About practicality of Hall-Petch law in metals

O.N.Ignatova, V.V.Losev, A.N.Malyshev, D.M.Petrova, A.M.Podurets, V.A.Raevsky, M.I.Tkachenko, A.N.Tsibikov

RFNC-VNIIEF, Sarov

To construct wide-range constitutive equations of solid substances suitable for calculations of dynamic processes accompanied by great deformations, temperatures and pressures, consideration must be given to structural changes to be occurred in this case. Shear stress is dependent not only on state parameters at the present instant of time, but also on the history of straining, which determines a substance structure at the given point of time. At the same time the most advanced models take into account a growth of dislocation density, a change of microcrystals sizes (grain size), twinning, appearing at high-rate strain, annihilation of dislocations (or an decrease in dislocation density) at heating higher than the critical one [1], [2].

The effect of the average grain size on stress intensity is expressed in terms of the so-called Hall-Petch law, which at other constant parameters takes the form of [3], [4]:

$$\sigma=\sigma_0+K_1 \cdot D^{-1/2}, \quad (1)$$

where σ_0 is the flow stress in a single crystal, K_1 is the constant of material, D is the average grain size. Hall justified this regularity in theory [3], and Petch confirmed it experimentally [4] (s.Fig.1). Similar relations exist for the flow stress at various degrees of strain and ultimate strength. It is agreed that relation (1) is performed in a wide interval of grain sizes down to nanosizes.

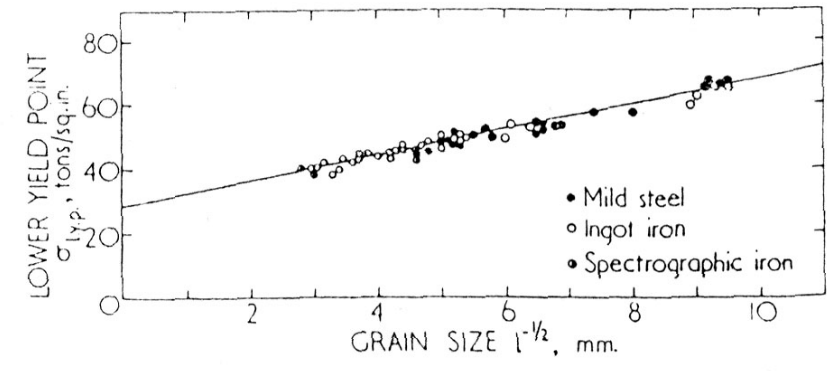
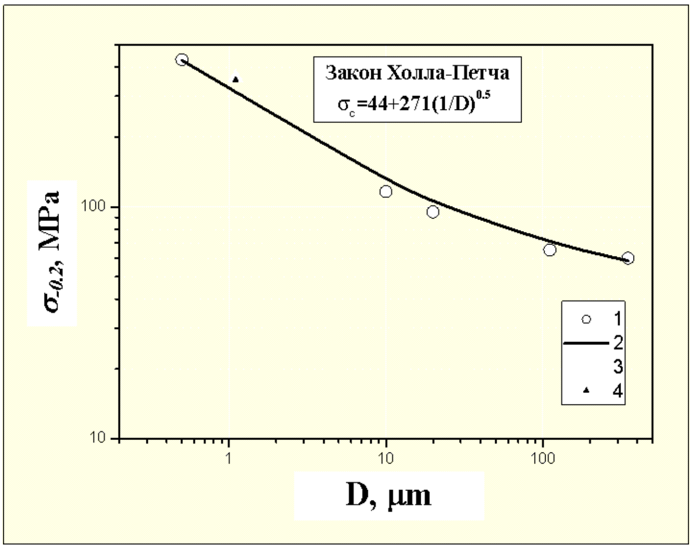


Fig. 1 – Relation between yield point of metals and grain size

Based on the present theory the researchers rely often upon one parameter – grain size [5], [6], [7], [8], [9] (s. Fig. 2) in studying the impact of structure factors upon strength characteristics of metals, but they do not check a value of another parameter influencing strongly on stress intensity of plastic flow– dislocation density. In this case, values of coefficients of equation (1) are selected on the basis of experimental data.



