ISSN 0010-5082, Combustion, Explosion, and Shock Waves, 2016, Vol. 52, No. 2, pp. 172–176. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © V.I. Bolobov.

Effect of Heat Transfer Conditions on the Critical Pressure of Metal Ignition in Oxygen

V. I. Bolobov[a]

UDC 620.193:669.295:669.243

Published in *Fizika Goreniya i Vzryva*, Vol. 52, No. 2, pp. 54–59, March–April, 2016.
Original article submitted January 28, 2015.

Abstract: Experimental data on the critical pressure of ignition of titanium alloy fragments in gaseous oxygen are analyzed. The fragments are obtained after fracture of alloy samples in the dynamic mode (p_2^*) and under natural convection conditions (p_1^*). The results are analyzed with allowance for the heat transfer coefficients from material ignition initiators under similar conditions. Based on the shape of the experimental thermograms of plate cooling, the coefficient of heat transfer from microcraters with a juvenile surface formed due to knockout of metal particles from the plate by the high-velocity flow is found: $\alpha_2 \approx 11$ kW(m$^2\cdot$K). The value of α_2 is close to the value of this coefficient calculated with the use of the coefficient $\alpha_1 \approx 5$ kW/(m$^2\cdot$K) of heat transfer from titanium rod microfragments (with the size of the order of metal grains) formed during titanium rod fracture in oxygen under conditions of natural convection with allowance for the ratio p_2^*/p_1^*.

Keywords: critical pressure of ignition, oxygen, ignition initiators, fracture fragments, titanium alloys, heat transfer coefficient.

DOI: 10.1134/S0010508216020064

INTRODUCTION

It is known that metal and alloy fragments formed after fracture of various structures in an oxygen-containing medium are capable of ignition (hereinafter, self-ignition). As was shown in [1–4], fracture microfragments serve as ignition initiators. By the instant of their interaction with oxygen, these microfragments are already heated to the temperature

$$T^* = T_0 + \Delta T, \tag{1}$$

which is the sum of the initial temperature T_0 and temperature of heating ΔT due to the heat released as a result of the fracture work. The temperature T^* up to which these microfragments can be heated is a critical parameter related to another critical parameter (oxygen pressure p^* or critical pressure of ignition) by the equation of Semenov' theory of the thermal explosion for the heterogeneous reaction [5]:

$$\frac{Q}{\alpha}\frac{K_0 E}{RT^{*2}}\bar{p}^{0.5}\exp\left(-\frac{E}{RT^*}\right) = \frac{1}{e}. \tag{2}$$

Here Q is the specific heat of the chemical reaction of interaction of the microfragment material with oxygen, α is the total coefficient of heat transfer from the microfragment experiencing ignition, R is the universal gas constant, K_0 and E are the pre-exponent and the activation energy in the Arrhenius equation for dissociative adsorption of oxygen molecules on the juvenile surface of fracture fragments, $\bar{p} \equiv p^*/p_{0.1}$, and $p_{0.1} = 0.1$ MPa is the oxygen pressure.

It was shown [1] that the fracture fragments of VT1-0 titanium samples can become heated by the instant of their contact with oxygen up to the temperature of ≈698 K (the value of T^* for this alloy). If the oxygen pressure is equal to or greater than 2.3 MPa (the value of p^*), the fragments become ignited.

As it follows from the theory proposed in [3, 4], the critical temperature of metal ignition T^* depends only on the fracture work [1], which, in turn, is determined by the strength properties of the material. Thus, it follows [see Eq. (2)] that the critical pressures of ignition p^* of

[a]St. Petersburg Mining University, St. Petersburg, 199106 Russia; boloboff@mail.ru.

samples made of the same metal, which are destroyed by different methods, are determined by conditions of heat transfer (values of the heat transfer coefficients, e.g., in the cases of natural convection α_1 and oxygen flow α_2) from fracture fragments. In accordance with Eq. (2), the following equality should be satisfied for two different ways of fracture of the same material:

$$(p_1^*)^{0.5}/\alpha_1 \approx (p_2^*)^{0.5}/\alpha_2. \quad (3)$$

The goal of the present paper is to analyze the effect of the coefficient α of heat transfer from initiators of ignition of metal materials with different methods of fracture of the samples in the oxygen medium on the critical pressure of ignition p^*. As the majority of investigations of metal self-ignition deal with titanium alloys, we also use these materials for our analysis.

