits of the group with definite chemical composition. The advantages of this approach lie in the simplicity, because it is necessary to know only the hardness value to obtain flow curve function. However, the method is characterized by rather large confidence intervals, which generally decreases the accuracy of the flow curve determination. In the study [4] it was suggested to use the ratio of the yield and break points as an additional condition to use, but in this case the error of the method is rather high.

Brinell hardness depends on the load applied (Fig.1). At high loads (20-30 kN, the diameter of the ball is 0.010 m), the function as a rule has long maximum, which corresponds to a small change of deformation values and stress state scheme in the imprint of the applied force [3, 8]. The basic, standard hardness value is obtained exactly in this area. However, at low loads the principle of similarity is not performed; and deformation reach small values about 0.05-0.1 (Fig. 2). Thus, the usage of standard equipment for the Brinell hardness test on the ball indenter with a diameter of 10 mm for small values of the applied loads makes the opportunity of additional conditions for determination the approximation coefficients of the flow curve without simplifying hypotheses.

The **work objective** is to determine the coefficients of flow curve approximation of A and n depending on the metal hardness by Brinell method obtained at different loads by FEM simulation.

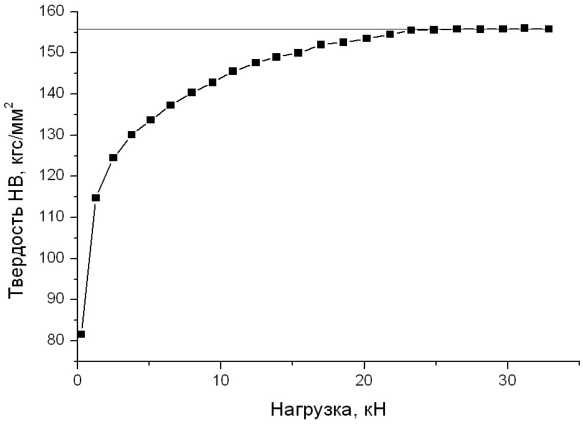
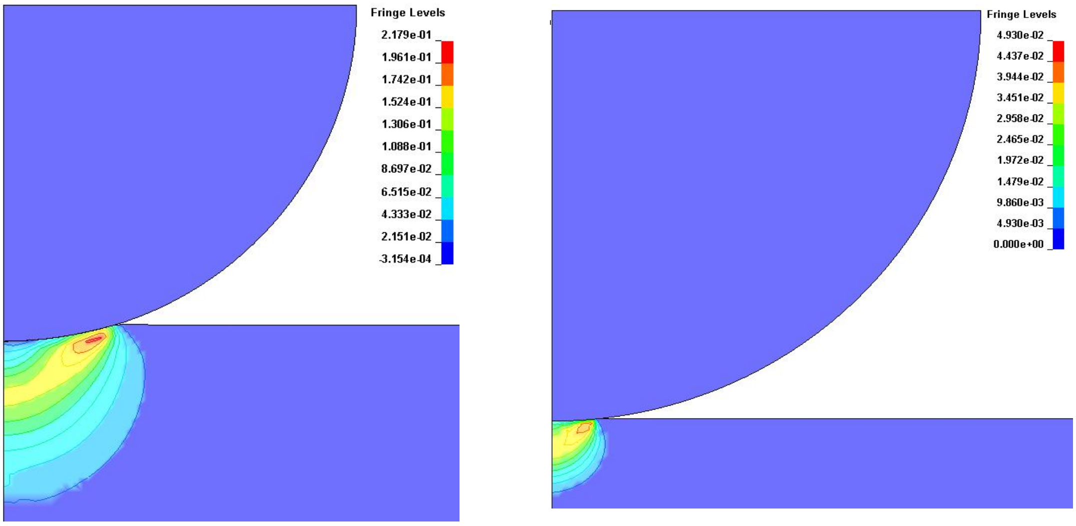


