SUPERPLASTIC BEHAVIOUR OF LOW-ALLOY TOOL STEELS

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Abstract

From tensile and upsetting tests performed at various strain rates and temperatures we have established that the W9 tool steel, which is alloyed with a little Cr and W, shows superplastic behaviour at 710 °C, with a strain rate in the order of $\dot{\varepsilon}=10^{-4}\ \mathrm{s}^{-1}$, and this state can be described by a sensitivity to strain rate exponent around $m=0.5$ (maximum $m=0.52$). The yield strength in this case is 60—100 MPa. On the basis of these data we can assume that the W9 steel is suitable for being processed by superplastic formation technology.

Introduction

By superplasticity a specific state of alloys is meant, in which the alloy can endure extraordinarily large plastic strains without fracture. Experience shows that mostly two- or multiphase fine-grained alloys can reach a superplastic state, usually at high temperatures and with very low strain rates. The superplastic state can further be described by the fact that the value of the effective yield point (yield strength) is also very low.

The phenomenon is of great practical, technological and economic significance, because when the material is in a superplastic state, extraordinarily large deformations can be required mechanical force and power input of the formation and the loading on the tools is very low. A disadvantage of the technological utilization of this phenomenon is that it requires a lot of thermal energy and owing to the low strain rates the process is very time-consuming.

As a consequence of the expected technical and economic utilization, a great many researchers all over the world are engaged in the design and research of the mechanism of this phenomenon and of alloys suitable for these purposes, in establishing the phenomenological, mechanical laws of materials describing the process, and in the solution of problems arising during practical application. Excellent surveys of the subject have recently been given e.g. by Sherby and Wadswoorth [1] and Kaibysev [2].

In Hungarian practice aluminium alloys and steels are used in the greatest quantity as metallic materials. That is why the research of the superplastic state of these alloys and its economic utilization are justified and possible mostly among these alloys.

In this paper the modes of bringing about the superplastic state of low-alloy tool steels are discussed and the technological parameters of formation characteristic of this state are determined.

The choice of the subject is justified partly by the fact that the superplastic formation of the ultrahigh-carbon (UHC) steels, a class of steels where most of the tool steels can also be included, has only very recently appeared in the literature, for this reason very little is known about these steels; on the other hand, tool manufacturing is a possible area of utilization of these research achievements, which can widely be used in Hungarian industry, too.

Low-alloy tool steels are principally used as materials of low-output cutting tools, hand tools, and cold-working tools. Tool manufacturing with superplastic formation is justified first of all in the case of tools of complicated shape; with these tools a considerable improvement in material savings can be expected.

One of the most important parameters of the formation technology of metallic materials is the actual yield point under the conditions of the formation process and the yield curve representing its dependence on the strain and on the strain rate. In the case of unalloyed metals the yield point decreases exponentially as a function of temperature is not continuous in the A_1—A_3 transformation range, but it is characterized by sudden changes. We wished to reveal this anomaly as a phenomenon which can incidentally cover a superplastic state, and this can be utilized technologically in the case of a tool steel alloyed with a little Cr and W, denoted W9 by the Hungarian Standard, and of an unalloyed tool steel denoted S101.

The experiment

The chemical composition of steels chosen for the experiment is presented in Table I:

Table I

Chemical composition in %

Symbol	C	Mn	Si	P	S	Cr	Ni	Cu	V	W
W9	0.92	0.94	0.31	0.026	0.009	1.1	0.21	0.12	–	1.63
S101	1.01	0.24	0.19	0.011	0.010	0.16	0.11	0.18	0.12	–

The transformation temperatures in °C determined by dilatometry can be seen in Table II.

Table II

Symbol of material	A_{c1}	A_{c2}
W9	725	745
S101	710	740

The strength properties of the above steels determined from a tensile test as a function of temperature are presented in Figs 1 and 2. According to this test the elongation at rupture of the W9 steels suddenly increases below the temperature of A_{c1} and the tensile strength has its express minimum around the deformation range.

From this experiment we can draw the conclusion that the W9 steel can reach subcritical superplasticity. This does not exclude the possibility that in another heat treatment state and perhaps with a considerably decreased grain size and at a different strain rate these steels could show structural superplasticity. Having obtained this result, we restricted our experiments to the study of the technological properties of W9.