1, 2, 4 – experiment, 2 – calculated dependence

Fig. 2 – Dependence of conventional yield strength on copper grain size

The problem of constancy or change of σ_0 and $К_1$ over various intervals of grain sizes continues to remain argumentative. One can set off the following behavioral versions from the most widespread versions of the behavior of $К_1$ parameter with decreasing a grain size: constancy of $К_1$ parameter [3]-[7]; stepwise decrease [10], [11] or replacement of a sign of the quantity $К_1$ when achieving some grain size [12], [13]. The systematized data for the parameter σ_0 and $К_1$ of copper disclose that σ_0 changes from 10 MPa to 90 MPa and the quantity $К_1$ changes from 0.1 MPa $m^{1/2}$ to 0.24 MPa $m^{1/2}$ with decreasing a grain size from 250 to 0.02 μm. The required grain size was gained through intensive plastic strain and subsequent annealing for copper.

However, the issue remains open concerning the influence of other structure factors on yield point, such as, for example, dislocation density.

The rise of dislocation density under deformation must increase flow stress in accordance with the expression [14]:

$$\sigma=\sigma_0+К_2\cdot\rho_d^{1/2}, \quad (2)$$

where $К_2$ is the constant of the material, ρ_d is the average dislocation density.

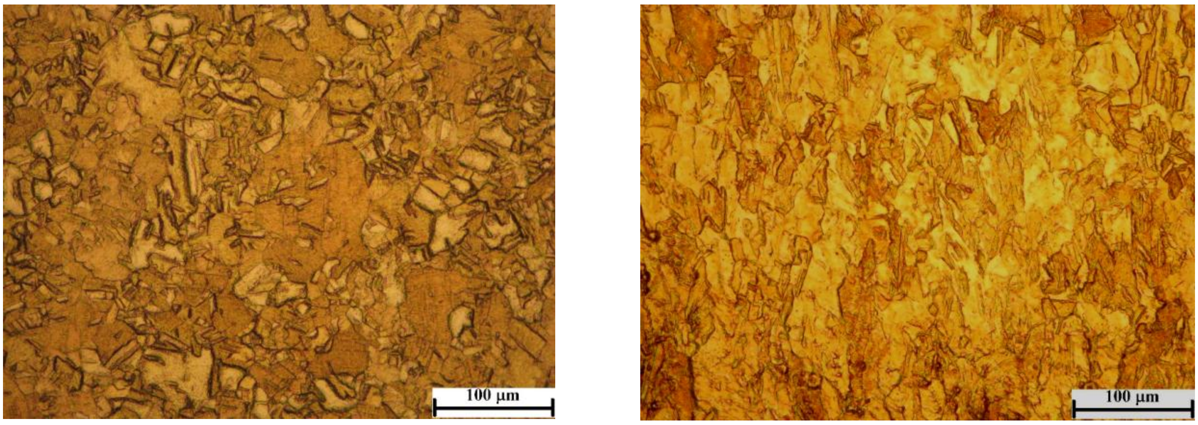
In the general case the effect of a grain size and dislocation density on mechanical properties can be written as [15]

$$\sigma=\sigma_0+К_1\cdot D^{-1/2}+К_2\cdot\rho_d^{1/2}. \quad (3)$$

The goal of the current work is to reveal experimentally a role of each of these factors with regard to yield point and to compare them with each other.

In the work mechanical properties of copper (M1) were measured depending on the grain size D and the diverse dislocation density ρ_d. For this purpose copper samples with known initial parameters – grain size D=20 μm[1] and D=100 μm and density dislocation ρ_{d0} ~10^8 cm^{-2} – were loaded by a shock wave having intensity of ~11 GPa via the method of impact (copper impactor with thickness of 2 mm, impact velocity W=540 m/s). The quantity of complete plastic flow ~0.1 and it did not exceed a critical value for the beginning of grain division, and dislocation density increased strongly.

The study of a microstructure of samples states is given in the metallurgical microscope METAM-LV-31. To analyze a substructure, X-ray analysis shooting was performed on a diffractometer DRON-UM1. The dislocation density ρ_d was defined by comparing with a standard sample, in which ρ_{d0} ~10^8cm^{-2}. The standard was obtained through annealing of coarse-grained copper at a temperature of 550ºC within two hours. This level is enough to conduct measurements, and there is no way to attain lower dislocation density through annealing. After loading measured dislocation density changed on three orders as compared with the initial one and amounted to ρ_d =~10^{11} cm^{-2}. As this takes place a grain size remained the same, shear bands were not discovered. Fig.3 shows photos of a copper microstructure prior to and after loading.



