Erosive Effects of High-Pressure Combustion Gases on Steel Alloys

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This study presents an experimental investigation of the thermal and chemical erosion characteristics of steel alloys under the short exposure (2-4 msec) of high pressure and high temperature propellant gases. The erosion in short duration tests is shown to be controlled by the chemical interaction of the propellant gases with the surface of the test specimens. The erosion experienced by the steel alloys increases with decreasing thermal conductivity and specific heat. The established linear dependence of mass eroded on number of firings suggests that any physical and chemical alterations undergone by the eroded surface do not influence future erosion tests. Finally, the effects of geometry of the orifice and sulphur addition in the propellant on the erosion of steel alloys were investigated.

Nomenclature

c	= specific heat
E	= activation energy
K	= thermal conductivity
$\dot{m}$	= steady-state melting rate
q_W	= rate of surface heat transfer per unit area
R	= gas constant
T_m	= melting or solidus temperature
T_0	= initial temperature
t_{pr}	= preheating time
T_s	= surface temperature
ΔH_L	= heat of melting
ρ	= density

Introduction

THE emphasis of this investigation was directed toward studying the mechanisms of erosion of steel alloy orifices under the action of high pressure and high temperature propellant gases flowing through them.

Vented-combustor erosion apparatuses have been widely used to study the erosion of metallic vents by high pressure and high temperature propellant gases.[1-5] These studies were prompted by the need to evaluate, in the laboratory, the erosion of gun barrels. However, the application of vented-combustor erosion apparatus to study gun barrel erosion is limited because it isolates the thermochemical interactions of the propellant gases with the metallic surface from the mechanical interaction of the projectile with the bore surface. Both of the above types of interactions contribute to the erosion of gun barrels.

The two leading hypotheses on the mechanism of erosion of steel alloys by propellant gases are: 1) the melt-and-wipe-off mechanism, based on the premise that erosion occurs due to inert heating and melting of the surface of the test specimen, with subsequent removal of the melt by the aerodynamic forces of the flow, and 2) the chemical mechanism based on the premise that erosion is due to the chemical interaction between the propellant gases and the solid surface.

Several investigations have been made of the erosion of steel alloys by hot, high pressure propellant gases. Greaves, et al.[1] and Wiegand[2] both found that, above a critical pressure of the gases in the combustor, erosion is due to melting of the

steel specimens. Below this characteristic threshold pressure for melting, the erosion of the steel vents was attributed to chemical effects.[2] Greaves et al.[1] have shown (as did Vieille[3]) that the erodibility of materials can be correlated with their melting temperature. However, both of the above studies had sufficiently long test times for the melting process to be established. Typical times for the efflux of gases through the test orifice in Greaves et al.[1] experiments were in the range of 0.5-1 sec.

The correlation of the erodibility of materials with their melting temperature is not strictly correct. Tests performed[6,7] on aluminum and titanium alloys have shown strong augmentations of erosion rates resulting from chemical interactions with the propellant gases. Furthermore, although the melting temperature of titanium is greater than, say, the solidus temperature of steel AISI 4340, titanium exhibits much larger erodibility.[7]

The purpose of this study was to examine the erosion characteristics of steel alloys in short duration (2-4 msec) combustor experiments and to provide comparative erosion data for three types of steel alloys. These short duration tests may not provide sufficient time for preheating and melting of the steel alloys, thus allowing the chemical interaction between the propellant gases and the steel surface to govern the erosion process.

Apparatus and Materials

The vented-combustor erosion experiments were carried out by igniting and burning propellant in a small combustor (5 cc) and allowing the products of combustion to pass through a test orifice made of the material under examination. The vented-combustor shown schematically in Fig. 1 is the same as that used in Refs. 6 and 7. The rapid burning of the propellant powder in the combustor generates a supply of hot, high pressure propellant gas. The gas flows out the combustor through the vent orifice and the test orifices. For a given propellant loading, the pressure-time curve is controlled by the outflow through the vent orifice whose initial area is about 20 times the area of the test orifice. Thus, the increase of the diameter of the test orifice due to erosion produces secondary effects on the pressure history of the combustor.

