

Conditions for Ignition of Iron and Carbon Steel in Oxygen

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UDC 620.22;546.21

Translated from *Fizika Goreniya i Vzryva*, Vol. 37, No. 3, pp. 52–57, May–June, 2001.

Original article submitted January 13, 2000; revision submitted June 2, 2000.

It is shown that the cylindrical iron and carbon-steel specimens of diameters 1.5 and 3 mm ignite in oxygen at the moment the oxide film loses its protective properties, supposedly, as a result of melting of its main component (FeO) at 1644 K. The ignition temperature does not depend on the oxygen pressure (in the range 0.2–20 MPa). The ignition is preceded by substantial (about 100 K) self-heating of a specimen owing to the heat released upon oxidation of the metal. A carbon-steel foil ignites in oxygen (0.14–0.6 MPa) according to the Semenov–Frank–Kamenetskii mechanism at an initial surface temperature not lower than 1233 K.

The widespread use of oxygen at high temperatures and pressures in various fields of science and engineering makes it necessary to determine the critical temperatures of safe utilization of structural materials operating under these conditions. In this connection, it is of importance to understand the ignition mechanism of metals and alloys in oxygen at different pressures. In a number of experiments addressing this problem, the specific features of the ignition of the following materials were studied: titanium [1], tantalum [2], magnesium [3], niobium [4], tungsten, molybdenum, and boron [5], copper, brass, and bronze [6], stainless steel [7], and nickel and chromium–nickel alloys [8]. Despite the fact that iron is the base of alloyed and carbon steels which are widely used in oxygen equipment, conditions for its ignition in oxygen have not yet been adequately determined. In particular, little information on the effect of the ambient pressure on the ignition temperature of materials T^* is available. The present study is an attempt to fill this gap.

Comparing the melting points of a metal (1809 K) and a presumed oxide (1838 K [9]), Breiter, Mal'tsev, and Popov [9] assign iron, together with aluminum, nickel, and copper, to the class of materials which ignite in oxygen at a temperature higher than the melting point of the metal, but the experimental values of T^* (>1273 K [10] and 1373 K [11]) given in [9] do not support this classification. It was found in [12–16] that compact specimens from iron and low-carbon steel ig-

nite in oxygen at different pressures at temperatures lower than the melting point of the materials. According to [15, 16], the values of T^* change only slightly as the pressure increases (≈ 1453 K for iron and ≈ 1483 K for steel); at the same time, it was found in [12–14] that these values decrease appreciably (from 1188 to 903 K for iron and from 1549 to 1218 K for mild steel as the pressure p increases from 1.0 to 12.6 MPa).

In the present paper, we give results of experimental investigation of the conditions for ignition of compact specimens and a foil from technical iron (99.9% Fe) and St. 3 low-carbon steel ($\approx 0.22\%$ C) in oxygen ($p = 0.2$ – 20 MPa).

Specimens shaped like cylindrical rods of diameters $d = 1.5$ and 3 mm and with a 40 -mm length of the working part were heated in gaseous oxygen in a high-pressure apparatus [7] upon passage of an alternating electric current of commercial frequency. The surface temperature T was measured by the contact method with the use of a Chromel–Alumel thermocouple with thermoelectrode wires of diameter 0.2 mm, calibrated to 1673 K; the e.m.f. was measured by a KSP-4 potentiometer with a tape-advance velocity of 5400 and $54,000$ mm/h. To decrease the systematic error ΔT_s (the difference between the actual and measured surface temperatures caused by heat removal through the thermoelectrode wires), we used a junction-free thermocouple, which allowed us to decrease the value of ΔT_s by approximately a factor of 4 compared to a thermocouple with a junction [8]. For this purpose, the thermoelectrode wires were welded to the middle part of the spec-

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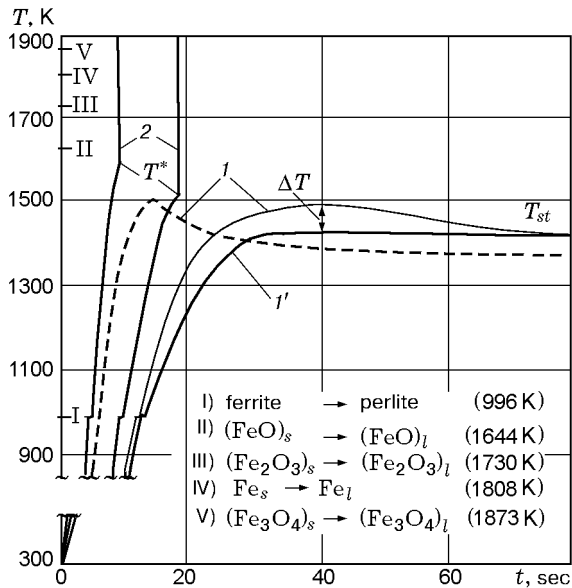