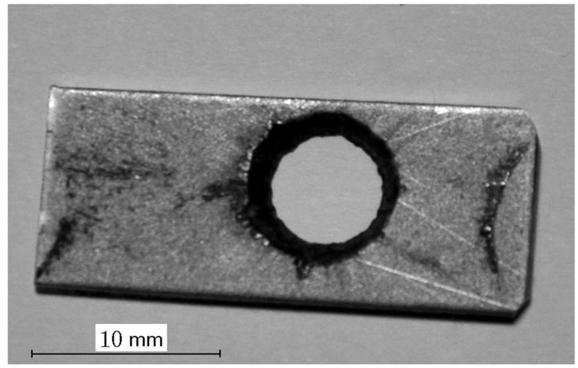

Fig. 1. VT1-1 titanium plate after self-ignition in the oxygen flow ($p_w = p_w^* = 7.7$ MPa).

ANALYSIS OF CONDITIONS OF SELF-IGNITION OF TITANIUM ALLOYS DURING FRACTURE

We analyzed the conditions of self-ignition of commercial titanium brands VT1-0 and VT1-1 and titanium alloys OT4-1, VT14, and VT6 in gaseous oxygen. Two methods were used to ensure fracture of samples made of these materials: fracture of rods under natural convection conditions [1–3, 6, 7] and frontal action of a high-velocity flow on flat plates made of these metals [8, 9].

Based on fractometric and metallographic observations, the following assumption was put forward in [3]: in the case of fracture of metal rods in oxygen, the primary initiators of ignition are completely or partially separated microfragments whose size is of the order of the metal grain. Ignition occurs when these fragments are located in the fracture crack filled by oxygen at the working pressure, which is not yet a through crack. The coefficient α_1 of heat transfer from these fragments, i.e., initiators of ignition of titanium and titanium alloys, was estimated as 5 kW/($m^2 \cdot$ K) [3].

The experiments [8, 9] revealed self-ignition of titanium alloy plates (Fig. 1) and zirconium alloy plates subjected to the action of a high-velocity flow ($\approx$ 340 m/s) escaping from a vessel filled by oxygen at an elevated pressure ($p_0 \leqslant 70$ MPa).

For the test conditions [8, 9], a formula was derived, which relates the total pressure of the gas near the plate surface (p_w) to the initial pressure of oxygen in the vessel (p_0), to the distance from the nozzle exit to the plate (l), and to the nozzle diameter (d):

$$p_w = 0.49 p_0 \exp(-0.65 l/d). \quad (4)$$

It was concluded that plate ignition occurs at the critical pressure of the gas near the plate surface (p_w^*); the values of this critical pressure are different for different alloys.

Explaining the mechanism of metal ignition in an oxygen flow, we concluded [9] that significant normal stresses arise in the surface layer of the plate already at comparatively low pressures p_w (for titanium, at $p_w \geqslant 0.5$ MPa) because of the high velocity and increasing dynamic pressure of the gas flow; these normal stresses are responsible for local fracture of the oxide film and the substrate in weakened areas. Fracture is manifested as knockout of metal particles from the plate (these particles immediately ignite in the flow, resulting in luminescence [8, 9]) and as formation of microcraters devoid of the oxide film on the plate surface (Fig. 2).

If the pressure is sufficiently high ($p_w \geqslant 3$ MPa), the metal of the juvenile surface of microcraters also experiences intense heating, reaching the titanium melting point (1941 K), which is evidenced by formation of shining hemispheres on the plate surface (Fig. 3). These hemispheres are formed from the melted and then recrystallized metal.

