Relationship between microhardness and yield strength of nanostructured CoCrFeNiMn high-entropy alloy at T = 77 - 290 К

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Uniaxial deformation at a constant rate and microindentation are traditional methods for studying the mechanical properties of materials. It is natural to expect that there is a certain relation between the characteristics measured by these methods, in particular between the yield strength and the microhardness. Numerous studies have been devoted to elucidating the nature of this relation and establishing quantitative relationships between the yield stress and the microhardness, but this issue has not yet received a final solution, and interest in this problem continues to this day. In this work, a comparative analysis of the temperature dependences of Vickers microhardness $H_V(T)$ [1] and conditional yield strength $\sigma_{0.2}(T)$ [2, 3], obtained in the temperature range T = 77 – 290 K, was carried out for coarse-grained (CG) and nanostructured (NS) samples of the CoCrFeNiMn high-entropy alloy. NS samples were prepared by severe plastic deformation via torsion under a quasi-hydrostatic pressure of 6 GPa (HPT) at temperatures of 300 K (RT-HPT) and 77 K (cryo-HPT). The grain sizes of the NS and CG samples were on the order of 40 – 100 nm and 4 μm, respectively.

Performance of experiments on microindentation and uniaxial compression on the same samples gave a unique opportunity to compare dependences $H_V(T)$ and $\sigma_{0.2}(T)$ for all types of samples (CG, RT-HPT and cryo-HPT) of CoCrFeNiMn alloy in a wide interval of low temperatures. The dependences of Vickers microhardness and conditional yield strength on temperature for three types of samples are shown in Fig. 1 and Fig. 2.

