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MECHANICAL TESTS AND CONSTRUCTION OF ANALYTICAL MODELS OF THE BEHAVIOR OF MATERIALS UNDER SUPERPLASTIC CONDITIONS. PART 1

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Different test methods are discussed for determining the mechanical properties of materials in the superplastic state. The flow stress depends on the degree and rate of deformation, a structural parameter, and temperature. The rheology and mechanics of superplastic deformation are discussed. In response to an order from the company EADS (Airbus), a new method was developed and has yielded good results in the testing of titanium alloys and the construction of mathematical models. The method, for conducting tests and then approximating materials' mechanical properties, is of great interest for the purpose of obtaining adequate predictions of the forming of materials under pressure.

Keywords: *mechanical properties of materials, superplasticity, modeling, mechanical tests.*

Titanium alloys have a high unit strength (ratio of ultimate strength to density), which makes them an effective material for use in the aerospace industry. At the same time, semifinished products made of titanium alloys are quite expensive, especially due to the large number of processing operations (repeated vacuum remelting, time-consuming hot forming, etc.) and the fact that sheets made of these alloys cannot be deformed by cold stamping. Deformation of materials in the superplastic state is an efficient method of obtaining complex parts from flat-rolled semifinished products and makes it possible to lower production costs [1–6]. As applied to polycrystalline materials, the term "superplasticity" means that when these materials are loaded under certain temperature-rate conditions they can undergo large amounts of deformation while exhibiting a relatively low yield point and no loss of integrity.

Superplasticity is characterized by the existence of the following main indicators:

1) the yield stress of the material is (compared to the plastic state) more sensitive to changes in the rate of deformation; in other words, superplastic materials display a heightened tendency to undergo rapid strain-hardening;

2) the flow of superplastic materials is very stable and thus allows them to undergo a large amount of deformation; as a result, the relative elongation of these materials in tension can reach several hundred or even several thousand percent; and

3) the yield point in the superplastic state is considerably (by an order of magnitude or more) lower than materials' yield point in the normal plastic state.

The most important of the above indicators is the first one, and the other two can be regarded as consequences of it. The strong dependence of the flow stress on deformation rate makes superplastic materials (SPMs) similar to viscous liquids in terms of their rheological characteristics. Indeed, it is the viscous behavior of superplastic materials that explains their abil-

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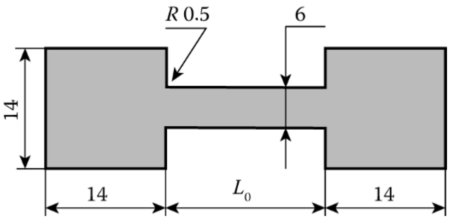

Fig. 1. Diagram of the specimen used to determine the superplasticity indices of sheet materials.

ity to flow at stresses appreciably below the yield point and to resist having strain become localized. As a result, record amounts of plastic strain are obtained with such materials [7].

One distinctive feature of titanium alloys is the ability of mass-produced alloy sheets to undergo superplastic deformation without special preparation of the structure. Thus, these materials are referred to as being “naturally” superplastic [1]. The optimum temperature for superplastic forming (SPF) for widely used titanium alloy VT6 (Ti – 6% Al – 4% V) is within the range 900–925°C. At the same time, it is highly desirable to lower the SPF temperature, which would make it possible to alleviate deoxidation and erosion of the matrix, reduce the cost of the equipment needed for the forming operations, and lengthen the service life of the product [8].

The foregoing makes it clear why scientists are interested in experimental methods and approximation of the mechanical properties of superplastic materials, especially titanium alloys. The standards on the quality and payload weight of the special products made for the aerospace industry are continually being elevated. The accuracy of calculations and predictions of the material’s flow under superplastic conditions cannot be greater than the accuracy of the mechanical properties that have been determined experimentally and the continuum models that have been developed.

General characteristics of the test methods. Test methods have been developed for ferrous and nonferrous alloys and procedures have been established for studying the superplasticity indices of sheet specimens at temperatures up to 1250°C. These methods and procedures are designed to be used for:

1) determining the temperature and rate ranges in which superplastic behavior takes place;

2) comparing the superplasticity indices of materials differing in chemical and phase composition and/or structure; and

3) choosing the temperature, rate, and force regimes for the shaping of metals in the superplastic state.

The term superplasticity index is regarded as including the following: flow stress σ; index of rate sensitivity to the flow stress m; and relative elongation (up to failure) δ for a fixed deformation rate $\dot{\varepsilon}$ and a fixed temperature T.