At the pressure p_w, taken in [8, 9] as the critical pressure (p_w^*), the plate area subjected to the oxygen flow ignites and completely burns out (see Fig. 1). It can be logically presumed that plate ignition is initiated by the above-mentioned microcraters because metal interaction with oxygen on the microcrater surfaces at $p_w \geqslant p_w^*$ passes to the stage of stable combustion.

As there is no information about the coefficients α_2 of heat transfer from these microcraters in [8, 9], their values are estimated below.

NUMERICAL ANALYSIS

The heat from the ignition initiator (microcrater surface) heated due to the chemical reaction of oxida-

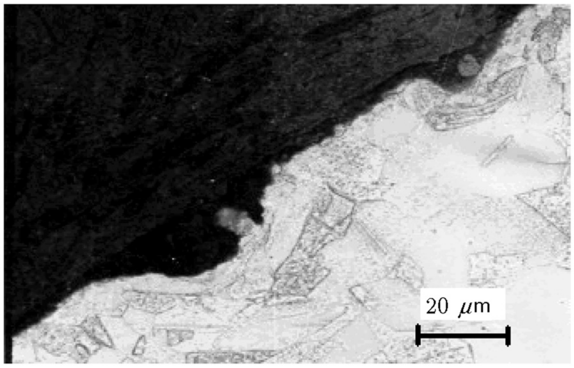

Fig. 2. Cross section of the VT1-1 titanium plate with microcraters on the surface after the action of the oxygen flow ($p_w < p_w^*$, $l = 5$ mm, and $d = 2$ mm).

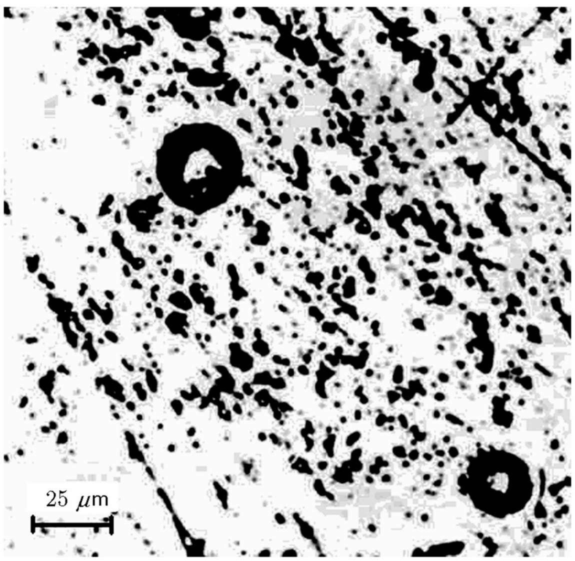

Fig. 3. Microphotograph of the VT1-1 titanium plate surface after the action of the oxygen flow.

tion is removed by the convective heat flux q_α to the gas flow moving past this microcrater with the heat transfer coefficient α_α, by the conductive flux q_λ to the surrounding parts of the plate not damaged by the flow with the heat transfer coefficient α_λ, and by the radiative flux q_ε to the ambient medium with the heat transfer coefficient α_ε:

$$q = q_\alpha + q_\lambda + q_\varepsilon. \quad (5)$$

The Biot similarity criterion for this case was calculated by the formula $\mathrm{Bi} = \alpha_\alpha l_1/\lambda$, where l_1 is one half of the length (30/2 mm) or width (15/2 mm) of the plate in the tests [8, 9] and λ is the thermal conductivity of the tested titanium alloys [8.4–16.8 W/(m·K)]. The values of this criterion for all directions of the plate are appreciably greater than unity [$\mathrm{Bi} \approx 6$–12 for $\alpha_\alpha \approx 10$ kW/(m^2·K)]. This fact shows that the temperature of the plate surface area subjected to the action of the gas flow almost coincides with the gas temperature owing to the large comparative intensity of convective heat transfer. For this reason, the conductive component q_λ of heat transfer in Eq. (5) can be neglected. It also turned out that the contribution of radiation to the total heat removal is negligible ($q_\varepsilon \leqslant 1.0\%$). Thus, the total coefficient α_2 of heat transfer from the heating initiators of ignition of titanium alloy plates is determined by the convective component α_α of heat transfer to the gas flow: $\alpha_2 \approx \alpha_\alpha$. (This conclusion is indirectly supported by the results of [8, 9] according to which the critical pressure of ignition p_w^* of this or that titanium alloy is almost independent of the size of plates made of these materials and subjected to the action of the gas flow.)