The pressure history of the combustor chamber was monitored by an ultra-high frequency Kistler 607 pressure transducer. The pressure and temperature transients of a typical test are shown in Fig. 2. The peak temperature in the combustor corresponds approximately to the isochoric flame temperature of the propellant.

For a given test firing, the erosion of the test specimen was obtained by the difference in mass of the specimen before and after the test. The mass reduction provides a gross measure of
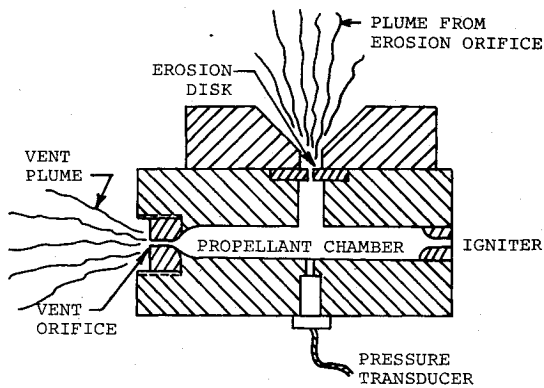
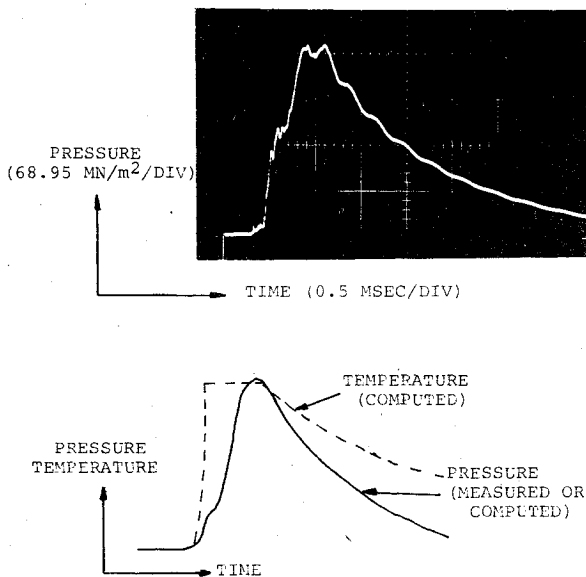Fig. 1 Schematic diagram of the vented-combustor erosion apparatus.

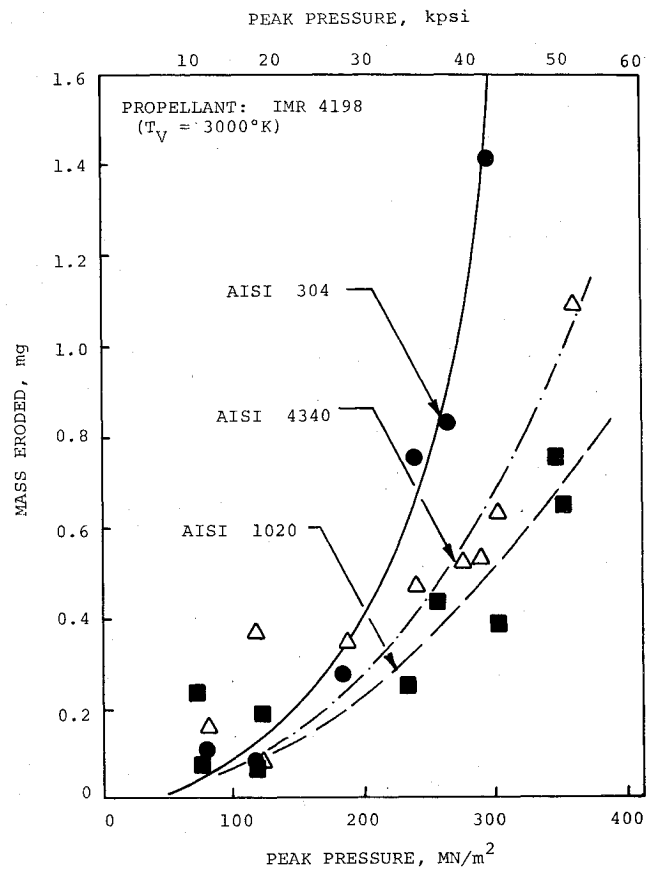Fig. 2. Typical pressure and temperature histories of the propellant gas in the vented-combustor apparatus.

