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Editorial

Creep and Deformation of Metals and Alloys at Elevated Temperatures

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1. Introduction and Scope

Various aspects of creep and deformation behaviors of metals and alloys at elevated temperatures are of great interest to materials scientists. Creep resistance is an extremely important characteristic to be evaluated for structural materials that are used, for example, in aircraft gas turbines, fossil power plants, nuclear reactors, etc. New heat-resistant materials such as nickel-based superalloys, heat-resistant austenitic and martensitic steels, and light alloys are being developed to meet the requirements for components operating at high temperatures. Advanced materials are designed to withstand creep based on the different approaches increasing their strengthening from solid solution, second-phase particles, and dislocation structure. On the other hand, understanding of deformation behavior of metals and alloys can help us to increase their hot workability and obtain the desired microstructure and properties for the finished product. The aim of this Special Issue is to present the latest achievements in the theoretical and experimental investigations of creep and deformation behavior of metallic materials.

2. Contributions

2.1. High-Entropy Alloys

High-entropy alloys are cutting-edge materials with complex compositions and unusual properties as compared to conventional alloys. Gadelmeier et al. [1] studied the creep behavior of a single crystal high-entropy CrMnFeCoNi alloy in comparison with single crystal pure nickel. This research revealed the effect of the solid solution strengthening and dislocation strengthening in the absence of grain boundaries on the creep strength at high temperatures (700–1200 °C). The single crystal specimens were obtained using pre-alloying by arc-melting and following casting by the Bridgman process. It should be noted that the fabrication of the single crystals is a complicated process. Crystal orientation of [001] with a maximum deviation of 3° was obtained due to a helical grain selector. The single crystal structure of both pure nickel and the high-entropy alloy was confirmed by electron backscatter diffraction. Creep testing was carried out under vacuum in order to exclude the oxidation effect. It is interesting that an increase in the creep strength of the CrMnFeCoNi alloy due to the solid solution effect was estimated by different techniques. It was revealed that sufficient solid solution strengthening effect occurs at 700 °C, whereas it reduces with temperature and disappears at 1100 °C.

2.2. Nickel-Based Superalloys

Kvapilova et al. [2] investigated the creep behavior of various nickel-based superalloys such as Inconel 713LC, MAR-M24, and B1914. It should be emphasized that new data on creep of conventional nickel-based alloys of several generations were obtained. Compositions of the selected alloys differ by the contents of solid-solution elements and elements forming the dispersed γ'-phase, carbides and borides. Deformation behavior was examined in terms of threshold stress specific for dispersion-strengthened alloys in a wide temperature–stress range (800–1000 °C and 150–700 MPa, respectively). All three

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superalloys demonstrated stress exponent $n = 5$, confirming the occurrence of power-law dislocation creep. The authors discuss the effect of chemical composition on the creep behavior and the value of threshold stress. The increased contents of Co, W, Hf, and Ta in the MAR-M24 superalloy resulted in its highest creep resistance. High boron content in the B1914 superalloy was revealed to affect the tensile strength and ductility due to formation of borides near the grain boundaries. The low-carbon Inconel 713 superalloy with high content of Mo and Nb and without Co and W showed the lowest creep strength among studied alloys.

Imayev et al. [3] suggested a new nickel-based SDZhS-15 superalloy as an advanced material for high-pressure discs in gas turbine engines. The chemical composition of this superalloy was developed by increasing the γ'-phase-forming elements (Al, Ti, Nb, and Ta), addition of Re, and rare earth elements (La, Ce, and Y). The authors investigated the effect of several post-forging heat treatments on the properties of the newly designed alloy. A detailed investigation of the microstructure and both tensile and creep properties at different temperatures up to 850 °C was presented. Specific attention was paid to the study of the parameters of γ-grains and γ'-phase particles. The best combination of tensile properties and creep data, presented using the Larson–Miller parameter, was obtained at an optimal solid solution treatment temperature of 1170 °C. It is interesting that the required properties were provided by a fine-grained structure of 10 µm and a size of secondary γ'-precipitates of 0.1 µm.

