Wear, 41 (1977) 223 - 231

EROSION IN ROCKET MOTOR NOZZLES

M. E. DE MORTON
Materials Research Laboratories, Maribyrnong, Victoria (Australia)
(Received April 21, 1976)

Summary

Examination of the nozzle assemblies of solid propellant rocket motors has shown that erosion of molybdenum inserts occurs by three distinct processes. Wear was initiated by the physical erosion of the steel nozzle body due to particles in the gas stream. Material removed in this manner wetted and alloyed with the surface of the molybdenum inserts in the high temperature reducing gas flame to form a low melting point Fe–Mo–C eutectic alloy. Subsequent liquid metal erosion occurred by blasting of the continuously forming liquid eutectic from the surface of the nozzle by the high velocity gas stream. Finally, additional erosion at the insert throat occurred by the rapid ingress of oxygen to grain boundaries; this weakened the cohesion between the grains and allowed whole grains to be eroded from the surface by the gas stream.

Introduction

Damage to rocket motor nozzles may take the form of thermal shock, oxidation and/or vaporization of the nozzle wall, ablation of the surface material weakened by the high operating temperature or removal of wall material due to the action of entrained solid or liquid particles [1]. The present work details several interconnected modes of erosion observed in the nozzle assemblies of a solid fuel rocket motor during proof firings.

The three modes of erosion observed in the partial breakdown of the Mo inserts were: (1) the abrasive action of solid particles in the gas stream on the steel body, (2) liquid metal erosion of Mo due to the presence of a low melting point eutectic and (3) erosion of Mo metal grains by the gas stream after grain boundary oxidation and embrittlement.

Although Mo melts at about 2885 K it has very poor resistance to oxidation above 800 K owing to the volatile nature of MoO_3; a self-protective oxide is therefore not formed [2].

Nozzle assembly

The particular nozzle assembly used in the motor is shown diagrammatically in Fig. 1. The Mo insert was assembled with an interference fit of 0.025 - 0.063 mm into a mild steel body which was in turn screwed to the end of a transfer tube transporting the high velocity gas stream.

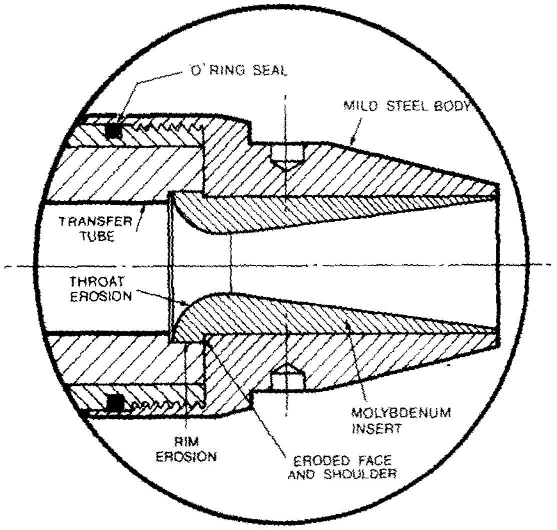


Fig. 1. Details of the Mo insert in the nozzle assembly and the position of the various forms of erosion.

Examination of proof firing records showed that motors using composite inhibitors had a higher incidence of erosion than motors using cellulose acetate inhibitors [3]. With composite inhibitors solid carbon char and metal oxides were transported along the transfer tube with the gas stream. High percentages of aluminium in the propellant are also likely to accentuate nozzle erosion caused by the abrasive action of solid particles [1].

A record of the pressure during proof firing indicated that the throat area of the eroded nozzle increased slightly 40 s after the start of firing; the total time of firing was 90 s.

After proof firing, throat erosion and movement of the insert along the body were observed. Detailed radiography indicated that no defects were present in the materials used for the assembly. In most cases the pressure drop and insert movement along the body did not seriously impair performance of the motor; however, because of the critical temperature and stress conditions of operation complete breakdown or ejection of the insert from the body must be considered a possibility.

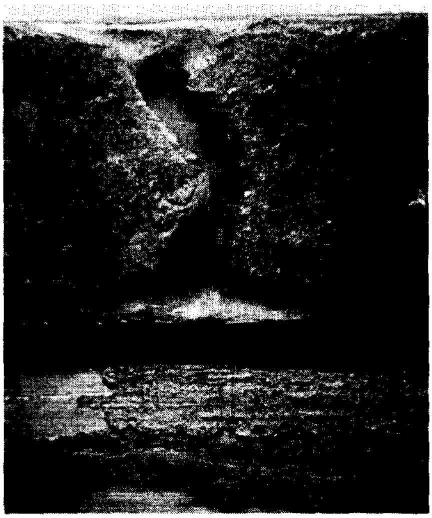


Fig. 2. Severe erosion at the throat and outer rim of the Mo insert (top). (Magnification 3.3 ×.)