Figure 1. Dependence of Brinell hardness on the load. $\sigma_i = 1000 e_i^{0,25}$

Main chapter

In such formulation of the problem it is important to choose the experimental conditions and further modelling of the test. The greater is the difference in the two values of hardness at different loads, the more accurate determination of the flow curve can be. Minimum force regulated by **GOST 9012-59** (ISO 6506-81, ISO 410-82 as amended in 1990) and implemented in standard Brinell hardness tester is 0.981 kN, the maximum is 29.43 kN. But under a force of 0.981 kN on a ball of 10 mm in most cases small prints with indistinct contours are formed; the average contact deformation becomes comparable with yield strain, all of which reduces the accuracy of hardness determination both in FEM simulation and in full-scale tests. Therefore, 2.453 kN (250 kgf) was taken as the following standard number according to GOST after 0.981 kN. The usage of heavier loads increases the strain in the print and changes hardness, compared to force of 29.43 kN, which in turn reduces the sensitivity of the method.



P = 29,43 kN; HB_{3000} = 385 $\frac{êãñ}{ìì^2}$ P = 2,453 kN; HB_{250} = 299 $\frac{êãñ}{ìì^2}$

Figure 2. The distribution of the intensity of accumulated deformations in the print at various loads on the identor of 0.01 m; $\sigma_i = 1500 e_i^{0,05}$

According to the method of study [5] the process of implementation of the ball with a diameter of 10 mm at a load of 2.453 kN into elastoplastic semispace was simulated using software package LS-DYNA (Fig. 3). There were set the following values by the characteristics of simulated material: Poisson's ratio μ = 0.3, Young's modulus E = 210 hPa, friction ratio between the ball and the surface according to Coulomb f = 0.1. Ball's material is perfectly elastic with μ= 0.3 and E = 210 hPa. Axisymmetric task description was used. The modulus value and hardening parameter n = 0.05-0.5 with interval of 0.05 and A = 500-1500 MPa with interval of 100 MPa were varied, which corresponds to the majority of materials to be processed by pressure. As a result, 209 calculations were performed.

By statistical processing of the data obtained by least squares method, the function with the best correlation to the calculated points was found, and the coefficients of regression were determined. The approximating function corresponds to the expression (2)

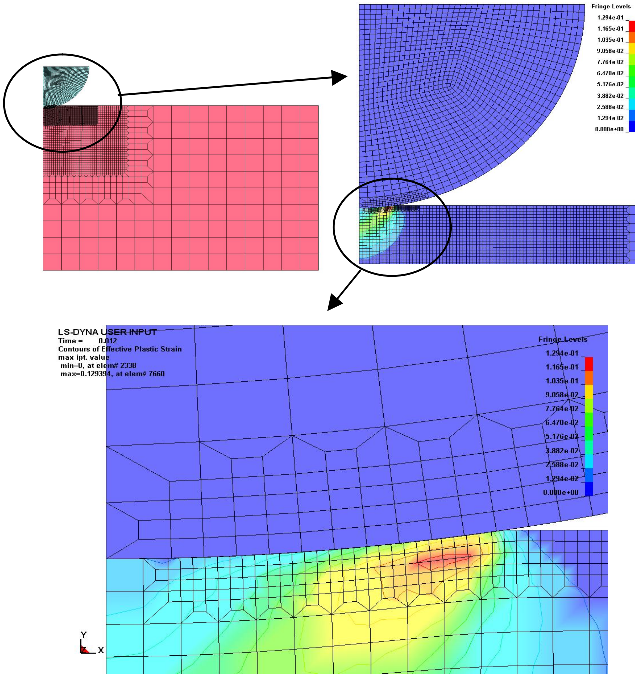
$$HB_{250} = -77,72 + 79,32 n^{0.396} + 5,603 A^{0,624} - 6,088 n^{0.396} A^{0,624}, \quad (3)$$

Deviation of the calculated values of HB_{250} for (2) and the values obtained by FEM simulation is not more than 6%, and for most values it is about 2-4%. This accuracy is sufficient for problems of technological mechanics.

