Marathon Manufacturing

Attorneys:

Julian Drake

Kelsey Lawson

Expert Witness:

Huy Ho

Overview of Presentation

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- Slides 2-3 — Marathon Manufacturing: Statement Against Negligence
- Slides 4-14 — Drummin Aerospace: Claim & SEM Evidence
- Slides 15-21 — Anticlimax Molybdenum: Claim & SEM/EDS Evidence
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Case Background on the GOTAHAV Aircraft

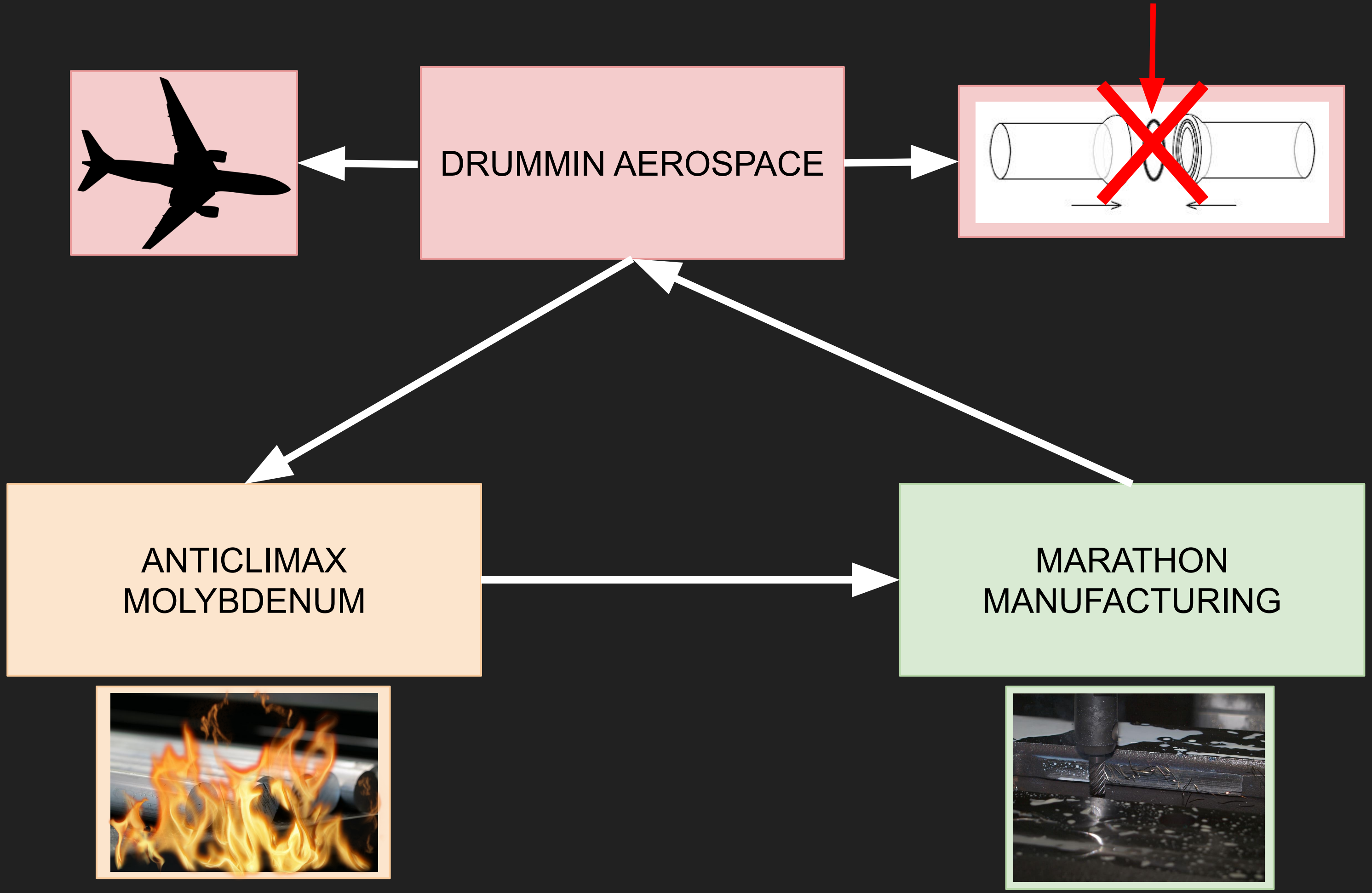
What happened:

