The number of automobile parts manufactured by traditional P/M methods — pressing and sintering — is limited because of the low strength, which is due to residual porosity. Of various methods of obtaining dense parts, the most promising is cold treatment under pressure, since it ensures high dimensional accuracy and good surface quality. However, this method is limited in practice by inadequate studies of the basic laws governing the process. It was shown in [1] that the theoretical concepts based on models of porous bodies [2, 3] do not agree with the experimental results due to the fact that the actual structure of porous materials was not taken into account. It was also reported in [4] that it is possible to describe the deformation of such materials by the Ludwig–Hollomon equation [5], which also holds true for the cast condition:

\[ S = \sigma_0 e^n, \]  

where \( S \) and \( e \) are the true stress and strain, respectively; \( K \) and \( n \) are coefficients. However, the simultaneous occurrence of densification and strengthening during deformation deprives coefficients \( K \) and \( n \) of a clear physical meaning. Up to the present time there have been no systematic studies of the variation of \( K \) and \( n \) with the original bulk density and parameters of the porous structure of materials. The purpose of this work was to determine the strengthening and change in the porous structure of sintered iron during upset forging.

Cylindrical samples with diameter \( d_0 = 11.30 \) mm and height \( h_0 = (1-1.5)d_0 \) were prepared from iron powder of grade PZhCh (0.8% total impurities) by bilateral pressing and sintering at 1150°C for 2 h in an atmosphere of dissociated ammonia.

To determine the effect of the granulometric composition of the original powder on strain hardening the powders were separated into fractions with particle sizes <50 \( \mu \)m (fraction I) and 63-100 \( \mu \)m (fraction II). The fractional distribution of particles by size, determined by means of automatic analysis of the images with a Leitz T.A.C. apparatus, is shown in Fig. 1.

![Intrafractional distribution of particles by size.](image1)

![Variation of true stress \( S \) with true strain \( e \) for sintered iron (the initial density, \( g/cm^3 \), is given on the curves).](image2)

Fig. 1. Intrafractional distribution of particles by size.

Fig. 2. Variation of true stress \( S \) with true strain \( e \) for sintered iron (the initial density, \( g/cm^3 \), is given on the curves). ●) Samples prepared from fraction I; ■) from fraction II. The dashed line refers to samples of Armco iron.
The characteristics of strain hardening were determined by stepped loading; along with a change in dimensions (measured with an accuracy of ±0.01 mm) at each stage of loading we also determined the change in density with an accuracy of 5·10⁻³ g/cm³ by hydrostatic weighing. To eliminate contact friction during upset forging, the polished surfaces of the samples were lubricated with molybdenum disulfide; no barrel effect was observed in the range of deformations investigated. Changes in diameter and the distribution of pores by size in the process of deformation were investigated on unetched microsections prepared by the method given in [6].

Figure 2 shows the change in true stress \( S = \frac{P}{F} \) (where \( P \) and \( F \) are the current values of the load and cross-sectional area, respectively) in relation to the true strain \( e = \ln \frac{h_0}{h} \) (where \( h \) is the current value of the height of the sample) for samples with different initial densities (each point is the average arithmetic value of the results for three samples). Increasing the initial density of the samples leads to an increase of true stress at the same strain. Thus, with \( e = 0.8 \) for samples with an initial density of 6.00, 6.50, 6.80, and 7.05 g/cm³ the true stress is respectively 45, 48, 50, and 53 kgf/mm². The process of strain hardening of sintered iron is satisfactorily described by Eq. (1): All curves of \( S \) vs \( e \) are linearized in logarithmic coordinates with the correlation coefficient at least 0.9.

No significant effect of the granulometric composition on the parameters of strain hardening \( n \) and \( K \) was observed.

The factor determining the values of \( n \) and \( K \) is the bulk density. Thus, an increase of the initial density from 6.00 to 7.05 g/cm³ leads to a reduction of the value of \( n \) from 0.43 to 0.30 and an increase of the value of \( K \) from 48 to 55 kgf/mm², respectively. By linear regression analysis, one obtains the following empirical relationships:

\[
\begin{align*}
n &= 1.14 - 0.11 \rho, \\
K &= 4.61 + 7.12 \rho.
\end{align*}
\]

In both cases the correlation coefficient is at least 0.7. With extrapolation of the equations to values characteristic of dense material (\( \rho = 7.78 \text{ g/cm}^3 \)) one obtains values of \( n = 0.28 \) and \( K = 60 \text{ kgf/mm}^2 \), which match the data in [7] and our experimental results for Armco iron with a total impurity concentration <0.25% (see Fig. 2). The change in the relative density \( \rho_{rel} = \frac{\rho_p}{\rho_C} \) (where \( \rho_p \) and \( \rho_C \) are the densities of porous and compact material, respectively) in relation to true strain is shown in Fig. 3 (average values are given for \( \rho_{rel} \) for three samples and the maxima dispersions of the average in separate points).