Thus, this material, set as a flow curve by coefficients, corresponds to the two values of hardness HB_{3000}, HB_{250} at different loads. These coefficients can be found by solving the system of equations (2) - (3). It should be noted that this system of equations is solved numerically. Its solution is represented in the form of nomograms with respect to parameter n (Figure 4), which in addition to clarity of solution, also gives an idea of the range of variation of coefficients A, n and the hardness values HB_{3000}, HB_{250}. Consolidation module with known n is easy to find, for example, from the equation, derived from (2)

$$\grave{A} = \left(\frac{HB_{3000} + 82.61 - 98.45 n^{0.349}}{1.942 - 1.989 n^{0.349}} \right)^{1/0.798}.$$

For the convenience of solution of this equation it can also be represented in the form of a nomogram (Fig. 4).



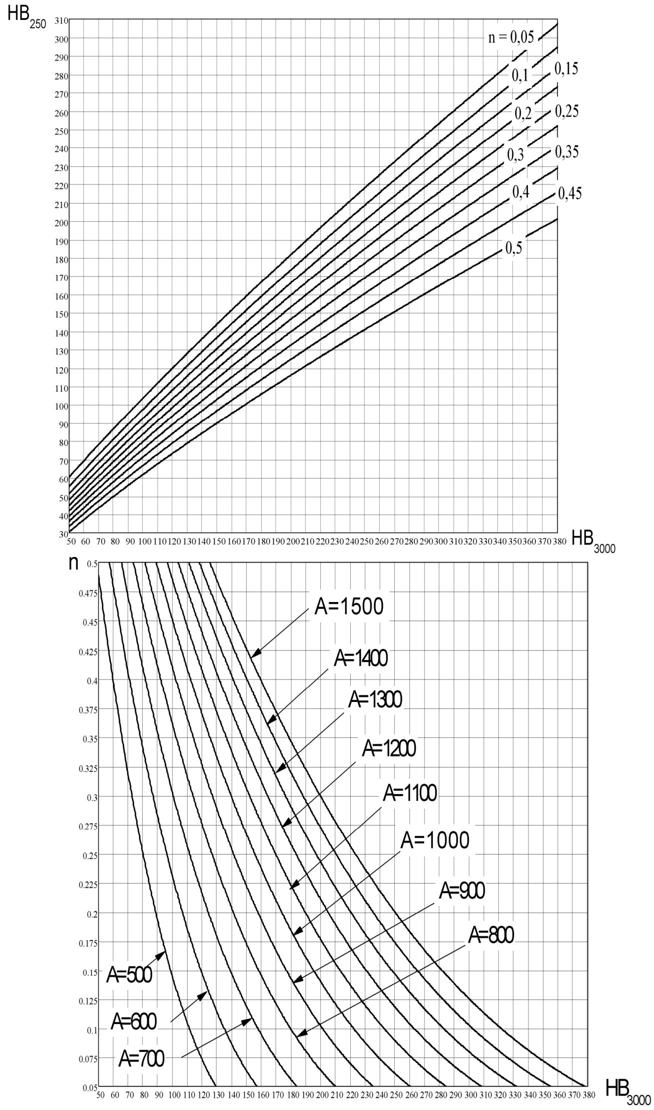
A = 1500 MPa; n = 0,5; P = 2,453 kN;

HB_{250} = 76 êãñ / ì ì ^{2}

Figure 3. Separation of the model into finite elements and distribution of deformation intensity in the print

Experimental verification of the suggested method for various materials is given in the Table 1.