Fig. 3. Liquid metal erosion at the shoulder and outer rim of the Mo insert. Note the metal wash, present as a thin layer below the shoulder. (Magnification 6.6 ×.)

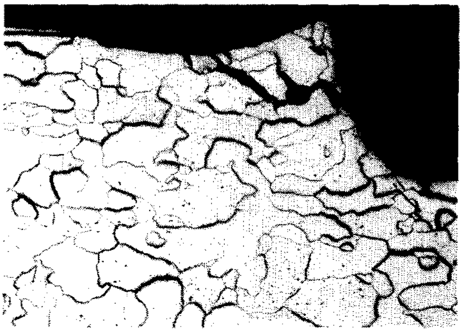
Materials

The material used for the manufacture of the nozzle assembly was 99.9% Mo which was forged from cold-pressed sintered Mo powder. A density of not less than 98% of the bulk metal was specified. The maximum iron and oxygen contents permitted were 500 and 200 ppm, respectively. The hardness of the inserts examined ranged from 175 to 205 HV. Commercial mild steel with a nominal composition of 0.26 wt.% carbon, 1.6 wt.% manganese and 0.3 wt.% silicon was used for the body housing the Mo insert.

Nature of erosion

The types of erosion observed in the three nozzle assemblies examined were similar and occurred in three separate sites, as illustrated in Fig. 1. Firstly, severe local erosion occurred at the throat section of the Mo insert and is shown in Fig. 2. Secondly, erosion tracks were present at the outer rim of the Mo inserts (Fig. 3) and thirdly excessive erosion was observed in both the insert and steel body at the restraining shoulder of the insert (Figs. 4 and 5). This erosion had allowed movement of the inserts relative to the body and in the direction of the gas stream of up to 6 mm.

Detailed examination of the inserts after removal from the body showed a close association between the position of the erosion tracks on the



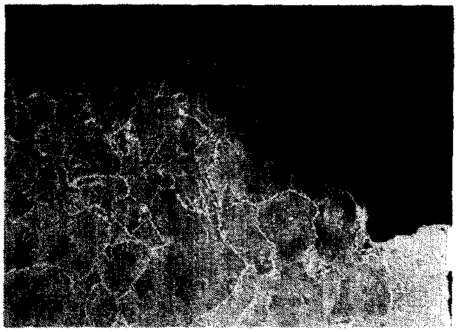


Fig. 4. Section through the Mo insert shoulder showing cracking caused by excessive loading. Dissolution of Mo to form an Fe Mo -C eutectic layer is shown at the top left of the figure. (Magnification 27.5 ×.)

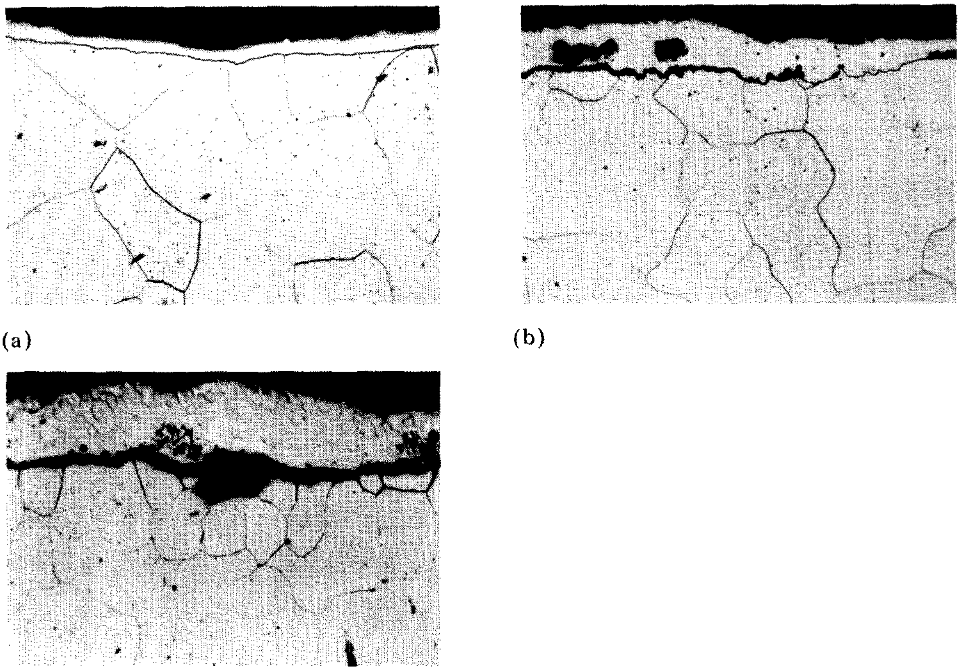
Fig. 5. Restraining shoulder of the mild steel body showing complete erosion of the corner, carbon pickup at the surface and a residual eutectic layer at the final seating. (Magnification 27.5 ×.)