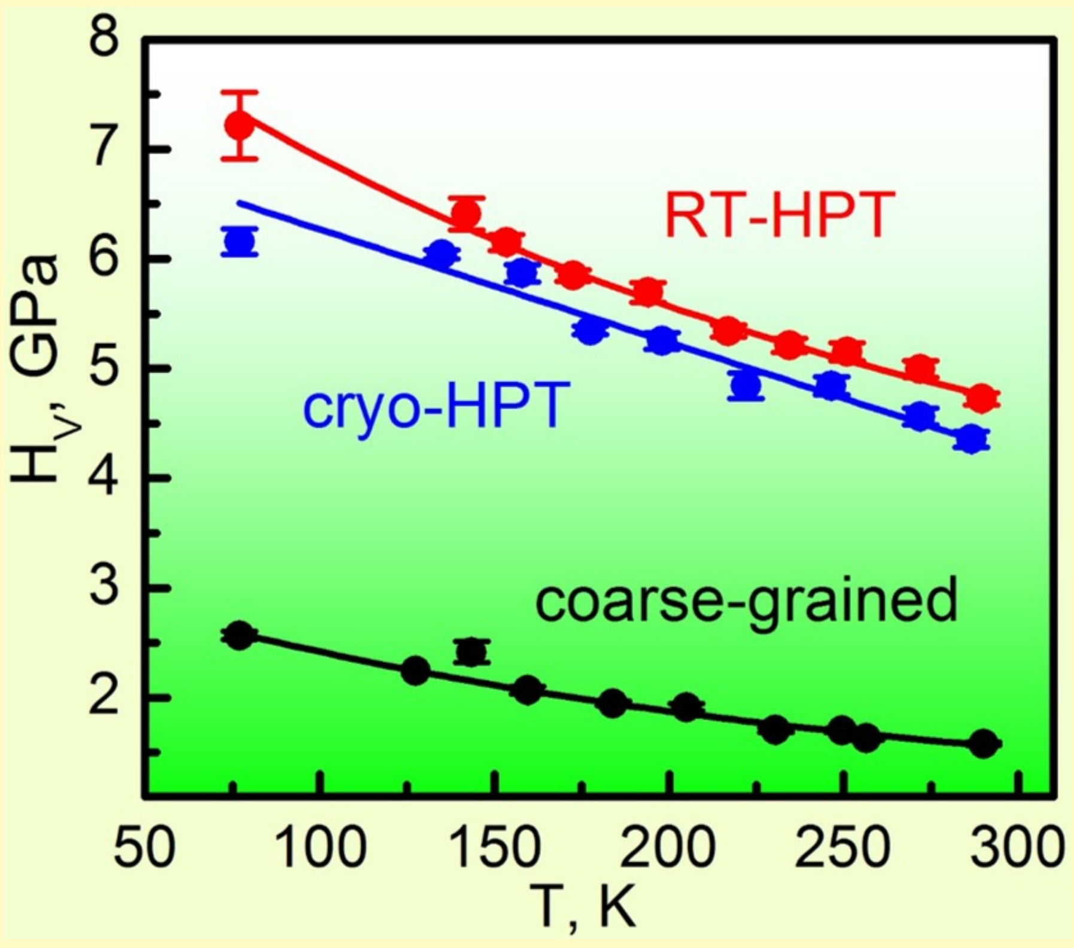

Fig. 1. Temperature dependences of microhardness H_V of CG, RT-HPT and cryo-HPT samples of CoCrFeNiMn alloy [1].

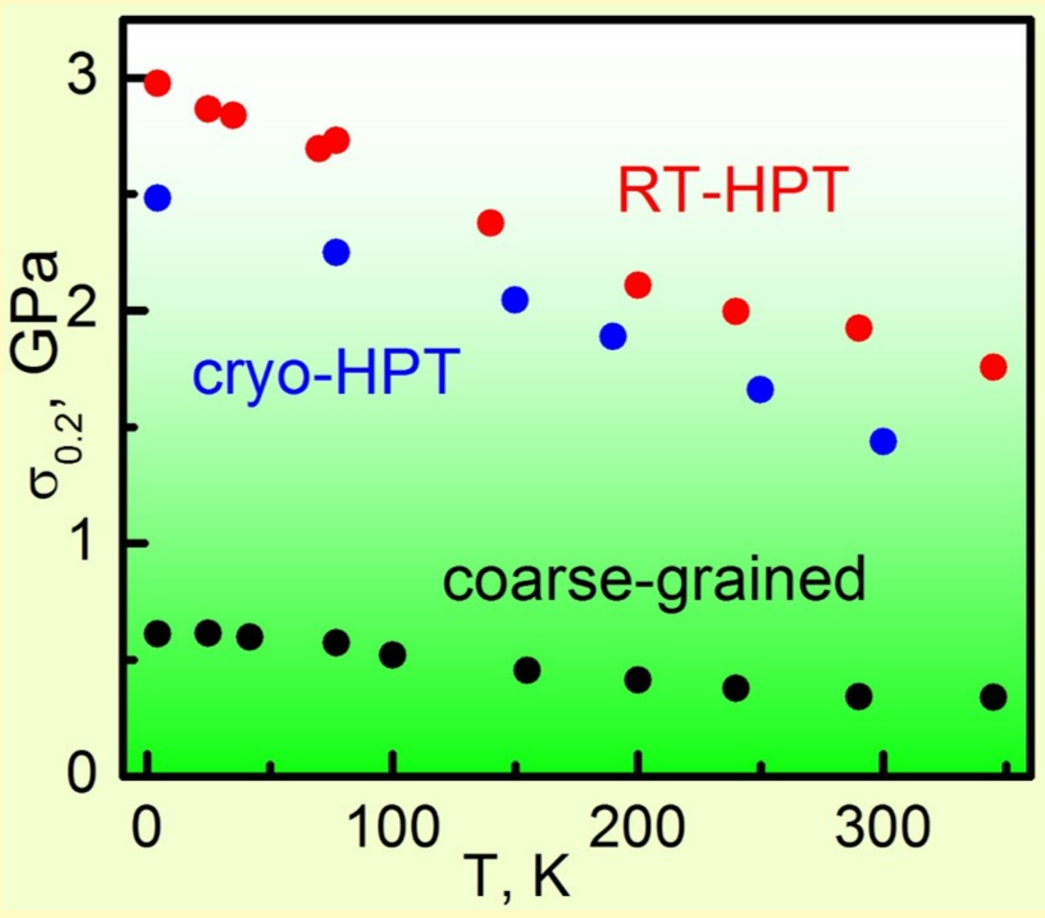

Fig. 2. Temperature dependences of conditional yield strength $\sigma_{0.2}$ of CG, RT-HPT, and cryo-HPT samples of CoCrFeNiMn alloy [2,3].