Calculations showed that the accuracy of hardening parameter n is slightly lower than that of the module A, and decreases with decreasing of parameters of n. This is connected with a greater degree of similarity of strained condition under the assumed loads for materials with low ability to hardening than for materials with significant hardenability. The average error of parameter determination for the studied metals was 7%, and for the module A it was 3%. Figure 5 shows the flow curves of steel 30H3MFA (heat treatment – improvement), made on the results of compression and stretching test of a series of samples. Curve 1 is obtained by statistical processing according to the least squares method (adjusted R-square is 0.921), curve 2 is calculated based on the results of hardness measurements (adjusted R-square is 0.911). The curves are situated close enough, despite a large error in determining of parameter n (13.8%). Thus, the accuracy of the method is sufficient for the majority of problems of technological mechanics.



HB_{3000}, HB_{250} in êãñ / ì ì ^{2}

Figure 4. The nomogram of determination of the coefficients A (MPa) and n by hardness at the load of 29.43 kN and 2.453 kN

Conclusions

Among other approximate methods [4-6] of flow curve determination, the suggested one gives the most accurate results comparable to common and rather time-consuming testing of samples under compression, tension and torsion [1-3]. The obtained flow curves are the integral, calculated from averaged strains in condition of volumetric compression. Consequently, they can be recommended to be used for calculations of processes of pressure treatment, which are characterized by volume of stress condition with the identity of plastic flow conditions of metal. The proposed method can be recommended as a rapid test to obtain characteristics of metal hardenability in production conditions.

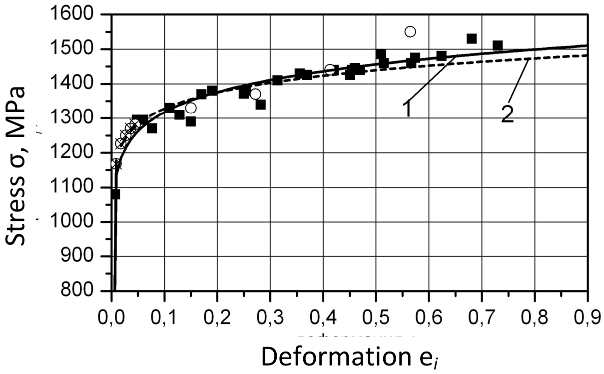


Table 1. Comparison of experimental and calculation data

Material	Experiment				Calculation		Error	
	A, MPa	n	HB_{3000}, êãñ/ìì²	HB_{250}, êãñ/ìì²	A, MPa	n	Δ_A, %	Δ_n, %
Steel 45	1230	0.28	177	136	1205	0.267	-2.0	-4.6
ШХ15	1155	0.217	190	148	1195	0.232	3.5	6.9
Х18Н9Т	1305	0.288	180	133	1359	0.308	4.1	6.9
Steel 20	810	0.205	138	116	791	0.205	-2.3	0.0
Steel 3	840	0.25	135	110	844	0.243	0.5	-2.8
Steel 20Х	930	0.215	157	130	899	0.201	-3.3	-6.5
30Х3МФА	1163	0.186	206	164	1203	0.199	3.4	7.0
30Х3МФА improved	1540	0.058	375	304	1487	0.05	-3.4	-13.8
38Х2МЮА	1396	0.104	252	237	1416	0.113	1.4	8.7
38Х2МЮА improved	1134	0.096	260	215	1107	0.085	-2.4	-11.5

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Развитие использования метода испытания твердости по Бринеллю для определения напряжения текучести при холодной деформации

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Предложен метод построения кривой течения черных металлов по определению твердости при помощи твердомера Бринелля. Кривая течения аппроксимирована степенной функцией по П. Людвику. Уравнения связи твердости по Бринеллю и кривой течения получены путем моделирования методом конечных элементов. В соответствии с методом необходимо провести два измерения числа твердости при нагрузках 29,43 и 2,453 кН на шаровой индентор диаметром 0,010 м. Искомыми коэффициентами являются показатель и модуль упрочнения, которые находятся решением системы нелинейных уравнений.