Fig. 3 Erosion results of three steel alloys, tested in the vented-combustor. The AISI 304 alloy experiences the greatest erosion.

Table 1 Nominal composition of the steel alloys used in the erosion tests

Nominal composition	Steel alloys, AISI		
	304	1020	4340
C	0.08(max)	0.18-0.23	0.38-0.43
Mn	2.00(max)	0.30-0.60	0.60-0.80
Si	1.00(max)	0.10	0.20-0.35
Ni	8-12		1.65-2.00
Cr	18-20		0.70-0.90
Mo			0.20-0.30
P(max)		0.040	0.040
S(max)		0.050	0.040

the erosion experienced by the specimen. For a more detailed examination of the effect of erosion on the steel orifices, microscopic examinations of the upstream and downstream side of the orifice and of sectioned orifices were performed.

The test specimen consisted of 0.250 cm thick steel alloy disk with a predrilled orifice at its center. The orifice diameter, in all the experiments reported, was 0.066 cm. The erosion tests were performed on three steel alloys, AISI 304 stainless steel, AISI 1020 carbon steel, and AISI 4340 chromium-molybdenum steel. Typical nominal compositions and room temperature properties of the above steels are shown in Tables 1 and 2 respectively.

The experiments were carried out using IMR 4198 single-base propellant. The chemical composition and propellant gas properties of IMR 4198 propellant is shown in Table 3.

Results and Discussion

The erosion of the three test steel alloys as a function of the peak pressure of the combustor is shown in Fig. 3. In all three cases, erosion increases as the peak pressure increases. The peak pressure in the combustor provides a measure of the heat

Table 2 Thermal properties of pure iron and of the three steel alloys under investigation

Metal or alloy	Density ρ g/cm^3	Thermal[a] conductivity K cal/cm sec°K	Heat[a] capacity c cal/g°K	Latent heat of melting ΔH_L cal/g	Solidus temperature T_M °K
Iron (pure)	7.87	0.192	0.108	65.0	1810
AISI 304	8.02	0.041	0.12	~65.0	1700
AISI 1020	7.86	0.124	0.107	~65.0	1789
AISI 4340	7.86	0.090	~0.107	~65.0	1778

[a] At room temperature.

Table 3   IMR 4198 propellant composition and combustion gas properties

Overall composition	
90.5	Nitrocellulose (13.15%N)
6.0	Dinitrotoluene
0.7	Diphenylamine
0.3	Graphite
0.5	Potassium Sulphate
2.0	Moisture

Product composition mole fraction	
CO $= 0.439$	$CO_2 = 0.104$
$H_2 = 0.126$	$H_2O = 0.215$
$N_2 = 0.111$	

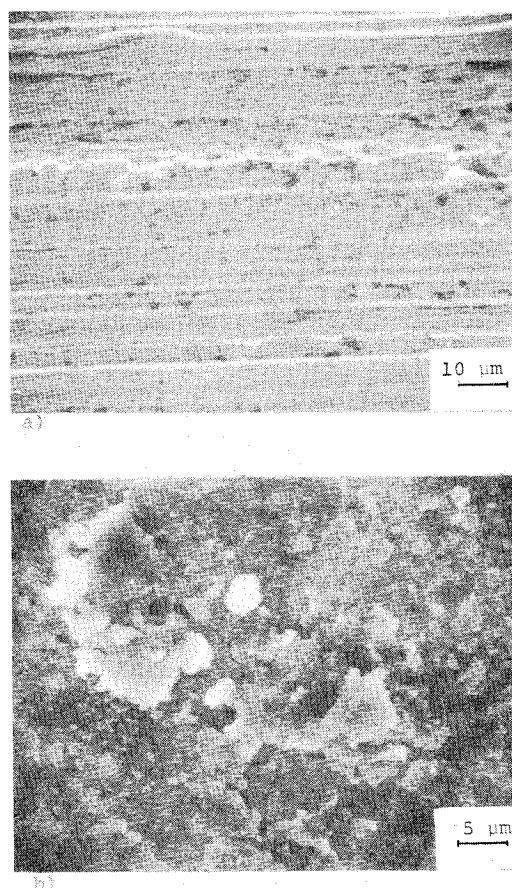| Properties |
| --- |
| Isochoric flame temperature $= 3000°$ K |
| Average molecular weight $= 24.25$ g/g mole |
| Force $= 344.041$ ft lbf/1bm |
| Ratio of specific heats $= 1.23$ |