Measurements of microhardness and conditional yield strength of the samples of CoCrFeNiMn alloy were carried out at different temperatures. To compare the dependences $H_V(T)$ and $\sigma_{0.2}(T)$, in Fig. 3 – Fig. 5, we plotted the average (calculated from 10 indents) microhardness values obtained at different temperatures, plus the values of the conditional yield strength, multiplied by the parameter C being the same for all temperatures. In this case, the task was to find such a value for the parameter C that all data $H_V(T)$ and $C\sigma_{0.2}(T)$ were described by one temperature dependence.

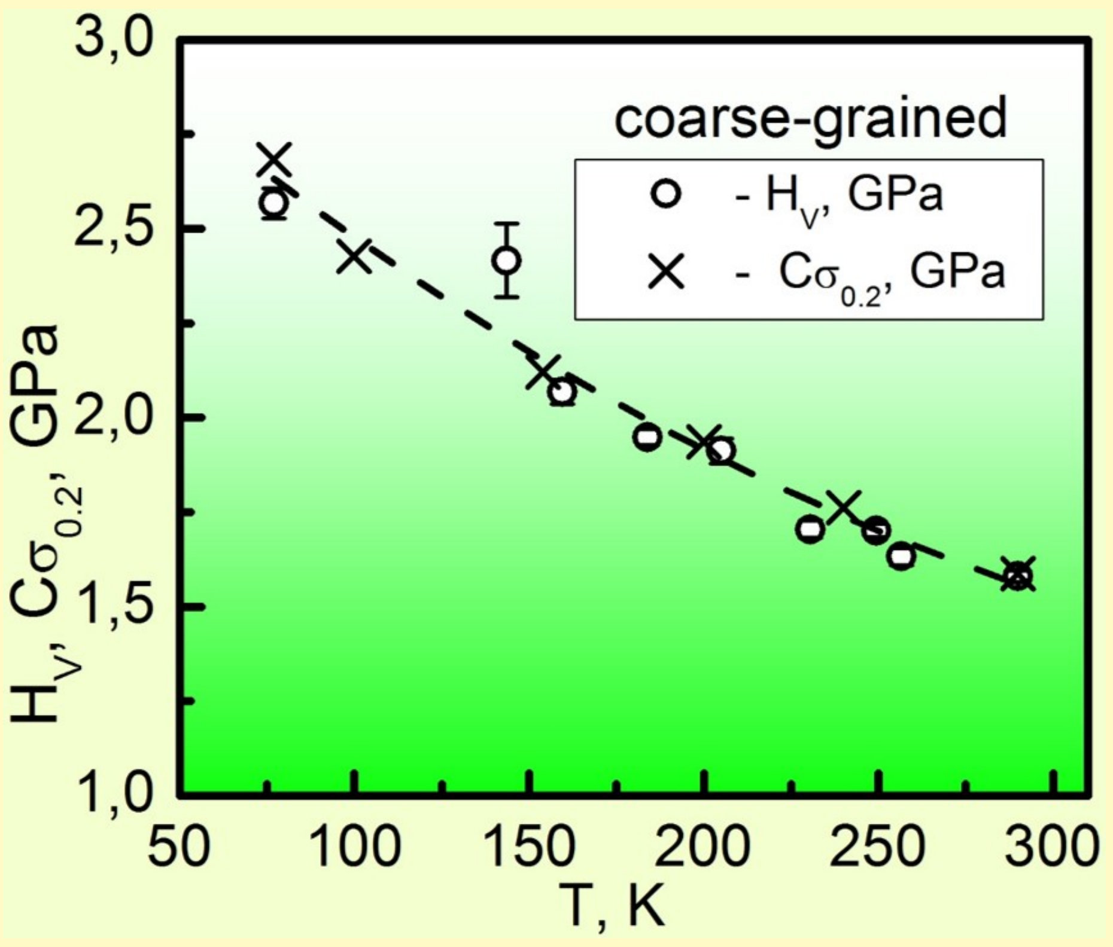

Fig. 3. Temperature dependences $H_V(T)$ and $C\sigma_{0.2}(T)$ (C = 4.66) of CG samples of CoCrFeNiMn alloy.