- Mr. B. Moore was killed as the civillian test pilot for the first prototype of an experimental hypersonic stealth aircraft designed by engineers at **Drummin Aerospace** named “Global Orbital Tactical Arsenal Hypersonic Aerospace Vehicle” (GOTAHAV).
- The Air Force Investigative Corps (AFIC) investigated the aircraft identifying the primary reason for the killing of Mr. B. Moore is from exhaust bleed seal rings failing during the flight.
- **Drummin Aerospace** hired **Marathon Manufacturing** and **Anticlimax Molybdenum** as subcontractors.

Statement on Behalf of Marathon Manufacturing

Marathon Manufacturing did not contribute to the failure of the seal ring based on negligence that caused Mr. Moore's death.

Comparing our company's involvement with both **Drummin Aerospace** and **Anticlimax Molybdenum**, we can confidently state that our machining schedule for the part did not affect the seal under the extreme conditions experienced during flight, but rather the negligence of design and stress analysis, material choice, and material processing led to the failure of the ring and ultimately, the Mr. B. Moore's death.


DRUMMIN AEROSPACE
ANTICLIMAX MOLYBDENUM
MARATHON MANUFACTURING

Claims Against Drummin Aerospace

Drummin Aerospace

1. **Neglected** that the seal material, TZM, had to be capable of undergoing rapid thermal stresses from -75℃ up to 1260℃ and continued to use it.

2. **Neglected** to use a sufficient analysis of TZM material properties, instead proceeded to only look at the room temperature properties when the material would realistically be exposed higher.

Provided Evidence

Drummin Aerospace: Design & Stress Analysis

DRUMMIN AEROSPACE

DESIGN ANALYSIS

PART: Exhaust Bleed Seal Ring

P/N: ME153-1

PROJECT: GOTAHAV

FUNCTION:

To force the exhaust bleed tubes (EBT) to seal tightly to the exhaust bleed throttle units (EBTU) while the engine is at full power. The EBT's cannot be welded to the EBTU's because the strong thermal transients lead to weld cracking. By placing the exhaust bleed seal ring (EBSR) in the hot exhaust gas, the EBSR reaches a higher temperature than the EBTU, so a radial interference is created by thermal expansion, which achieves the gas-tight seal.

LOADINGS:

1. Hoop compression of the EBSR because of the interference fit at full power.

2. Thermal strains within the EBSR due to temperature gradients after
   a) Idle to full power (I.D. of the EBSR gets hot and goes into compression).
   b) Full power to idle (I.D. of the EBSR cools faster than the rest of the EBSR and goes into tension).

   The stresses and strains will be in the circumferential direction since they are due to a radial temperature gradient.

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DRUMMIN AEROSPACE

STRESS ANALYSIS:

1. Overall Hoop Compression of the EBSR - There should not be any fracture problem in compression. Buckling is a possibility (the ring is partially restrained from buckling by the tab on the EBT) and an adequate tab size to prevent buckling should be determined experimentally by rig testing.

2. Thermal Strains - The DECEL (full power to idle) transient is the worst case because the exhaust gas temperature drops very fast. The rate of metal surface temperature drop will determine the thermal stresses. As an absolute upper bound on the thermal strains, we calculate $\alpha \Delta T_{max}$, where ΔT_{max} is the maximum possible temperature gradient.