Fig. 4 SEM photomicrographs showing surface modifications resulting from the erosion process. a) Surface of untested specimen. b) Eroded surface (propellant: IMR-4198. $p_{max} = 89.6$ MN/m^2).

transfer at the gas/solid interface by means of the dependence of the Reynolds number on density. The peak temperature in the combustor is approximately equal to the isochoric flame temperature of the propellant. Thus the higher the peak pressure, the higher the surface heat flux which results in high surface temperature of the test material. Furthermore, the pressure is also a measure of the collision frequency of the gaseous molecules. The higher the pressure, the greater the number of collisions of the gaseous species with the solid surface. Both the surface temperature and the frequency of collisions of the gaseous species with the surface, augment the chemical interaction of the propellant surface.

Of the three alloy steels tested (in the vented chamber), the carbon steel AISI 1020 eroded the least, followed by the chromium-molybdenum steel AISI 4340 and, last, the stainless steel alloy AISI 304. The differences in the erosion characteristics of the three alloys are more pronounced as the peak pressure increases. In the range of peak pressures lower than 200 MN/m^2 the erosion of the three alloys is indistinguishable as a result of the scattering of the experimental data.

The difference of the erosion characteristics of the three alloys are due to their varying thermal properties. A comparison of the thermal conductivity and specific heat of the three alloys shows that the stainless steel alloy AISI 304 has the lowest thermal properties followed by AISI 4340 and last AISI 1020. Low values of thermal properties result in high values of the surface temperature of the specimen. This results in higher erosion rates. At high temperatures (>1300°K), however, the difference in the thermal properties of these alloys diminish.

The variation of the erosion characteristics of the three alloys with respect to peak pressure also provides a clue to the nature of the erosion process. As we have stated earlier, there are two leading hypotheses on the mechanism of erosion of steel alloys: 1) the melt-and-wipe-off mechanism, based on the premise that erosion occurs due to inert heating and melting of the surface of the test specimen, with subsequent removal of the melt by the aerodynamic forces of the flow, and 2) the chemical mechanism, based on the premise that erosion is due to the chemical interaction between the propellant gases and the solid surface.

The steady-state one-dimensional melting rate is given by[8,9]

$$\dot{m} = q_w/[\Delta H_L + c(T_m - T_0)] \tag{1}$$

The properties of the alloys in Eq. (1) are evaluated at the solidus temperature of the alloys. Since at these high temperatures the properties of the tested alloys do not differ appreciably and likewise their solidus temperature, one will ex-

pect that their melting rate should be approximately the same. On the other hand, the preheating time, i.e., the time required for the surface temperature of the specimen to reach its solidus temperature which is given by Eq. (2)[9] will vary considerably owing to the large differences of their thermal properties.

$$t_{pr} = \pi/4(\rho c K)(T_m - T_0)^2/q_w^2 \tag{2}$$

Equation (2) is valid for one-dimensional geometry, constant heat flux system. Thus it is assumed, if the inert mechanism of erosion is the controlling mechanism, that the erosion characteristics of the three alloys will differ appreciably at the lower peak pressure range (onset of erosion).

On the other hand, if we assume that the chemical interaction between the gaseous propellant combustion products and the steel alloy is the governing mechanism of erosion, then the erosion characteristics of the three alloys are in accordance with this hypothesis. The rate of chemical reaction is dependent on the surface temperature through the Arrhenius expression $\exp(-E/RT_s)$, which indicates that as the temperature increases, the reaction rate and hence the erosion will increase exponentially. Furthermore, for a given surface temperature difference between two alloys, the difference in their reaction rates will increase as the level of temperature increases. Therefore the experimental erosion results of the three steel alloys indicate that at least the onset of erosion is very dependent on the chemical reactions between the gaseous species and the solid surface.