The values of α_α were calculated on the basis of thermograms (Fig. 4) obtained by measuring the temperature of titanium plates at the instant when they were subjected to the oxygen flow in the experiments [9]. (In [9], the temperature T_w of the plate area subjected to the action of the gas flow was measured by a thermocouple flush-mounted into the metal plate.)

A minor increase in temperature from $T_{w,0} = 303$ K to $T_{w,\max}$ on the thermograms (see Fig. 4) at the initial instant of the flow action was explained in [9] by compression of air between the nozzle and the plate. Subsequent cooling during ≈0.3 s to a constant value $T_{w,k}$ was attributed to the throttling effect. It turned out that each value of the temperature $T_{w,k}$ on the plate area experiencing the action of the gas flow corresponds to a certain initial pressure of oxygen in the vessel and monotonically decreases, reaching 222 K at $p_0 = 50$ MPa. These observations [$T_{w,k} = \mathrm{const}(t) = f(p_0)$] allowed us to assume that the experimentally measured value of $T_{w,k}$ is actually the stagnation temperature of the gas flow T_g in the near-wall layer on the plate, and it can be used instead of T_g in subsequent calculations.

Tangent lines to the resultant curves $T_w = f(t)$ were plotted in the interval $T_{w,\max}$ to $T_{w,k}$. The tangent of the angle of the slope of these curves was taken as the rate of cooling $\dfrac{\partial T_w}{\partial t}$ of the plate area subjected to the action of the gas flow for a particular value of the oxygen pressure p_0. The value of $\dfrac{\partial T_w}{\partial t}$ corresponding to $p_0 = 20$ MPa (level of pressure in the vessel at which ignition of titanium alloy plates was observed in the experiments [8, 9]) was used to solve the equation of the thermal balance of the cooled area with respect to its heat transfer coefficient α, which is derived below [Eq. (6)].

Critical pressure of ignition of alloys in gaseous oxygen ($T_0 \approx 303$ K) and coefficients of heat transfer from ignition initiators for different types of fracture of the samples

Alloy	λ, W/(m·K)	Type of sample fracture			
		rod breakdown under conditions of natural convection		action of the gas flow on the plate	
		p_1^*, MPa	α_1, kW/(m^2·K)	p_2^*, MPa	α_2, kW/(m^2·K) [calculation by Eq. (3)]
VT1-0	16.8	2.3 [1, 6]	5 [3]	10.0	10.4
VT1-1	16	2.0 [7]		7.7 [8]	9.8
OT4-1	9.6	1.5 [1]		6.5 (OT4) [8]	10.4
VT14	8.4	1.3 [7]		7.0 [8]	11.6
VT6	8.4	0.8 [7]		3.1 [8]	9.9

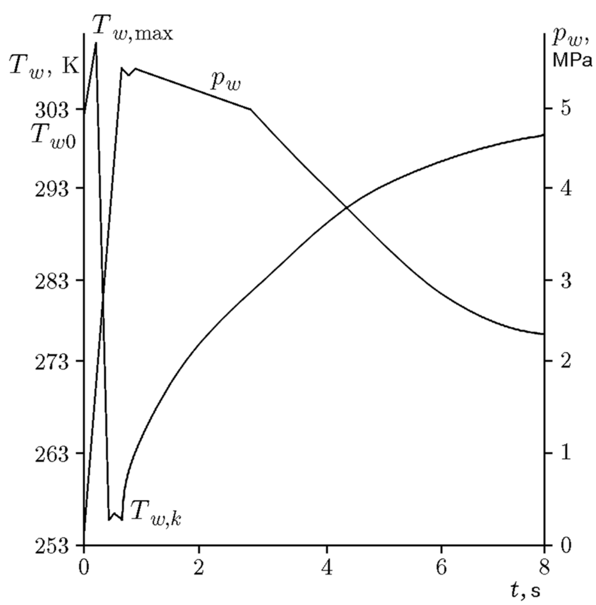

Fig. 4. Time evolution of the parameters T_w and p_w in the oxygen flow past the VT14 titanium alloy plate ($p_0 = 20$ MPa, $l = 2$ mm, $d = 2$ mm, and $\delta = 1.5$ mm).