The methods entail either conducting either tensile tests of a series of specimens at different temperatures with a stepped change in deformation rate or conducting stress-relaxation tests.

The maximum value of the rate-sensitivity index m is used to determine the temperature-rate regime of deformation that is optimum from the viewpoint of inducing superplastic behavior. That regime is used with a constant deformation rate in conducting tensile tests of specimens so as to evaluate the alloy’s ductility δ, construct tensile stress-strain curves, and determine the strain-hardening coefficient γ as a function of the degree of deformation.

Tests with a stepped change in deformation rate are performed to select the temperature and rate regimes for forming metals in the superplastic state.

Stress-relaxation tests are conducted to determine and compare the superplasticity indices of materials differing in their chemical and phase composition, their structure, and the methods used to make them.

Thus, the tests establish the dependences of the flow stress σ and the rate-sensitivity index m on strain rate $\dot{\varepsilon}$ for different temperatures. We have also obtained curves describing the dependence of elongation in tension and the strain-hardening coefficient γ on deformation ε for the optimum deformation rate $\dot{\varepsilon}$ at each temperature.

Tests were performed on specimens (see Fig. 1) with a working part 6 mm wide. The thickness of the specimens was determined by the thickness of the rolled product. The distance between the ends L_0 was calculated from the formula $L_0 = 5.65(F_0)^{1/2}$, where L_0 is the initial cross-sectional area of the working part of each specimen.

The calculated length L_0 was rounded to the nearest whole number. However, this length should not be less than double the specimen's width. The main values of the gage length of the specimens prepared from sheets of different thicknesses are shown below:

Sheet thickness. mm	≤0.85	0.90–1.15	1.20–1.40	1.45–1.80	1.9–2.2	2.3–2.6	2.7–3.0
Gage length. mm	12	14	16	18	20	22	24

The allowable deviation of the width of the working part of the specimens was ±0.1 mm, while the surface-roughness parameter was no greater than 2.5 μm. The deviation from the prescribed value of specimen length – the value against which elongation was measured – could not exceed ±1%. The maximum deviation allowed for cross-sectional area was 0.5%.

The form and dimensions of the heads of the specimens were the same for sheets of all thicknesses, which made it possible to use the same method to secure the specimens in the clamps of the testing machine. The specimens were elongated by hundreds of percent during tension, although the marking made on them to indicate the initial length was usually obliterated. Thus, it turned out to be more convenient to determine the initial length as the distance between the shoulders. The head and working part of each specimen could therefore be joined to each another at a right angle without a smooth transition, since the superplastic alloys were not sensitive to stress concentrators.

To study indices of superplasticity within a broad range of temperatures and deformation rates, it is most convenient to use sheets with a thickness of about 1 mm. This is due to the considerable range of forces exerted on the specimen when studying its behavior within a wide range of strain rates. To ensure accurate results, it is important that the entire range of values for the forces be recorded with the use of the same gage. In tests of specimens made from sheet, this can be done by simultaneously testing several specimens of the same dimensions. Thus, by changing the number of specimens being tested, it is possible to conduct tests with same accuracy at a lower temperature.

The specimens were tested without prior machining of their surface layer, since they were designed to evaluate the suitability of the sheets for SPF under factory conditions. None of the test specimens were allowed to have mechanical damages or surface defects such as exogenous inclusions, delaminations, pores, cavities, or cracks prior to the test. The sheets that were tested after heat treatment could have some distortion. Since such sheets are used in SPF and since superplastic alloys rapidly relax during their heating to the superplasticity temperature, the semifinished products could have been subjected to straightening or some other type of modification. If the metal is tested in the heat-treated state, then the semifinished products used to obtain the specimens are also heat-treated.

The specifications of the machines used to determine superplasticity indices are the same as those of universal testing machines employed for static tests. Nevertheless, the behavior of a specimen of a superplastic material during tension is such as to make it necessary that universal machines meet certain special requirements.

The ability of an specimen to increase in length by a factor in the range 3–20 during tension places special requirements on the furnaces in which the specimens are tested. Accordingly, those requirements dictate the dimensions of the frame of the testing machine. The use of specimens prepared from rolled sheet (see Fig. 1) and having a constant working width of 6 mm makes it possible to use a 500-mm-long furnace with a uniform heating zone of about 200 mm. In this case, the frame of the machine must be compatible with furnaces of this length and must allow the cross-arm to freely travel at least 250 mm.