rim of the insert (Fig. 3) and the localized erosion in the throat, as shown for example in Fig. 2. Melted material had also flowed into the gap between the insert and body during firing, as shown in Fig. 3. Talysurf measurements of these droplets gave a thickness of 0.12 mm.

Microscope examination of the droplets indicated a two-phase eutectic-type structure and electron probe microanalysis (EPMA) showed that the droplets contained 12 - 40 wt.% Mo. Subsequent analysis showed carbon also to be present. The ternary C–Fe–Mo equilibrium diagram [4] indicates that an Fe–Mo–C eutectic occurs in the composition range 2 - 20% Mo and 4.2% C. This eutectic has a melting point of about 1370 K, *i.e.* less than half the melting point of Mo and well below measured gas flame temperatures.

Microscope examination

Examination of metallographically prepared sections from the throat of the Mo insert showed that an adherent eutectic layer had formed at the shoulder region which had completely wetted the surface of the Mo; cracking had also occurred in this region (Fig. 4). These features allowed the insert to move along the steel body in the direction of the gas stream. Detailed examination of the surface layer showed that, as the thickness of the eutectic layer increased from the outer rim of the insert to the hotter throat area, the adherence of the layer to the Mo surface became poorer. This is shown progressively in Fig. 6(a), (b) and (c). Furthermore where excessive breakaway of the surface layer occurred there was evidence of diminishing grain boundary cohesion in the insert and removal of whole grains of Mo from the surface was observed (Fig. 6(c)). Additional EPMA work on the insert surface layers (Fig. 7(a)) showed that they contained basically Mo



(a)

(b)

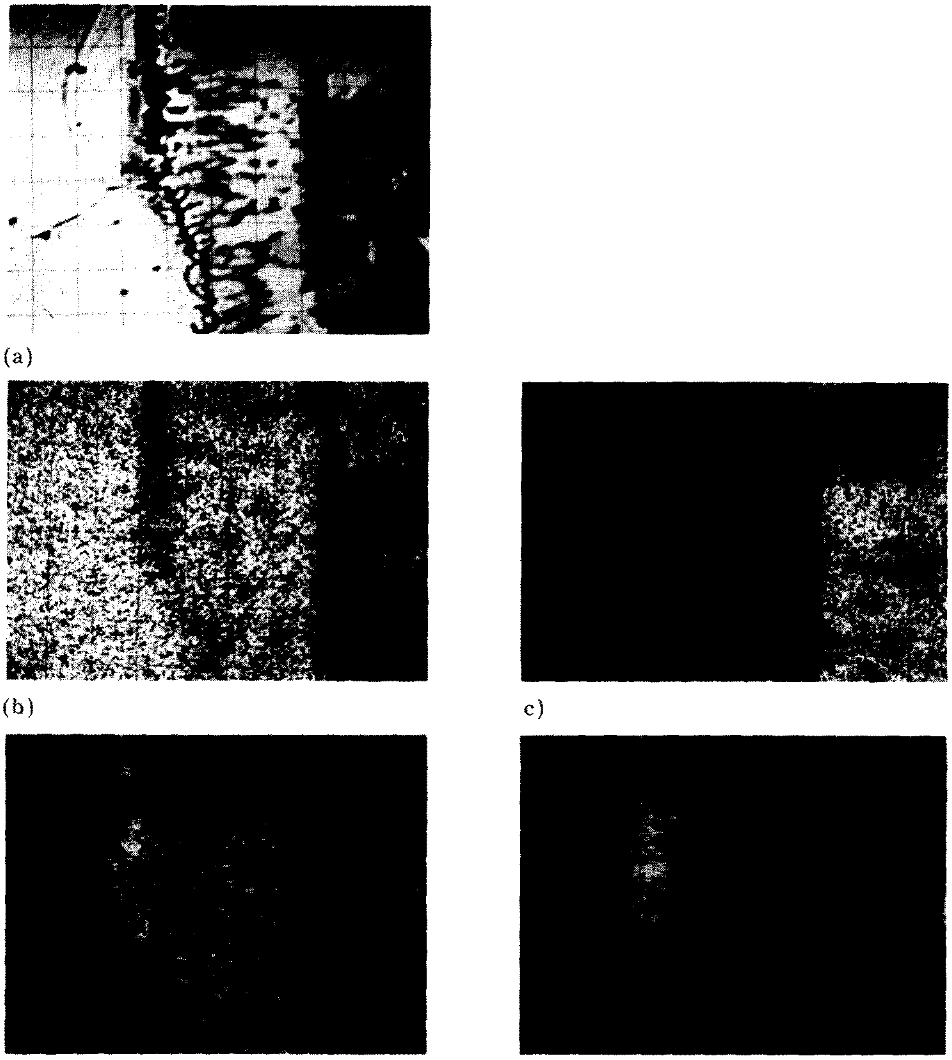
(c)