Prior to experiment ρ_{d0} ~10^8cm^{-2}

After experiment ρ_d =~10^{11} cm^{-2}

Fig. 3 - Photos of a copper microstructure with a grain size of D=20 μm prior to and after loading

Dislocation density was decreased up to ρ_d=~3.6·10^{10} cm^{-2} and up to ρ_d~10^{11} cm^{2}. in some samples using a high-temperature anneal. Here, it is worth noting that to accomplish identical dislocation density in copper with the various grain size D, the varied annealing temperature T_{ann} was demanded, T_{ann} was increasing with increasing a grain size, what is due, most likely, to a lesser quantity of boundaries, namely the less a grain the less a distance, which dislocation should cover up to annihilation. After a preliminary preparation, the investigators measured mechanical properties (compression-

[1] Copper with the grain size of D=20 μm was produced in BelSU by the method of all-round forging in the laboratory of D. Sc. (Tech.) G.A.Salishchev.

test diagrams) of samples with a variation of an initial grain size and dislocation density. Compression-test diagrams were gained via the Hopkinson split bar method (HSB) at strain rate of ~10^3 1/s (copper samples of a cylindrical form, 8.5 mm in diameter, 6 mm in length). Figures 4 and 5 show compression-test diagrams with a various grain size and dislocation density, and Table 1 demonstrates the conventional yield strengths $\sigma_{0.2}$ measured from processing of diagrams.

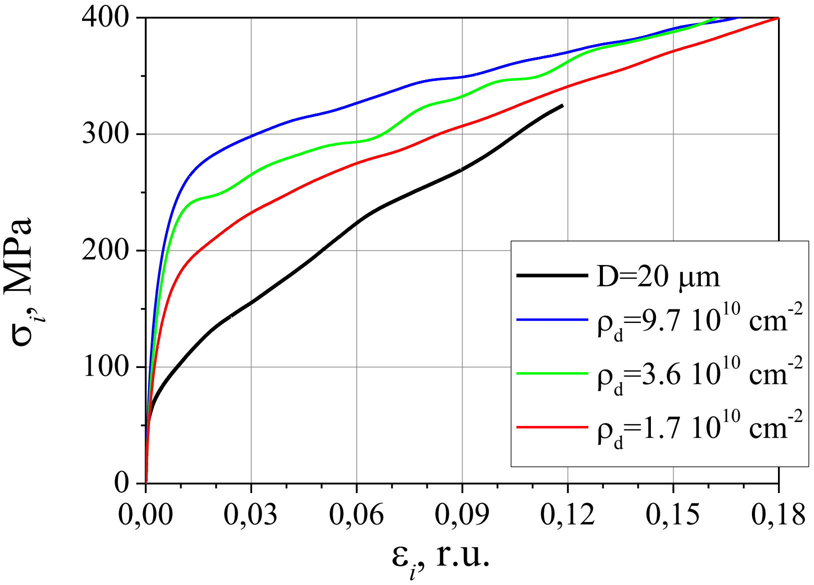


Fig. 4 – Average true σ-ε compression-test diagrams of copper with a grain size of 20 μm and different dislocation density