Fig. 1. Thermograms of heating (curves 1 and 1') and ignition (curve 2) of steel compact specimens in oxygen for $p = 1.0$ MPa and $d = 3$ (solid curves) and 1.5 mm (dashed curve).

imen, where the temperature was constant, with 5-mm intervals.

This connection of electrode wires is equivalent to a thermocouple junction with a third thermoelectrode (material of the specimen), which has no effect on the e.m.f. of the thermocouple provided the temperatures at the sites where the thermoelectrodes of the thermocouple are connected to the third electrode are the same [17]. The constancy of temperature at the welding site was checked by measuring the temperature profile along the specimen. The error in determining the surface temperature of the central part of the specimen was estimated by the above-mentioned method with the use of reference points. As reference points, we used the temperature of the ferrite → perlite phase transition, which was determined from the thermograms of steel specimens heated in oxygen at different pressures (microplateau on the curves shown in Fig. 1) and by comparison with tabulated data (996 K [18]), the difference was not greater than 5–15 K.

Depending on the electric power q , the time it took for specimens to ignite was 4–20 sec. Ignition was observed through the viewing window of the apparatus. To clarify the mechanism of high-temperature processes, we performed a series of experiments with the same and oxidized specimens heated in an inert medium (nitrogen) and vacuum. The phase composition of the oxide film formed on the specimens before ignition was determined by the x-ray phase method.

We also performed experiments with specimens from a $5 \times 5 \times 0.5$ mm low-carbon steel foil with welded thermoelectrode wires of a Chromel–Alumel thermocouple. The specimens were heated to a specified temperature T_0 in vacuum by means of a tubular electrical heater [6]; thereafter, oxygen was supplied at a specified pressure (0.14–0.6 MPa) in a jump-like manner. If the foil did not ignite, the oxidized specimen was replaced by another specimen, and the next test was performed at a higher value of T_0 . As the ignition temperature T_0^* , we used the arithmetical mean between the maximum value of T_0 for which no ignition of the specimen occurred and the minimum value for which the oxygen inlet was accompanied by ignition of the foil.

The experimental results show that, for iron and carbon steel, the thermograms and the characteristic temperatures of heating and ignition of compact specimens in oxygen differ insignificantly and change only slightly in the range of pressures considered (0.2–20 MPa). For small heat loads ($q < q^*$), the temperature attained the maximum and then decreased (by the quantity ΔT), taking a constant value T_{st} characteristic of a given heat load (curve 1 in Fig. 1); when the same specimen was heated again (for $q = \text{const}$) in oxygen or nitrogen at the same pressure, the temperature increased to the same level T_{st} without reaching the maximum (curve 1' in Fig. 1). For specimens of diameter $d = 1.5$ mm, the time required for the temperature to reach a stationary value (≈ 40 sec) is approximately 2 times smaller than that for specimens with $d = 3$ mm (dashed and solid curves 1 in Fig. 1). The specific feature was revealed: if the given (oxidized) specimen is heated to the transition temperature $T_{tr} \approx 1573$ K in vacuum or an inert medium, it behaves like the initial specimen, i.e., upon subsequent heating in oxygen, the maximum is observed again on its thermogram. The oxide films on iron and steel (at $T \approx 1473$ K) have an identical composition 70–85% FeO + 30–15% Fe₃O₄ + Fe₂O₃ (traces), which depended only slightly on the oxygen pressure.

The specimens ignited when the electric power exceeded the critical value q^* [$q^* = f(p)$]. The break on the temperature curve (curves 2 in Fig. 1) corresponds to the temperature T^* at which the onset of ignition was observed. This temperature value was taken as the ignition temperature. For iron and steel, the values of T^* varied in the range 1523–1613 K and depended slightly on the oxygen pressure and the specimen diameter and the heating rate.

The maximum temperatures T_{\max} of cylindrical iron and steel specimens determined experimentally for $q < q^*$, the corresponding maxima $\Delta T = T_{\max} - T_{st}$, the ignition temperatures T^* (arithmetical mean of the