Fig. 6. Sections through a Mo insert showing an increasing thickness of both the eutectic layer and the subsurface oxide: (a) on the outer rim, (b) near the throat and (c) in the region of severe throat erosion. Note the grain boundary oxidation and the absence of grains in (c). (Magnification 275 ×.)

(Fig. 7(b)) and Fe (Fig. 7(c)) with carbon distributed fairly uniformly throughout (Fig. 7(d)). Oxygen, however, was localized in the subsurface layer (Fig. 7(c)). In the region of the insert throat where excessive erosion had occurred a dark phase was present along grain boundaries (Fig. 6(c)). An EPMA scan for oxygen across the dark phase showed a high concentration, as indicated in Fig. 8. In some areas oxygen had infiltrated to a depth of five to ten grain diameters.

Discussion

Detailed micro-examination and analysis of fired inserts has shown that erosion of the Mo was basically due to a twofold process involving firstly the formation of a low melting point Fe–Mo–C eutectic and secondly the infiltration of oxygen along grain boundaries to weaken the cohesion between grains. Whole grains were then eroded by the shearing forces associated with the high velocity gases passing through the nozzle throat. The conditions existing in the throat were certainly conducive to physical



(a)

(b)

c)

(d)

(e)

Fig. 7. Electron probe microanalysis results on the Mo insert and surface layers showing the distribution of Mo, Fe, C and O. (a) Area scan, (b) Mo X-rays, (c) Fe X-rays, (d) C X-rays, (e) O X-rays. (Magnification 825 ×.)

separation of grains after embrittlement of the boundaries since the gas velocity and temperature were 490 m s^{-1} and 2400 - 2700 K, respectively [3]. However, in proposing this breakdown mechanism for erosion two important questions need to be answered: firstly, how was the Fe–Mo–C eutectic that brought about the liquid metal erosion formed and, secondly, what was the source of oxygen to cause intercrystalline embrittlement at the throat of the insert (Fig. 6(c))?

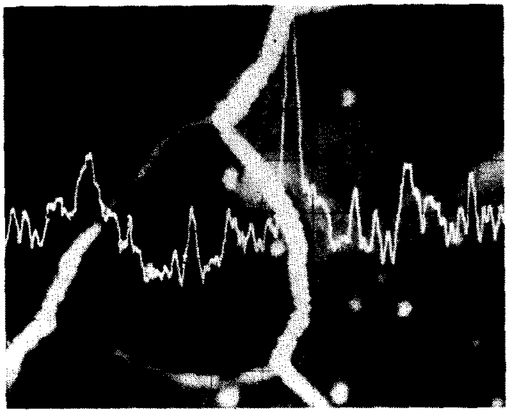


Fig. 8. Electron microprobe scan showing the concentration of oxygen in the dark phase present at grain boundaries near the insert throat. (Magnification 1500 ×.)

With respect to the origin of the Fe–Mo–C eutectic a factor concerned with the burning of the solid propellant is relevant. As mentioned earlier, nozzle erosion is more prevalent in motors that contain a composite inhibitor. In this case flame temperatures during the first 20 s were higher than those for cellulose acetate inhibited motors. During firing some 60 - 80% of the inhibitors entered the nozzle as solid carbon char and metal oxides (50% iron oxides) and this char appeared as a black non-adherent deposit on the face of the steel body supporting the insert.