Evidence of the chemical interaction between the steel surface and the propellant gases is provided by SEM examination of the eroded surface. Figure 4 shows a comparison between an untested surface (Fig. 4a) and a surface exposed to high pressure propellant gases (Fig. 4b). The horizontal bands
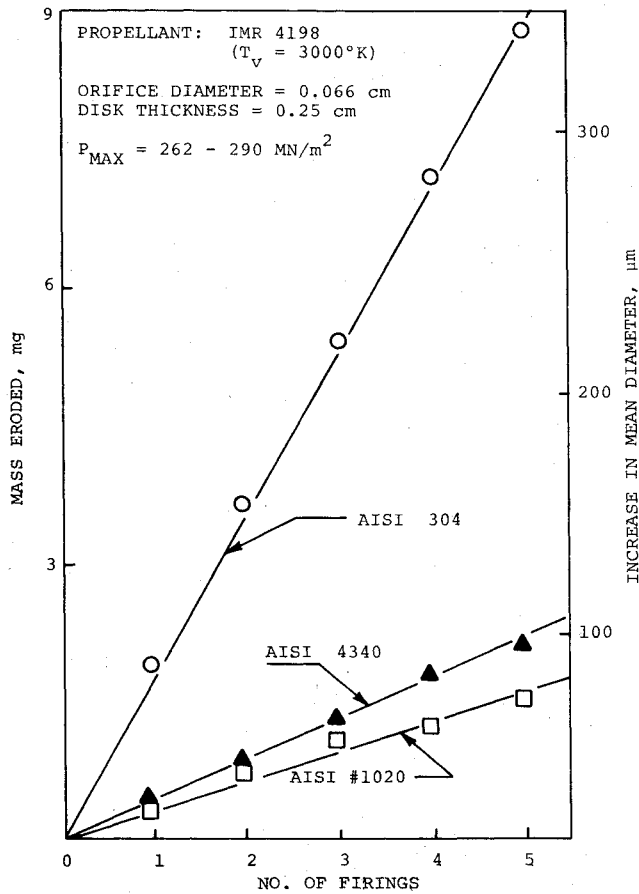
Fig. 5   Erosion of steel alloys as a function of number of firings. The linearity of the curves indicates that the mechanism of erosion does not vary from test to test. Total number of firings: 5.

shown in Fig. 4a are machining marks. The photomicrograph of the eroded surface (Fig. 4b) shows the presence of a scale that resulted from the chemical attack of the propellant gases on the surface. Electron microprobe analysis of the surface indicates a marked increase of carbon content in comparison with the unexposed specimens. The oxygen levels were shown to be comparable. The chemical nature of the scale, however, has not yet been resolved.

Another interesting characteristic of the eroded surface is the presence of cracks in the underlying metal surface. The origin of these cracks is believed to be due to thermal stresses. The examination of the mechanism of crack formations is the subject of future study. At this time, we do not have conclusive evidence that, for present exposure conditions, cracks do not contribute to the mass removal experienced by the test specimen.