To ensure uniform deformation of the specimen's working part in the test, the temperature gradient along the specimen during tension should not exceed 10°C. This requirement is satisfied by the use of a three-section furnace in which the operation of the sections can be controlled individually or as a group. However, to conduct tests in a protective argon medium, it is more convenient to use a monolithic tubular furnace in which the distance between the turns of the heating coil is variable. Such a furnace design creates a uniform heating zone about 200 mm long. In this case, the interior volume of the heated part of the tube is hermetized by plugs of kaolin wool and is then filled with argon. Two disk-shaped aluminum reflectors 200 mm in diameter and 1 mm in thickness are secured to a tie affixed to the top clamp above the furnace in order to keep the operation of the force gage from being affected by the heat. The disk reflectors are continuously enveloped in a flow of air created by a fan during the entire time the furnace is in operation.

After being subjected to a specified amount of tensile deformation carried out at an optimum constant rate, the specimens underwent structural analysis to determine the kinetics of the changes in their structure during tension. Thus, the clamps for the heads of the specimens were designed so as to allow them to be quickly relieved of the load and permit the specimens' working part to cool while they were being extracted from the furnace. One possible method of cooling the specimens is to use special tongs with cooled grips.

The machines that are used to test specimens make it possible to subject specimens to tension with movement of the active clamp at a wide range of speeds. The testing machine is equipped with a computer system that controls recording. The design of the machine and the computer software that is used make it possible to conduct tests at a constant strain rate in the range 10^{-6}–10 $\sec^{-1}$ and keep that rate constant to within ±(0.3–1%). In the case of titanium alloys, for example (a sheet specimen with a thickness of 1 mm and a gage length of 14 mm), the elongation can reach 1000% if the loading of the specimen is begun at low rates and increased to 0.05 $\sec^{-1}$. It can reach 250% with a strain rate of 0.02 $\sec^{-1}$. The computer's memory records the load with an accuracy on the order of 0.1% up to a force value of 1000 N.

The software can interrupt the constant-strain-rate loading of the specimen when a specified degree of elongation is reached and can then commence load-relaxation testing. The forces exerted on the specimen during tensile loading and then during the initial stage of relaxation – from 2 to 5 sec after stoppage of the cross-arm – are recorded at a frequency of 30–50 Hz. The forces exerted on the specimen after this stage are recorded at a frequency of 0.1–1 Hz. The software also allows tests to be performed with a stepped increase or decrease in the rate of tension and a prescribed increase in strain between each step. The number of stages can be chosen by the user and the stress which exist during stable flow of the metal can be recorded during each stage.

Conducting tests and principles of calculation of the parameters. The specimens used to conduct tests of sheet materials are installed in clamps with the aid of special bushings. The bushings have slits that are positioned under specimens of different thicknesses with an intervening 0.5-mm gap. Since the heads of the specimens prepared from rolled products of different thicknesses differ only in their thickness, specimens prepared from sheets can be installed in the clamps in the form of a pack which contains 2–6 specimens. This makes it possible to better control the force so that it is more accurately recorded; the use of packs of specimens increased the acting force at low rates or high temperatures and decreased that force at low temperatures or high rates. The prismatic bushing, with the specimens located in the slits, is moved forward into the jaw of the clamp until it contacts a stop. The bushing is then squeezed together with the specimens as the clamp's head is rotated. The specimens are suspended on lugs inside the clamp. The bushing is needed not only to insert the specimens into the clamp but also to prevent bending of the specimens' heads while they are freely suspended.

The specimens are heated to the prescribed temperature after they are installed in the testing machine and placed in the furnace. The heating time should be as short as possible while still ensuring that the specimen is uniformly heated. This time is usually 15–20 min for sheet specimens.

Temperature is measured at the ends of each specimen's working part by two thermoelectric converters, the hot junctions of the converters being inserted through holes in the clamps until they come into contact with the specimen. Specimen temperature should not deviate more than ±2°C from the prescribed temperature at any moment during the entire test.

After a specimen has been heated and held at the specified temperature, it is either subjected to tension with a stepped change in deformation rate while the force-displacement curve is recorded or it is loaded with a constant rate of deformation and the load is then relaxed to record the change in the force over time.

Conclusion. This article has described all of the main requirements for testing specimens under conditions that subject them to superplastic deformation. The second part of the article will examine specific test methods (tests with a stepped change in strain, tests with a constant strain rate, and relaxation tests), the rheology and mechanics of superplastic deformation, and equations of state.

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