For the description of the superplastic state it is expedient to apply the m exponent to be found in the following form of the yield curve equation:

$$k_f = K\varepsilon^n \dot{\varepsilon}^m \tag{1}$$

In the formula k_f is the yield strength or actual yield point, which depends on the ε actual strain and the $\dot{\varepsilon}$ strain rate; K, n, m are materials characteristics which depend, besides the internal state coefficients of the material (chemical composition, grain size, etc.), mostly on temperature. It can easily be proved (see e.g. [3]) that the ε_m uniform elongation of the tested material at a given temperature mostly depends on the n hardening exponent and the m sensitivity to strain rate exponent:

$$\varepsilon_m = \frac{n}{1-m} \tag{2}$$

From the formula it follows that if $m \to 1$, then $\varepsilon_m \to \infty$. Relation $m = 1$ corresponds to Newton's material law of liquids. Alloys can be regarded as technically superplastic if $m > 0.3$. For most of the fine-grain alloys specifically developed for superplastic forming $m \cong 0.5$. If hardening due to formation reaches a very low value, e.g. $n = 0.001 \sim 0.0001$, at the given temperature, the order of magnitude is $\varepsilon_m = 2 \sim 20$, i.e. $200 \sim 2000\%$. According to data in the

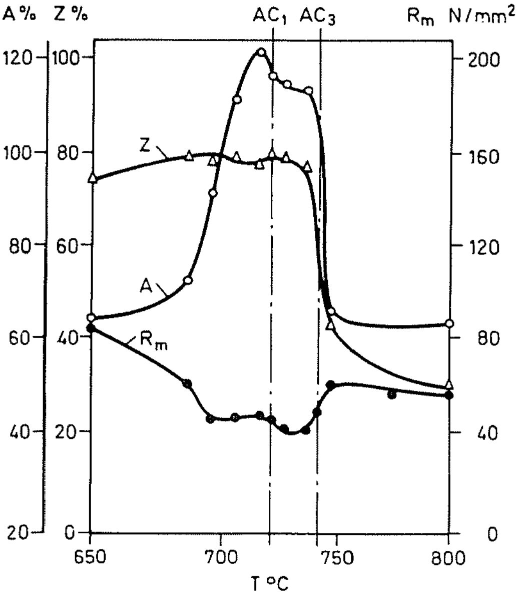

Fig. 1. Mechanical properties of the W9 steels as function of the temperature (determined by tensile test) A = elongation to rupture %; Z = reduction of area %; R_m = ultimate tensile strength N/mm²

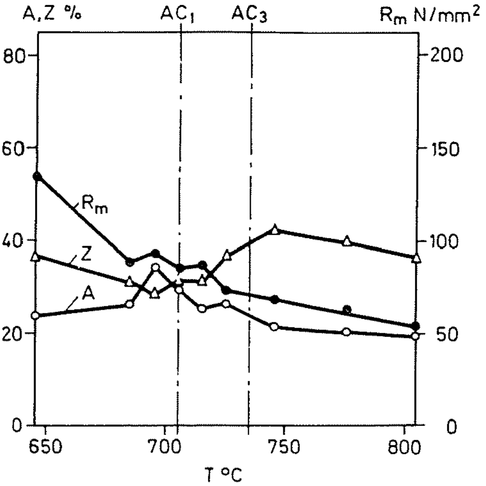

Fig. 2. Mechanical properties of the S101 steel as function of the temperature (determined by tensile test) symbols see at the Fig. 1

literature [1] with a 1.6% C steel of 2 μm grain diameter at 650 °C 1150% elongation at rupture was measured.

In our case the *m* sensitivity to strain rate exponent characteristic of the W9 steel was measured by a method called two-stage tensile test in material testing. The essence of this method is that a tensile test is performed at a given temperature, at a certain v_1 crosshead velocity and in the uniform elongation range. The force meter of the tensile test machine shows F_1 force; if the machine is switched over to a $v_2 > v_1$ crosshead velocity, the force meter signals $F_2 > F_1$ force. Recording these values, the *m* sensitivity to strain rate exponent valid under the given conditions can be calculated as follows:

$$m = \frac{\ln \frac{F_1}{F_2}}{\ln \frac{v_1}{v_2}} \tag{3}$$

The values of the velocity exponents determined from a tensile test by the above method, as a function of testing temperatures and strain rates, can be seen in Fig. 3. From this figure it can be seen that with the W9 steel $m = 0.52$ can be reached at 710 °C and in the $\dot{\varepsilon} = 10^{-4}$ s^{-1} order, which corresponds to a superplastic state.