In view of the results for the flow past the plate [9], the problem was solved under the following assumptions:
—the thermograms (see Fig. 4) correspond to the thermograms of cooling of a cylindrical fragment with the base area equal to the area of the cross section of the nozzle ($d = 2$ mm) from which the flow escapes and with the height equal to the plate thickness (1.5 mm);
—owing to equality of the temperatures of the plate area experiencing the action of the flow and the remaining part of the plate at the initial instant of the flow action, the heat transfer q_λ to this plate area can be ignored;
—as the plate temperature is close to the temperature of the surrounding walls of the box, the radiative component of q_ε of heat transfer to the cooled area can be neglected; as a consequence, $\alpha \approx \alpha_\alpha$.

Under these assumptions, the thermal balance equation for the cooled area of the plate takes the form

$$\left(\pi\frac{d^2}{4}\right)\delta\rho c_p\left(\frac{\partial T_w}{\partial t}\right) = \alpha_\alpha(T_{w,\max} - T_{w,k})\left(\pi\frac{d^2}{4}\right), \qquad (6)$$

whence it follows that

$$\alpha \approx \alpha_\alpha = \delta\rho c_p\left(\frac{\partial T_w}{\partial t}\right)\Big/(T_{w,\max} - T_{w,k}), \qquad (7)$$

where ρ and c_p are the density and specific heat of the plate material in the temperature interval $T_{w,\max}$–$T_{w,k}$ [$4.52 \cdot 10^3$ kg/m^3 and 0.521 kJ/(kg·K), respectively].

At the pressure $p_0 = 20$ MPa corresponding [see Eq. (4)] to the level of p_w^* for titanium alloys in the experiments [8, 9] ($p_w^* = 3.1$–10.0 MPa), the rate of cooling of the cylindrical fragment $\dfrac{\partial T_w}{\partial t}$ is estimated as 180 K/s (see Fig. 4), and the estimate of $\left(\dfrac{\partial T_w}{\partial t}\right)\Big/(T_{w,\max} - T_{w,k})$ is 3.3 s^{-1}, whence it follows that $\alpha \approx \alpha_\alpha \approx 11$ kW/(m^2·K). It is assumed that the coefficient α_2 of heat transfer from the ignition initiator (microcrater on the plate surface) is also close to the obtained value of α.

DISCUSSION OF RESULTS

As it can be concluded from the numerical analysis, heat removal from the heating ignition initiator in the experiments [8, 9] is determined by convection into the gas flow past the plate with the heat transfer coefficient $\alpha_2 = \alpha_\alpha$; as a consequence, it is independent of thermophysical properties of the plate material. For this reason, the coefficients α_2 for all analyzed titanium alloys for the test conditions [8, 9] are expected not to differ too much and to be close to the value of 11 $kW/(m^2 \cdot K)$.

The heat transfer coefficient α_2 calculated by Eq. (3) with allowance for the coefficient $\alpha_1 \approx 5$ $kW/(m^2 \cdot K)$ obtained for rod fracture under natural convection conditions and with allowance for the relationship of the critical pressures of material ignition in the oxygen flow ($p_2^* = p_w^*$) and in the case of rod fracture (p_1^*) turned out to be really identical to the above-found value of ≈11 $kW/(m^2 \cdot K)$ for all analyzed titanium alloys (see the table).

As is seen from the table, regardless of thermophysical properties of the tested titanium alloys [$\lambda = 8.4$–16.8 $W/(m \cdot K)$], the coefficients α_2 of heat transfer from ignition initiators in the oxygen flow past the plate predicted by Eq. (3) are close to the value calculated by Eq. (7): ≈11 $kW/(m^2 \cdot K)$.