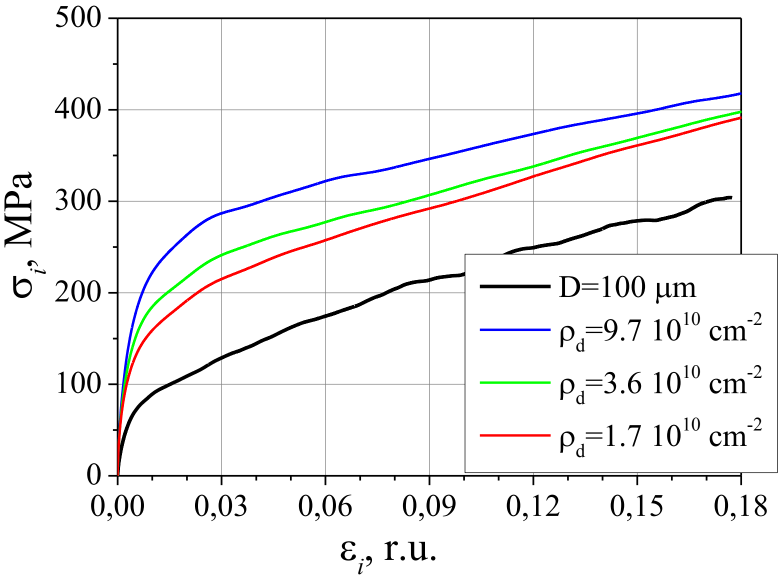


Fig. 5 - Average true σ-ε compression-test diagrams of copper with a grain size of 100 μm and different dislocation density

Table 1

Grain size, μm	ρ_d, $\cdot 10^{10}$ cm^{-2}	$\sigma_{0.2}$, MPa	Annealing temperature, C
20	9.7	190±13	0
	3.6	155±11	260
	1.7	118±9	275
	0.01	72±5	360
100	9.7	153±10	0
	3.6	126±9	330
	1.7	110±8	400
	0.01	70±3	550

For comparison figures 6 and 9 show compression-test diagrams of copper with a varied grain size, but with identical dislocation density.

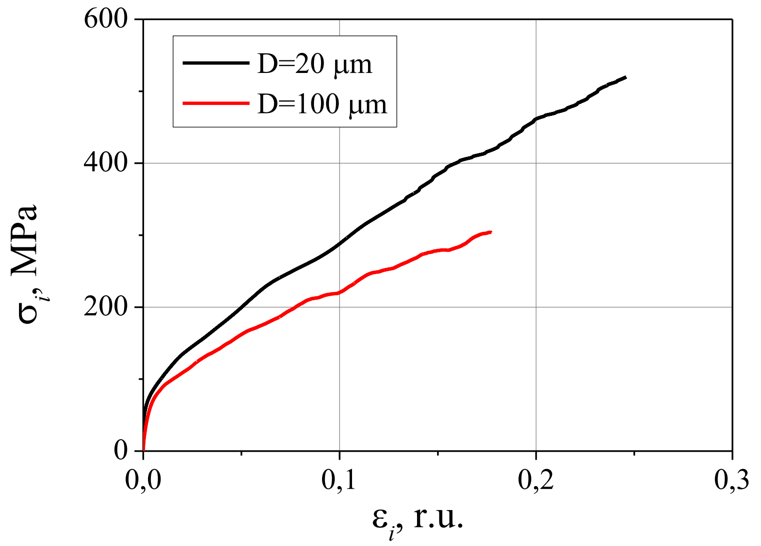


Fig. 6 - Average true σ-ε compression-test diagrams of copper with a grain size of 100 μm and 20 μm and with dislocation density of ρ_{d0} ~10^8cm^{-2}

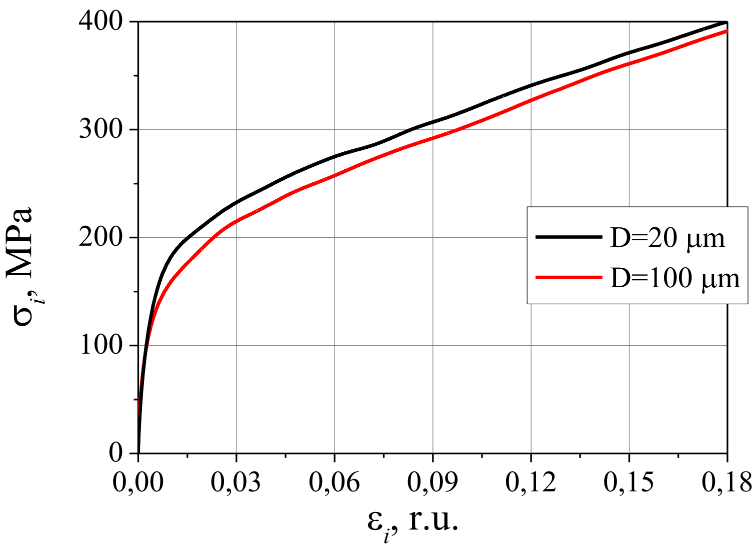


Fig. 7 - Average true σ-ε compression-test diagrams of copper with a grain size of 100 μm and 20 μm and with dislocation density $\rho_d \sim 1.7 \cdot 10^{10} cm^{-2}$