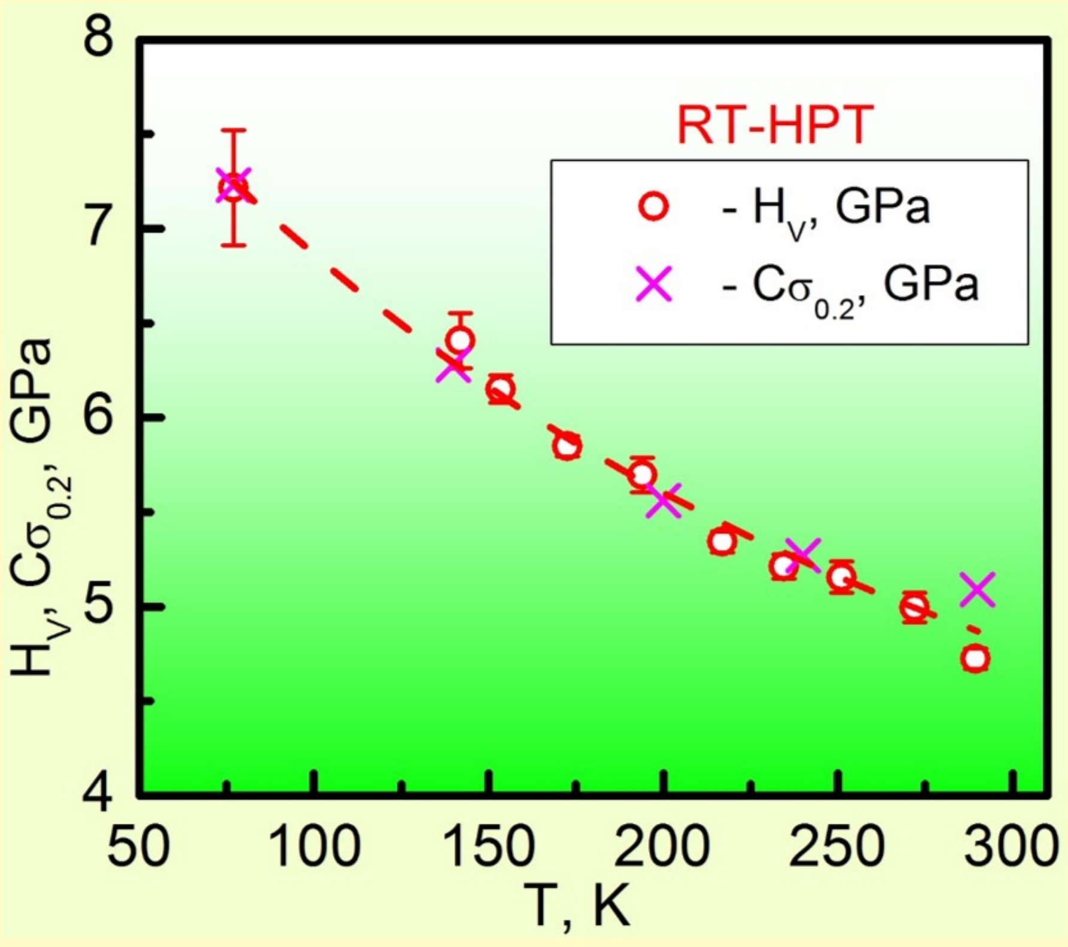

Fig. 4. Temperature dependences $H_V(T)$ and $C\sigma_{0.2}(T)$ (C = 2.64) of RT-HPT samples of CoCrFeNiMn alloy.