Comparing the regular features of self-ignition of the rod in the oxygen flow under static conditions and of the plate in the dynamic regime, we can note that the process starts from ignition of metal microparticles in both cases. In the case of rod fracture, these microparticles, which are completely or partially separated microfragments of the fractured volume, being located in a narrow non-through fracture crack with constrained heat transfer [$\alpha_1 \approx 5$ $kW/(m^2 \cdot K)$], ignite at a comparatively low pressure of oxygen and serve as initiators of ignition of the main mass of the metal by providing a moderate critical pressure of ignition (p_1^*). In the case with the metal plate, the particles knocked out from the plate are immediately entrained by the gas flow and burn far from the metal surface. For this reason, the initiators of plate ignition are microcraters remaining on the plate surface after knockout of microparticles, which provide more intense heat transfer with the ambient medium [$\alpha_2 \approx 11$ $kW/(m^2 \cdot K)$] and require a higher pressure of oxygen for their ignition (p_2^*). It is this difference in the nature of the material ignition initiators under static and dynamic conditions that makes the inequality $p_2^* > p_1^*$ valid.

CONCLUSIONS

It is shown that the main heat transfer from ignition initiators (microcraters with the juvenile surface) in the case of self-ignition of titanium alloy plates in a high-velocity oxygen flow proceeds through convection with the heat transfer coefficient $\alpha_2 \approx 11$ $kW/(m^2 \cdot K)$, which is independent of thermophysical properties of the plate material. The found value of α_2 is close to the results [9.8–11.6 $kW/(m^2 \cdot K)$] calculated by using the coefficient $\alpha_1 \approx 5$ $kW/(m^2 \cdot K)$ of heat transfer from ignition initiators in the form of titanium rods during their fracture in oxygen under the conditions of natural convection with allowance for the relationship of the critical pressures of ignition of the analyzed titanium alloys under dynamic (p_2^*) and static (p_1^*) conditions.

REFERENCES

1. V. I. Bolobov, "Mechanism of Self-Ignition of Titanium Alloys in Oxygen," Fiz. Goreniya Vzryva **38** (6), 37–45 (2002) [Combust., Explos., Shock Waves **38** (6), 639–645 (2002)].
2. V. I. Bolobov, "Possible Mechanism of Autoignition of Titanium Alloys in Oxygen," Fiz. Goreniya Vzryva **39** (6), 77–81 (2003) [Combust., Explos., Shock Waves **39** (6), 677–680 (2003)].
3. V. I. Bolobov and N. A. Podlevskikh, "Mechanism of Metal Ignition due to Fracture," Fiz. Goreniya Vzryva **43** (4), 39–48 (2007) [Combust., Explos., Shock Waves **43** (4), 405–413 (2007)].
4. V. I. Bolobov, "Theory of Ignition of Metals at Fracture," Fiz. Goreniya Vzryva **48** (6), 35–40 (2012) [Combust., Explos., Shock Waves **48** (6), 689–693 (2012)].
5. D. A. Frank-Kamenetskii, *Diffusion and Heat Transfer in Chemical Kinetics* (Nauka, Moscow, 1987) [in Russian].
6. F. E. Littman, F. M. Church, and E. M. Kinderman, "A Study of Metal Ignitions. The Spontaneous Ignition of Titanium," J. Less-Common Metals **3**, 367–378 (1961).
7. E. A. Borisova and K. V. Bardanov, "Ignition of Titanium Alloys in Oxygen-Containing Media," Tsvetn. Metallurg., No. 2, 47–48 (1963).
8. V. I. Bolobov, "Deflagration of Titanium in an Oxygen Flow," Fiz. Goreniya Vzryva **29** (2), 12–15 (1993) [Combust., Explos., Shock Waves **29** (2), 138–141 (1993)].
9. V. I. Bolobov, "Mechanism of Metal Ignition in an Oxygen Flow," Fiz. Goreniya Vzryva **34** (1), 50–56 (1998) [Combust., Explos., Shock Waves **34** (1), 44–50 (1998)].