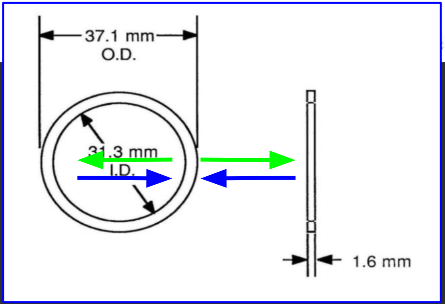
   The upper temperature limit is the steady-state temperature of the EBSR, 1260°C.

   The lower temperature limit is the exhaust temperature at idle (burners off) which is -75°C (ambient temperature) when plane is descending from 70,000 ft. cruising altitude. The high velocity still present due to ram air while the aircraft is descending will also maximize heat transfer and make this the worst case.

   For TZM, $\alpha = 4.9 \times 10^{-6}\ (°C)^{-1}$.

   The maximum possible thermal tensile strain is

   $\alpha \Delta T_{max} = 4.9 \times 10^{-6}\ (°C)^{-1} \times (1260°C-75°C) = 6.54 \times 10^{-3}$



Provided Evidence

Drummin Aerospace: Material Properties

DRUMMIN AEROSPACE

MATERIAL PROPERTIES:

The main property of concern is the tensile ductility. Available data are:

Material	Temperature	Tensile Ductility
TZM	Room Temp.	5-30% (elongation)
Mo	Room Temp.	40-42% (elongation)
Mo	Room Temp.	60-80% (R/A)

Minimum ductility is 5%; actual ductility is probably greater.

DESIGN ADEQUACY:

1. Hoop Compression - Buckling
   Prove by rig test; tentatively OK

2. Thermal Strains
   Maximum possible thermal strains are lower (by an order of magnitude) than minimum ductility; thus thermal strain fracture should not occur.

Certified by: *C. U. Lader*

C. U. Lader
Analytical Engineer

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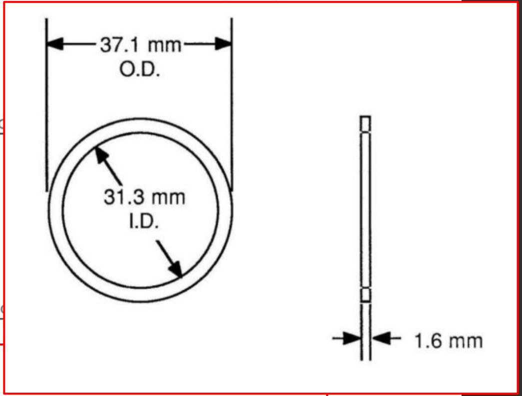
Provided Evidence

Marathon Manufacturing: Machining Schedule in Relation to the Provided Schematic from Drummin Aerospace

Marathon Manufacturing

We may be slow but we do the job right



Customer: Drummin Aero

Project: GOTAHAV

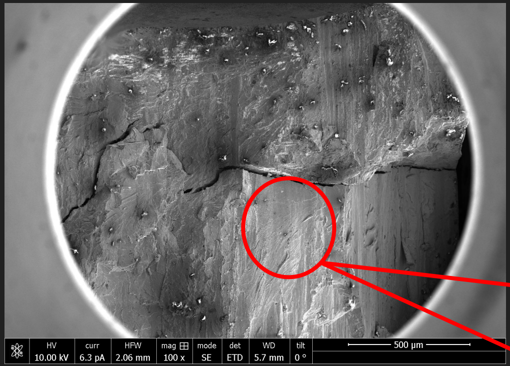
P/N: ME153-1

Material: TZM, Round R

Procedure:

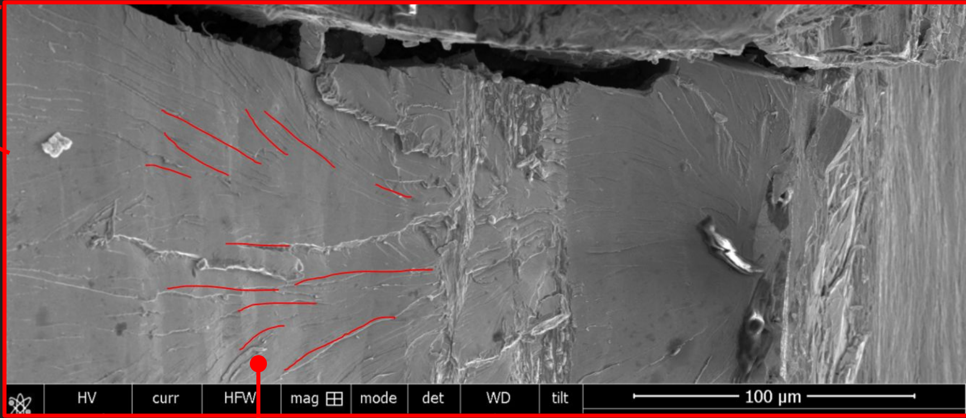
1. Cut to length require for several pieces
2. Turn O.D.
3. Bore out I.D.
4. Cut piece to length
5. Grind sides, I.D., O.D. to size
6. Polish all surfaces

Approved by: Y. U. Frade



SEM Evidence

Drummin Aerospace



Feather Pattern

What is Feather Pattern?

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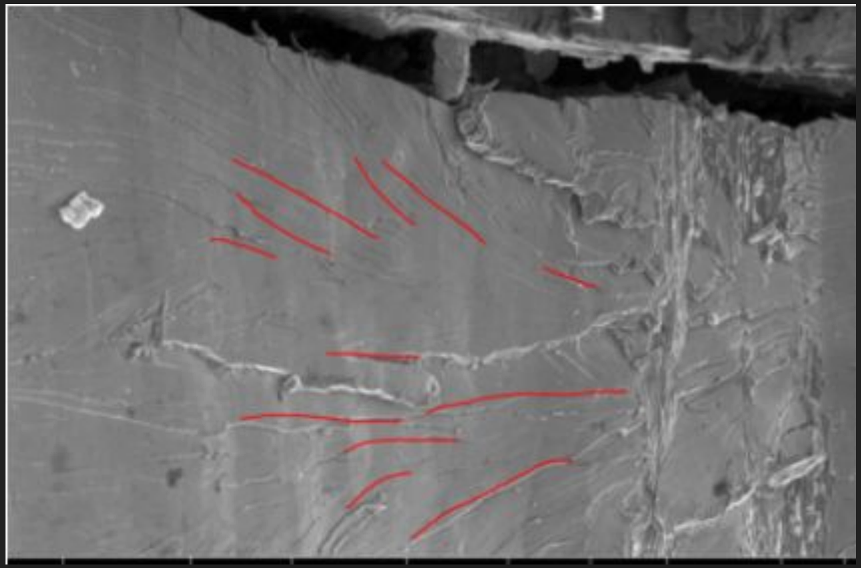
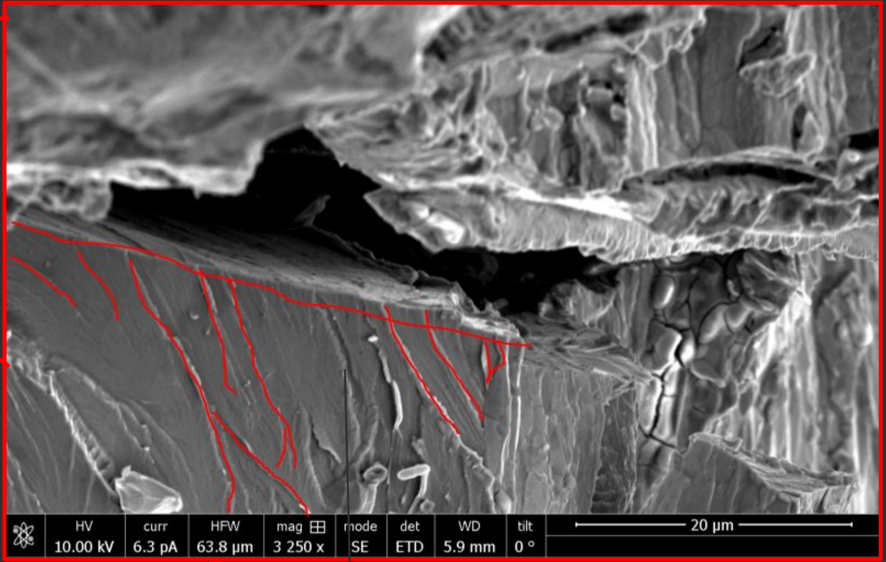


