During the pressing of metal powders, the plastic deformation of their grains is accompanied by two opposing processes – an athermal strengthening process and a thermally-activated strength-loss process. The resulting pressing curve reflects the simultaneous action of both processes. To obtain an understanding of factors initiating and controlling plastic flow, it is necessary to separate these two processes and study the propagation of each of them individually.

The temperature dependence of deforming stress for powders may be expressed, at any given deformation rate, by the exponential function [1]

\[ \sigma = \sigma_0 e^{-\beta T} \]  

(1)

Here the preexponential factor \( \sigma_0 \) is the deforming stress at \( T = 0 \), when there are no thermally-induced effects, i.e., a stress corresponding to "pure" strengthening. For different deformation rates, \( \sigma_0 \) will have the same value at any given degree of powder densification, and all such values taken together give a curve of powder flow at the absolute zero, i.e., a curve of athermal strengthening.

Plotted in \( \sigma_0 \) vs ln\( \delta \) coordinates, where \( \delta \) is the relative density, this curve becomes a straight line in the zone of plastic deformation. The equation of such a straight line is [1, 2]

\[ \sigma_0 = \sigma_0^* \delta^k. \]  

(2)

Here \( \sigma_0^* \) depends on neither the relative density nor the temperature.

The thermally-controlled part of the pressing curve (the strength loss experienced by the metal) is described by the exponential factor [2]

\[ e^{-\beta T}. \]  

(3)

Using curves of powder pressing, it is possible to find the magnitude of the stress reduction (the decrease in stress resulting from thermal relaxation) occurring during the actual plastic deformation process. The stress reduction \( \sigma_{\text{red}} \) for a given density, temperature, and deformation rate is obtained as the difference between corresponding stresses given by the athermal strengthening curve \( \sigma_0 \) and the pressing curve \( \sigma \):

\[ \sigma_{\text{red}} = \sigma_0 - \sigma. \]  

(4)

In the present work, an attempt was made to separate the simultaneous strengthening and strength-loss processes and calculate the extent of stress reduction. Figure 1 shows curves, plotted for copper against density, of stress at the absolute zero \( \sigma_0 \) (taken from [1]), pressing stress \( \sigma \) [1], and stress reduction

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### Table 1

<table>
<thead>
<tr>
<th>Density, g/cm³</th>
<th>Pressing stress ( \sigma ), kg/cm²</th>
<th>Strengthening stress ( \sigma_0 ), kg/cm²</th>
<th>Strength-loss factor ( e^{-\beta T} )</th>
<th>Stress reduction ( \sigma_{\text{red}} ), kg/cm²</th>
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<td>0.560</td>
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Fig. 1. Effect of density of copper on stress at absolute zero $\sigma_0$, pressing stress $\sigma$, and calculated stress reduction $\sigma_{\text{red}}$. Test temperature 473 K, deformation rate 50 mm/min.

Fig. 2. Effect of density on stress reduction at temperature of 473 K and deformation rate of 50 mm/min.

$\sigma_{\text{red}}$ calculated from Eq. (4). The pressing temperature was 473 K and the deformation rate 50 mm/min. Figure 2 illustrates the density dependence of the stress reduction for various materials at a temperature of 473 K and a deformation rate of 50 mm/min. It will be seen from this figure that, with increase in the degree of powder densification, the stress reduction also increases. Relaxation is promoted, as will be demonstrated later, by a rise in temperature.

Figure 3 depicts the effect of density $\gamma$ on $\sigma_{\text{red}}$ for copper deformed at various temperatures and a constant deformation rate, 50 mm/min. Curves of $\sigma_{\text{red}}$ vs T for copper at the same deformation rate and various densities are illustrated in Fig. 4. It will be seen from these figures that the extent of stress reduction monotonically increases with rise in both density at a given temperature and temperature at a given density.

Since increasing the degree of densification and raising the temperature act in the same direction by promoting stress reduction (Figs. 2 and 3), the magnitude $\sigma_{\text{red}}$ for a given deformation rate can conveniently be expressed as a function of the product of the relative density $\delta$ and the temperature $T$:

$$\sigma_{\text{red}} = f(\delta T).$$  \hfill (5)

Plotting this function in In $\sigma_{\text{red}}$ vs In ($\delta T$) coordinates yields a straight line which is described by the equation [1, 2]

$$\sigma_{\text{red}} = \sigma_0 (\delta T)^\phi.$$  \hfill (6)

From Eq. (6) it follows that the effect of pressing rate on $\sigma_{\text{red}}$ is allowed for in the magnitude $\sigma_*$, which increases with decreasing pressing rate. A constant $\phi$ takes into account the effect of the temperature and the density of the powder being pressed. Values of $\sigma_*$ and $\phi$ for a number of metals will be found in [1].

For the temperature dependence of $\sigma$, two equations have been obtained [1, 2]:

$$\sigma = \sigma_0 e^{-\beta T} = \sigma_* \delta^\phi e^{-\phi T}.$$  \hfill (7)

where $\beta = f(\delta V)$, and, in accordance with Eq. (4),

$$\sigma = \sigma_0 \delta^\phi - \sigma_*(\delta T)^\phi.$$  \hfill (8)

where $\sigma_* = f(V)$.

Neither of these equation can be analytically transformed into the other. They were both obtained empirically and reflect the existence of the two opposing - strengthening and strength-loss - processes.