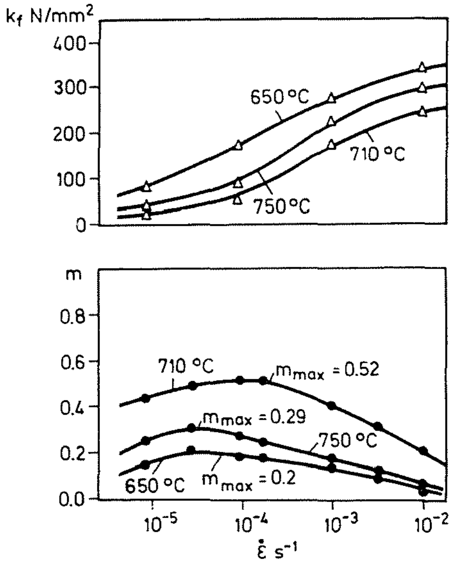

Fig. 3. W9 steel *m* velocity (strain rate) exponents as a function of the testing temperatures and strain rates

The mean grain size of the W9 steel was 20 μm, which is too big from the point of view of structural superplasticity. An exponent of high sensitivity to strain rate, experienced during direct allotrope transformation of relatively coarse-grained materials, indicates subcritical superplasticity.

In a superplastic state, besides extraordinarily great formability, the material is also characterized by extraordinarily low yield strength. In the technological process this means very low power input and an almost negligible mechanical loading on the tools.

The yield curve was obtained from an upsetting test. The yield curve of the W9 steel tested at 710 °C and at $\dot{\varepsilon} = 3 \cdot 10^{-4}\ \mathrm{s}^{-1}$ strain rate can be seen in Fig. 4. The dependence of yield strength on temperature and deformation, with the above strain rate, can be seen if Fig. 5. The yield strength values belonging to the $\varepsilon = 0.7$ actual (logarithmic) strain are shown in Fig. 6 as a function of the strain rate.

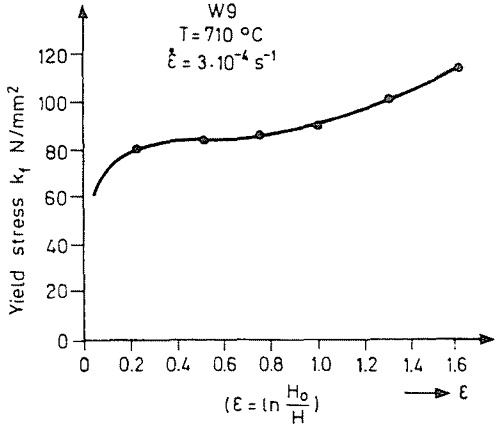

Fig. 4. Flow curve of the W9 steel

From these data it can be seen that the yield strength of the W9 tool steel at 710 °C is in the order of magnitude of that of soft, unalloyed aluminium measured at room temperature, consequently the latter can be used as a model material for the experimental testing of the tool manufactured for the superplastic formation of W9.

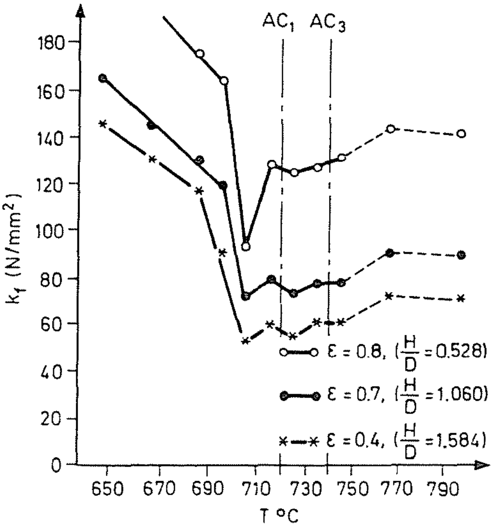

Fig. 5. Dependence of yield strength on temperature and deformation of the W9 steel

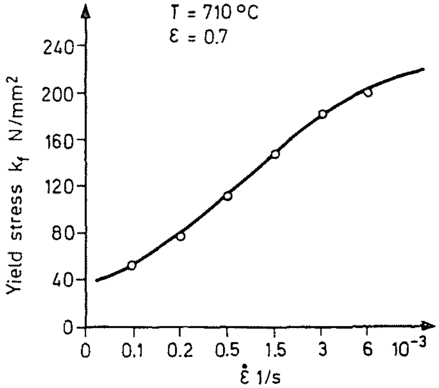

Fig. 6. Yield strength of W9 depending on strain rate

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