Figures 5 and 6 show the erosion of the three steel alloys tested as a function of the number of firings. Figure 5 is a sequence of 5 firings and Fig. 6 is a sequence of 20 firings. These tests were performed at approximately constant combustor conditions. Similar to the results of Fig. 3 the erosion experienced by the stainless steel alloy AISI 304 is greater than by AISI 4340 and AISI 1020. The linear behavior of the eroded mass vs number of firings curve indicates that the erosion process of these alloys, under the particular environmental conditions are apparently independent from test to test, i.e., the erosion experienced by a test specimen produces minor physical and chemical alterations on the eroded surface that apparently do not affect the subsequent erodibility of the material. The linearity of the erosion results with respect to number of firings excludes the possibility of accumulation of oxide on the eroded surface; however, it does not exclude the possibility of oxide formations that were removed by the shear forces of the flow and similarly, integranular changes are not excluded.
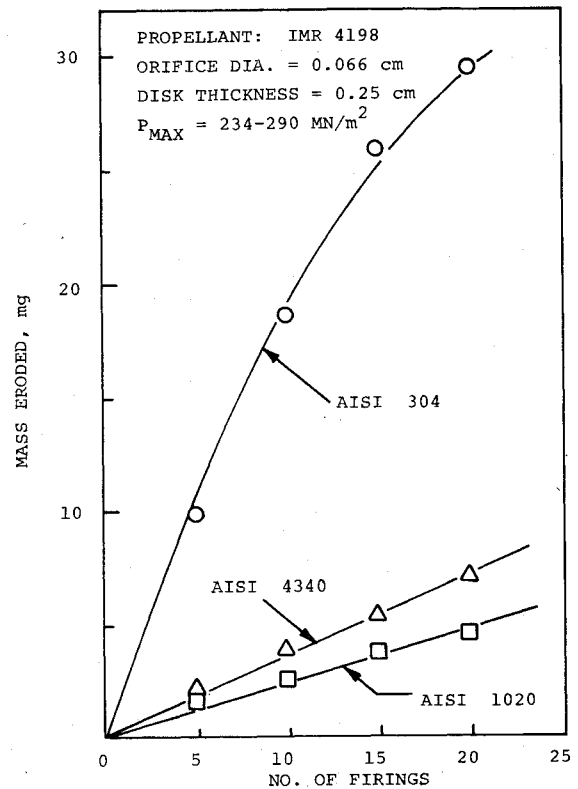

Fig. 6   Erosion of steel alloys as a function of number of firings. Total number of firings: 20.
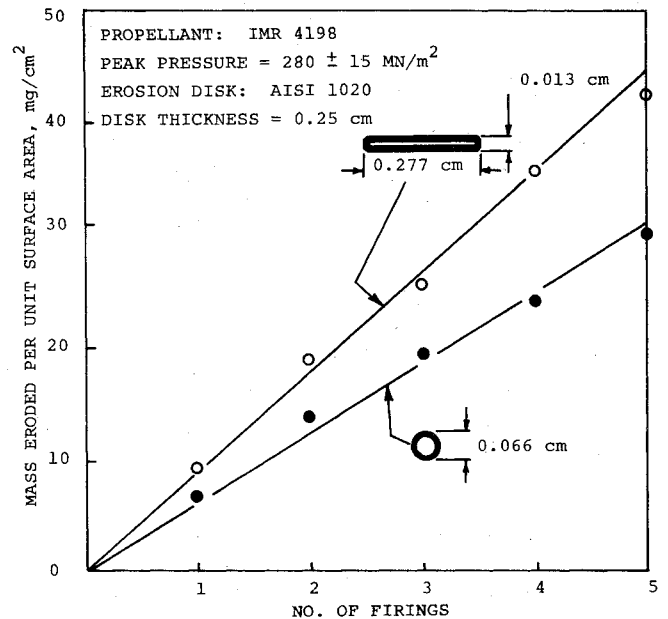

Fig. 7   Augmentation of the erosion of steel alloys using rectangular flow passage instead of cylindrical flow passage.

Figure 6 (sequence of 20 firings) shows a nonlinear relationship between the mass loss and number of firings in the case of AISI 304. The decrease of erosion experienced by the stainless steel alloy at high number of firings results from loss of combustor pressure because of the large erosion experienced by the alloy. The loss of pressure between test No. 1 and test No. 20 was 70 MN/m².

The effect of curvature on the erosion characteristics of AISI 1020 carbon steel is shown in Fig. 7. This is a plot of mass eroded per unit surface area vs number of firings for two cases: 1) cylindrical orifice, and 2) rectangular flow passage. The height of the rectangular passage is 0.013 cm, compared

Table 4   Effect of sulphur additive on the erosion of steel alloys[a]

| Peak pressure MN/m²	Sulphur %	Mass eroded five consecutive tests mg
148	0	0.25
	·1	0.29
200	0	0.34
	1	0.54
275	0	1.88
	1	1.68
377	0	4.31
341	1	3.15

[a] At low peak pressures sulphur increases erosion. At high peak pressure it decreases erosion. Propellant: IMR 4198, $T_v = 3000°$K, erosion disk = AISI 4340, orifice diameter = 0.066 cm, orifice thickness = 0.25 cm.

to 0.277 cm for its width, which provides two flat surfaces for the chemical and thermal interactions with the propellant gases. In order to have similar pressure and temperature histories of the propellant gases in the combustor, the cross-sectional area of the two configurations are approximately the same. As shown in Fig. 7 the erosion per unit surface area experienced by the flat surfaces is greater than the erosion experienced by the circular orifice. The difference in the erosion of the two geometries is due to the effect of curvature on the heat dissipation in the interior of the specimen; the smaller the curvature, the smaller the portion of heat dissipated in the interior of the test disk. In the limit of zero curvature, i.e., one-dimensional slab, the heat dissipated in the interior is minimum, with the result of maximum suface temperature, hence, maximum erosion rate.