Wei et al. [4] proposed the model predicting the creep rate and rupture time for a nickel-based single crystal DD6 superalloy. This superalloy belongs to the second generation of superalloys and was developed for aero engine turbine rotor blades by the AECC Beijing Institute of Aeronautical Materials, Beijing, China. The temperatures and applied stresses were considered in the range of 760–1070 °C and 50–600 MPa, respectively. The model developed on the base of the proposed equivalent stress predicts the creep life for all crystal orientations, [001], [011], and [111]. Theoretical calculations were confirmed by experimental results.

2.3. Austenitic Steels

High-strength austenitic steels are advanced materials used for a wide range of applications. Astafurova et al. [5] used alloying of austenitic Fe-22Cr-26Mn-1.2V steel by ultra-high contents of interstitial elements—1.2% N and 0.7% C—as an effective way to enhance the solid-solution hardening. The authors investigated the tensile mechanical properties, microstructure, and fracture micromechanisms in the temperature interval −60–300 °C. This steel showed an abnormal dependence of the yield strength with decreasing temperature from +60 to −60 °C. Different temperatures of the solid solution treatment changed the contribution of solid solution and grain boundary strengthening. The effect of the treatment and testing temperatures on the deformation behavior was discussed. It should be noted that the proposed alloying design shifted the temperature range of the dynamic strain aging to higher temperatures of 200–300 °C as compared to the carbon-bearing steels.

Baraldi et al. [6] developed the theoretical model describing creep behavior of the widely used 316L(N) austenitic steel used as a heat-resistant material in conventional and nuclear power plants. It is interesting that the developed creep model can also be used for other materials and covers the whole creep process from initial loading up to failure. Three different models were used for plotting the dependence of the creep rate on the creep stress and strain. All three developed creep models showed the satisfactory coincidence of predicted and experimental results.

2.4. Ferritic/Martensitic/Cainitic Steels

Creep degradation of martensitic heat-resistant steels is affected by precipitation behavior, mainly, of $M_{23}C_6$ carbides and the Laves phase (Fe_2(W, Mo)). Fedoseeva et al. [7] investigated the 9–10% Cr, Co-modified martensitic steels, which can be considered as advanced heat-resistant materials for new-generation fossil power plants. The effect of alloying by (W + Mo), B, and Re on the coarsening behavior of the Laves phase under creep conditions at 650 °C was studied. This research aimed for the development of an alloying design of martensitic steels. Laves phase particles grow during creep deformation, and their coarsening negatively affects the creep strength. It was shown that increasing the B content provides a slower coarsening of the Laves phase due to fine $M_{23}C_6$ carbides that are densely distributed along the boundaries. Re was reported to sufficiently decrease the coarsening of the Laves phase. The Laves phase evolution was discussed as a possible reason for the creep strength breakdown appearance in the "stress–time to rupture" dependence that indicates the degradation of long-term creep resistance. Detailed microstructural analysis showed the relation between the distribution type of Laves phase particles along the low-angle and high-angle boundaries and their coarsening rate.

Heat-resistant steels are subjected to complicated loadings during operation, so the failure can be caused by creep, fatigue, and their interaction. Jiang et al. [8] investigated the cyclic creep in 2.25Cr-1Mo bainitic steel at 455 °C as the creep–fatigue behavior. This steel is a material for pressure vessels and pipeline systems in petroleum and power industries. The authors compared the static creep and cyclic creep behavior of 2.25Cr-1Mo steel. It is interesting that cyclic creep resulted in longer life duration than static creep. This fact was associated with the effect of anelastic recovery. Additionally, the model predicting the life assessment of steel was suggested.

3. Conclusions and Outlook

Various high-strength and heat-resistant materials were considered in the present Special Issue of Metals. The authors shared their latest research and introduced the effective ways to enhance the properties and the durability of steels of different classes, nickel-based superalloys of several generations, and a new high-entropy alloy.

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