Examination of the etched radial section of the steel body near the restraining shoulder (Fig. 5) showed that the hot reducing gases had penetrated along the interface between the transfer tube and the insert and carburized the surface layer to a depth of 0.2 - 0.3 mm causing substantial grain growth in this area. This surface of the body was badly eroded and almost entirely eutectoid (about 0.8% carbon) in the form of fine pearlite. Furthermore, material at the shoulder of the steel body had been removed to form a circumferential groove beneath the insert shoulder. The formation of this groove and the eroded top surface during firing suggests an explanation for the origin of the low melting eutectic. This explanation is based on the assumption that the carbon char, accelerated down the transfer tube at velocities near to the gas velocities, would remove material on impact with the heated steel surface at the shoulder region. This process would be similar to the mechanical erosion observed in coal-fired boilers, caused by the impact of high velocity abrasive ash particles on mild steel heater tubes [5], where it is found that the metal loss is proportional to the impact velocity of the ash and is a maximum at oblique impact angles. Particles removed from the surface of the steel body in this manner* would quickly melt at the gas

---

*It is known that high local temperatures are induced in the surface layer of a material under attack from high velocity particles [1]. Mechanical erosion is therefore increased.

temperatures existing in this region and would alloy with Mo at the surface of the insert and with carbon present in the reducing flame to form a low melting point eutectic. Droplets of this eutectic would then be available to flow into the insert body gap, as observed. Once the low melting eutectic had formed at the shoulder region and wetted the surface in the reducing gas stream, both forward flow in the gas stream of droplets into the colder insert/body gap and backward flow by surface capillary action to the hotter insert throat would follow. The continuous formation of the molten eutectic in the gas stream at the shoulder region would ensure constant liquid metal erosion at the outer rim and throat of the insert. Neilson and Gilchrist [1] have shown that, in the absence of particles, material is readily removed in a hot gas stream from the throats of simulated rocket nozzles once local melting has occurred.

The existence of oxygen at the grain boundaries in the eroded regions in the insert throat is a more problematical issue because of the reducing nature of the burnt gases. A possible explanation for this intergranular oxidation, however, is that small amounts of oxygen would be available for exchange in the localized non-equilibrium regions from oxides transported with unburnt char in the combustion gases and this would form a subsurface oxide. Diffusion of oxygen from this subsurface oxide layer to and along grain boundaries would occur more rapidly in the higher temperature throat region (Fig. 6(c)). After grain boundary embrittlement, removal of the grains from the surface by the forces associated with the high velocity gas stream would follow as a consequence.

It is worth noting that Harwood [6] has emphasized that grain boundary oxidation is important in the early failure of oxidation-resistant metallic coatings used to protect Mo. In this process the formation of subsurface oxidation products plays an important role in the overall failure mechanism.

Conclusions

(1) Examination of proof fired nozzles of solid propellant rocket motors showed that erosion and subsequent melting had taken place at the corners of the restraining shoulders of both the Mo inserts and the steel bodies. The melted material was identified as an Fe–Mo–C eutectic having a melting point of about 1370 K, which is less than half the melting point of unalloyed Mo.

(2) It is suggested that the initiation of melting occurred by the removal of Fe in a highly divided form from the hot surface of the steel body by the high speed impact of solid char present in the gas stream; this was followed by alloying with Mo from the insert and carbon in the gas stream to form a low melting eutectic alloy. Grooves were then formed on the outside of the insert by liquid metal erosion of the continuously forming eutectic in the gas stream. Molten eutectic was also transported to the insert throat by surface capillary action.

(3) A subsurface layer observed beneath the Fe–Mo–C eutectic in the high temperature throat region was high in oxygen. Further erosion in this region occurred by the rapid diffusion of oxygen along grain boundaries; this reduced the cohesion between the grains and accelerated erosion by allowing easy removal of the grains in the high velocity gas stream.

Acknowledgments

Acknowledgment is made to Mr. A. L. Gunner and Mr. T. V. Rose for the EPMA and metallography, respectively.

References

1 J. H. Neilson and A. Gilchrist, An experimental investigation into aspects of erosion in rocket motor tail nozzles, Wear, 11 (1968) 123.
2 L. Northcott, Molybdenum, Butterworths, London, 1956.
3 J. Watson, Personal communication, 1975.
4 Metals Handbook, Am. Soc. Metals, Metals Park, Ohio, 1948, p. 1253.
5 E. Raash, Tube erosion by ash impaction, Wear, 13 (1969) 315.
6 J. J. Harwood, The protection of molybdenum against high temperature oxidation. In J. J. Harwood (ed.), The Metal Molybdenum, Am. Soc. Metals, Metals Park, Ohio, 1958, p. 453.