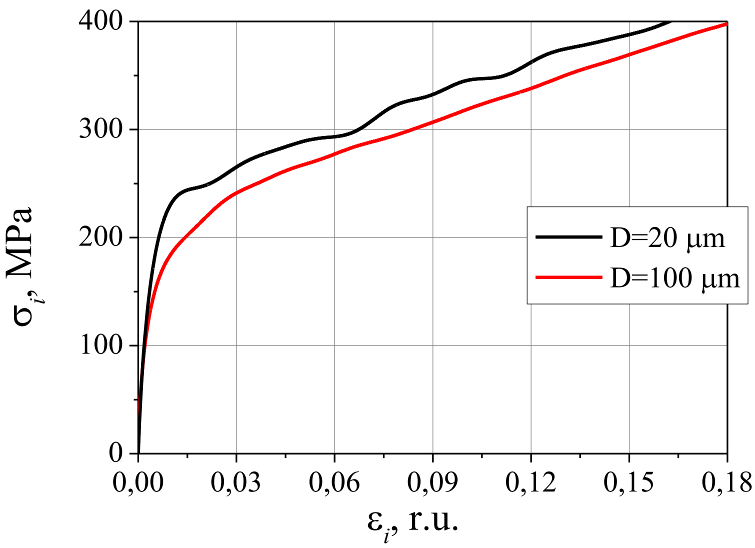


Fig.9 - Average true σ-ε compression-test diagrams of copper with a grain size of 100 μm and 20 μm and with dislocation density $\rho_d \sim 3.6 \cdot 10^{10} cm^{-2}$

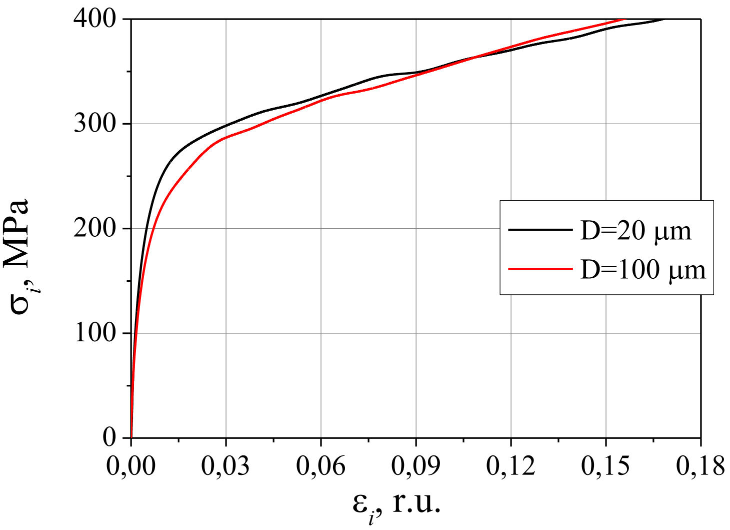


Fig 9 - Average true σ-ε compression-test diagrams of copper with a grain size of 100 μm and 20 μm and with dislocation density $\rho_d \sim 9.7 \cdot 10^{10} cm^{-2}$

In this manner, the performed studies show that within the framework of experimental accuracy an increase in a grain size by a factor of ~5 at equal dislocation density does not lead to any significant changes in strength characteristics.

The obtained values of conventional yield strength from/using dislocation density and a grain size can be approximated through unified dependence:

$\sigma = 65 + 20 \cdot D^{-1/2} + 3.6 \cdot 10^{-4} \cdot \rho_d^{1/2}$ [MPa].

Fig. 10 presents experimental points and approximating curves.