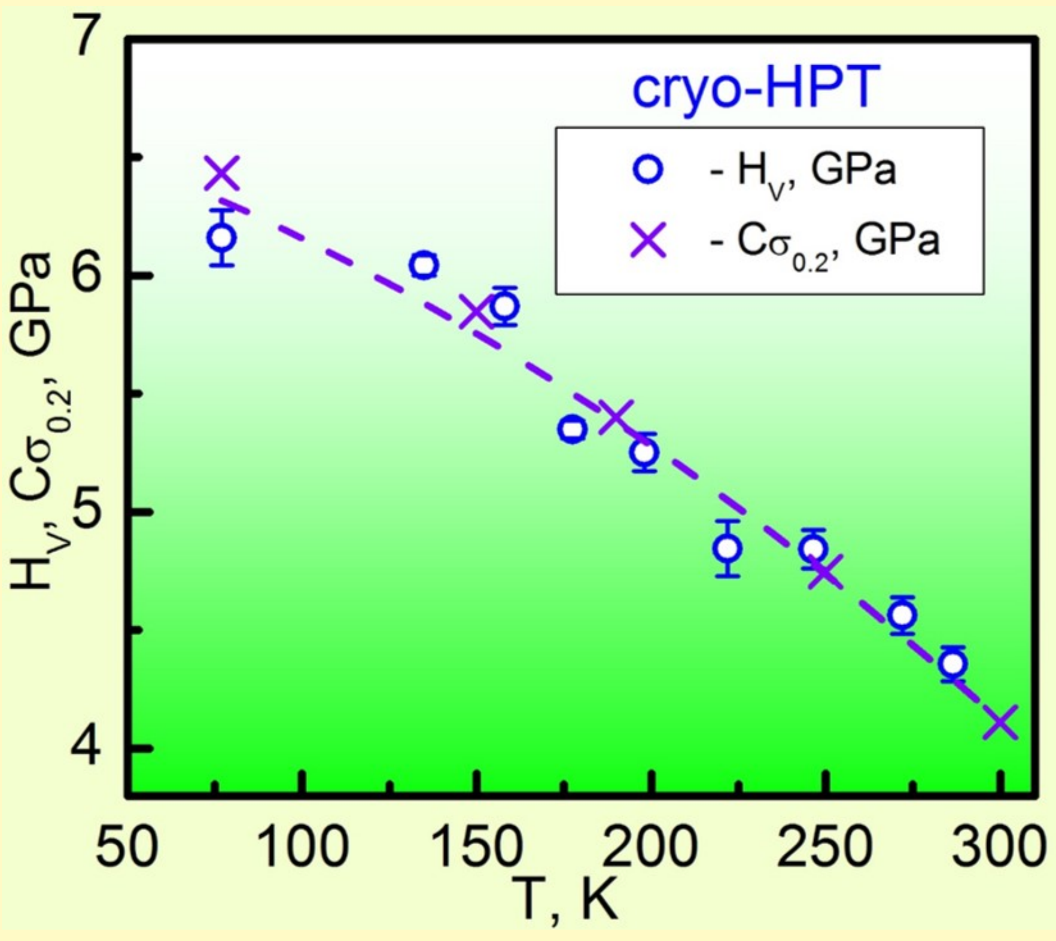

Fig. 5. Temperature dependences $H_V(T)$ and $C\sigma_{0.2}(T)$ (C = 2.83) of cryo-HPT samples of CoCrFeNiMn alloy.

It can be seen from Fig. 3 – Fig. 5 that for all types of samples in the whole studied temperature range of 77 – 290 K, the following relationship takes place between the values of microhardness and conditional yield strength:

$$H_V(T) = C\sigma_{0.2}(T),$$

with the parameter C to depend on the microstructure of material investigated. The value of parameter C was determined in a self-consistent manner using the procedure of joint approximation of experimental data using the least squares method. It has been established that for all types of samples, temperature has little effect on the value of the parameter C, and its values are equal to: C ≈ 4.66 for CG samples and C ≈ 2.64 and C ≈ 2.83 for NS samples, RT-HPT and cryo-HPT respectively.

The performed procedure for processing the results made it possible to estimate the values of the Tabor parameter for CG and NS samples of the CoCrFeNiMn alloy $C_T = H_M/\sigma_Y$, where H_M is the Meyer microhardness ($H_M = 1.08 \cdot H_V$), σ_Y is the deforming stress. When calculating the Tabor parameter, we used a conditional compression yield strength $\sigma_{0.2}$ as σ_Y. It was found that for all types of samples, temperature has little effect on the value of the Tabor parameter. In the temperature range T = 77 – 290 K, the average values of C_T are equal to: $C_T \approx 2.85$ for RT-HPT samples and $C_T \approx 3.06$ for cryo-HPT samples, which is close to the theoretical value of C_T for a rigid-perfectly plastic solid ($C_T = 3$) [4]. This result indicates the applicability of this model to describe the deformation of NS samples of the high-entropy alloy CoCrFeNiMn in the studied temperature range.