The erosive action of sulphur on steel alloy AISI 4340 was investigated in a special test series. One percent by weight of sulphur powder was mixed with the IMR 4198 propellant. This addition provided no alterations in the pressure history of the combustor. Attempts, however, to use a higher percentage of sulphur were not successful because the presence of sulphur altered considerably the pressure history of the combustor. In general, the addition of sulphur tended to increase the pressurization time of the propellant.

The erosion results of the above tests shown in Table 4 indicate that the addition of 1% sulphur produces different effects depending on the peak pressure of the combustor. At low peak pressures (220 MN/m² or lower) sulphur increases erosion, whereas at high peak pressures (275 MN/m² or higher) erosion is decreased by the addition of 1% sulphur. The increase of erosion at 200 MN/m² was by a factor of 1.6 times, whereas at 275 MN/m² erosion was decreased by a factor of 1.1. Similar results were obtained by Wiegand[2] who made comparative studies of the erosion of cold rolled AISI 1020, using primers with and without sulphur. The increase in erosion of steel alloys by the addition of sulphur at low peak pressures was attributed to the fact that in this region the chemical action of the propellant gases is the controlling mechanism of erosion and that sulphur increases the reactivity of the propellant gases.

The role of sulphur in the chemical attack of the steel alloys by the propellant gases is not well understood. The leading hypothesis[10,11] is that hydrogen sulphide (H₂S), produced by the reaction of sulphur with propellant gases, acts as a catalyst for the carbonyl reaction

$$Fe + CO \rightarrow Fe(CO)_5$$
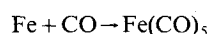
which is considered to represent the chemical interaction of the propellant gases and the steel surface. Another hypothesis,[12] however, is that H₂S attacks iron to form ferrous sulphide

$$Fe + H_2S \rightarrow FeS + H_2$$
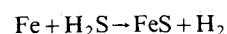
Augmentation in erosion may result due to either: a) the formation of FeS and the removal of FeS by the shearing forces of the flow, or b) the above reaction, believed to be highly exothermic, may provide enough heat to increase considerably the surface temperature of the alloy which in turn will increase the reaction rate of the steel surface.

The effect of sulphur at high peak pressures is very unclear. No explanation has been given in the literature. One possible explanation of the observed reduction in erosion is that at high peak pressures the surface temperature of the specimen reaches the melting or decomposition temperature of the ferrous sulphide. Both processes are endothermic which will result in a net decrease of the surface heat flux and a corresponding decrease in the erosion.

Conclusions

The experimental investigation of the erosion of steel alloys by propellant gases, using the vented-combustor apparatus, provided the following conclusions:

1) In short duration combustor tests (2-4 msec) the erosion of steel alloys is strongly controlled by the chemical interaction of the propellant gases with the steel alloys.

2) The erosion experience by the steel alloys is dependent upon the thermal properties of the alloys. The higher the thermal conductivity of the alloy the lower the mass removal experienced by the alloy.

3) Erosion is strongly influenced by the geometry of the test orifice. The greater the radius of curvature of the test wall relative to the thermal thickness the smaller the portion of heat dissipated in the interior of the test specimen and the greater the erosion. Flat surfaces experience the greatest erosion.

4) The erosion of the three alloys tested was found to be linearly dependent on the number of firings, which indicates that any physical or chemical alterations produced by the erosion process do not influence the future erosivity of these alloys. The average mass removal per firing of AISI 304 stainless steel, AISI 1020 carbon steel, and AISI 4340 chrome-moly steel were 1.78 mg. 0.34 mg and 0.45 mg, respectively.

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