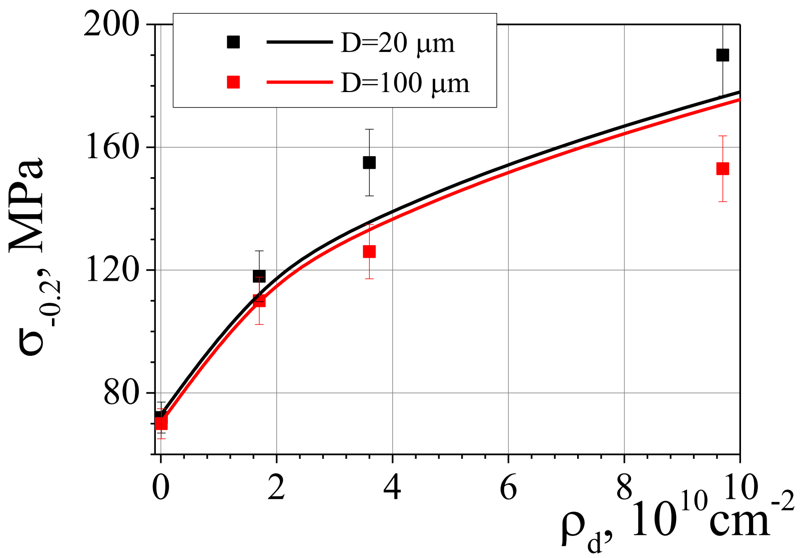


Fig. 10 – Dependence of conventional yield strength on dislocation density in copper with a various grain size

The implemented experiments testify to the fact that yield strength increases in copper at the expense of a grain size occurs only by 6.8%, the rest of the increase depends on changes in dislocation density.

There is no doubt that the current measurements can be made applying more accurate methods, but it is already obvious now the dependence of yield strength on grain size is one order less as compared to the effect of dislocation density in copper. It is safe to say that the influence of dislocation density on copper hardening is a crucial factor.

It makes sense to perform the similar researches using other metals.

References

1. N. R. Barton, J. V. Bernier, R. Becker, A. Arsenlis, R. Cavallo, J. Marian, M. Rhee, H.-S. Park, B. A. Remington, and R. T. Olson. A multiscale strength model for extreme loading conditions // Journal of applied physics 109, 073501 (2011).
2. O.N.Ignatova, V.A.Raevskiy. Energy model of metal hardening // VANT. A series of mathematical modeling of physical processes. Issue 3. 39-44. Sarov, 2011.
3. Hall E.O. The deformation and ageing of mild steel: III Discussion of results // Proc. Phys. Soc.-1951.-V.64B.-P.747-753
4. Petch N.J. The cleavage strength of polycrystals // J.Iron Steel. Inst. – 1953.-V.174.-P.25-28.
5. Johnson T.H., Feltner C..E. Grain size effects in the strain hardening of polycrystals // Metall. Trans. -1970- V.1-p.1161-1167
6. Thompson A.W., Backofen W.A. Production and mechanical behavior of very fine –grained copper // Metall Trans.-1971-V.2-P.2004-2051
7. Hansen N., Ralph B. The strain and grain size dependence of the flow stress of copper // Acta Met., -1982-V.30-P.411-417
8. Gertsman V.Y., Hoffman M., Gleiter H. The study of grain size dependence of yield stress of copper for a wide grain size range // Acta Metall. Mater. -1994-V.42.-No10.-P.3539-3544
9. Gray III G.T., Lowe T.C., Cady C.D. Influence of strain rate and temperature on the mechanical response of ultrafine-grained Cu, Ni and Al-4Cu-0.5Zr // Nanostructured Materials.-1997.-V.9.-P.477-480.
10. Sanders P.G., The strength of nanocrystalline metals with and without flaws // Mater Sci. Eng. -1997-V.A234-236. –P.77-82
11. Masumura R.A. Yield stress of fine grained materials // Acta Mater – 1998-V.46-No13-P.4527-4534
12. Liu X. The Hall-Petch relationship in nanocrystalline materials // Mater Trans. JIM.-1997-V.38-No12-P.1033-1039
13. E.V.Kozlov, N.A.Koneva, A.N.Zhdanov et al. Structure and strain resistance of bcc ultra-fine-grained metals and alloys. Physical mesomechanics. 7. 4. (2004) 93-113
14. Bergstrom, Y., Mat. Sci. Eng. 5, 193. 1969
15. L.E.Murr Microstructure and mechanical properties of metals and alloys after loading by shock waves. Shock waves and phenomena of high-rate strain of metals. Edited by M.A.Meyers and L.E.Murr. Moscow. Metallurgy.1984.p.202