For CG samples, the average value of C_T in the temperature range T = 77 – 290 K is equal to $C_T \approx 5.03$, which is significantly greater than the values of C_T for NS samples. This is probably due to the fact that CG cast samples of the CoCrFeNiMn alloy are prone to significant hardening during deformation and are described by the model of a rigid-plastic body with hardening. In this case, when calculating the Tabor parameter, the deforming stress σr corresponding to a representative strain ε_r of the order of 8% should be used as the value σ_Y [4]. The high value of the C_T parameter for CG samples indicates that the deforming stress σr at a uniaxial strain $\varepsilon r \approx 8\%$ can be approximately 1.6 times higher than the value of the nominal yield strength $\sigma_{0.2}$.

Conclusions

1. For the first time, the micromechanical properties of high-entropy alloy CoCrFeNiMn samples in three structural states (CG, RT-HPT, cryo-HPT) were studied in the temperature range 77–290 K.
2. With a decrease in temperature from 290 K to 77 K, the microhardness of all types of samples monotonically increased by about 40 – 60% which indicates the thermally activated nature of plastic deformation under the indenter.
3. At all studied temperatures T = 77 – 290 K, the RT-HPT samples had higher microhardness values than the cryo-HPT samples. This result generalizes results that were previously obtained only at 290 K and 77 K [5].
4. The $H_V(T)$ dependences for CG and NS samples are compared with the corresponding dependences of the conditional compression yield strength $\sigma_{0.2}(T)$. It is shown that for all types of samples the parameter $C = H_V/\sigma_{0.2}$ is constant over the whole studied temperature range. For NS samples C ≈ 2.64 (RT-HPT) and C ≈ 2.83 (cryo-HPT), which is close to the theoretical value of the parameter $H_V/\sigma_Y = 0.9272 \times C_T \approx 2.8$ in the model of a rigid-perfectly plastic solid ($C_T \approx 3$ – theoretical value of the Tabor parameter). For CG samples C ≈ 4.66. Such a high value of parameter C may indicate that the initial CG CoCrFeNiMn alloy is a highly hardening material, for which the deforming stress at a uniaxial representative strain $\varepsilon_r \approx 8\%$ is approximately 1.6 times higher than the value of the conditional yield strength $\sigma_{0.2}$.

[1] H.V. Rusakova, L.S. Fomenko, S.N. Smirnov, A.V. Podolskiy, Y.O. Shapovalov, E. D. Tabachnikova, M.A. Tikhonovsky, A.V. Levenets, M.J. Zehetbauer, E. Schafler, Mater. Sci. Eng. A 828, 142116 (2021). http://dx.doi.org/10.1016/j.msea.2021.142116.
[2] A. V. Podolskiy; E. Schafler; E. D. Tabachnikova; M. A. Tikhonovsky; M. J. Zehetbauer, Low Temp. Phys. 44, 976 (2018). https:// doi.org/10.1063/1.5052688
[3] Yu. O. Shapovalov, E. D. Tabachnikova, M. A. Tikhonovsky, A. V. Levenets, M. J. Zehetbauer, and E. Schafler, V.N. Karazin National University. Series Physics. 32, 59 (2020). https://doi.org/10.26565/2222-5617-2020-32-07
[4] D. Tabor, Rev. Phys. Tech. 1, 145 (1970). doi:10.1088/0034-6683/1/3/101
[5] A.V. Podolskiy, Y.Shapovalov, E.D. Tabachnikova, A.S. Tortika, M.A. Tikhonovsky, B. Joni, E. Odor, T. Ungar, S. Maier, C. Rentenberger, Michael Zehetbauer, E. Schafler, Adv. Eng. Mater. 22, 1900752 (2020). http://dx.doi.org/10.1002/adem.201900752.