Failure site of the seal ring

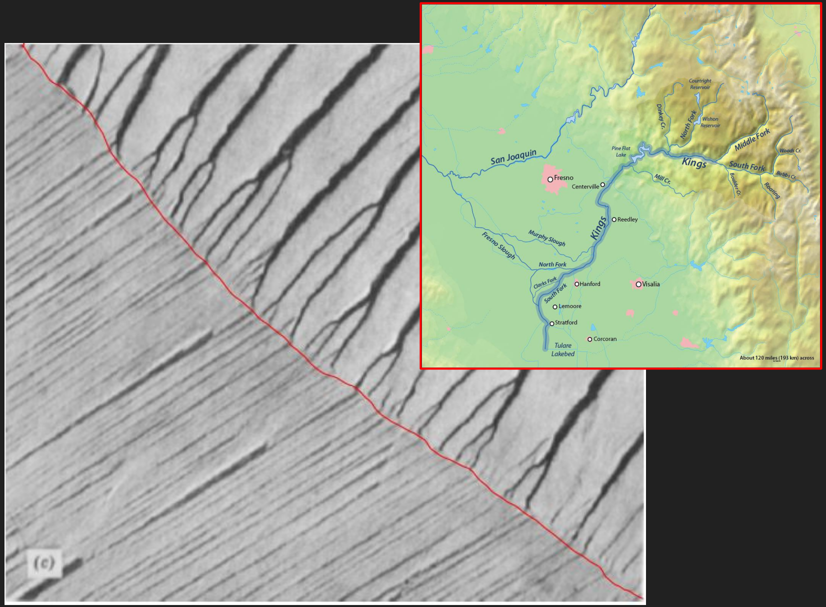
SEM Evidence

Drummin Aerospace



River pattern

What is River Pattern?



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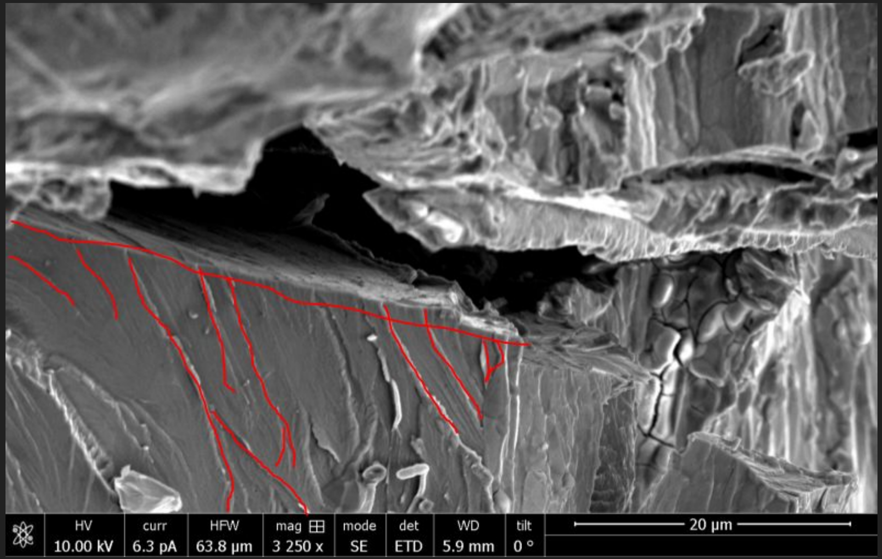

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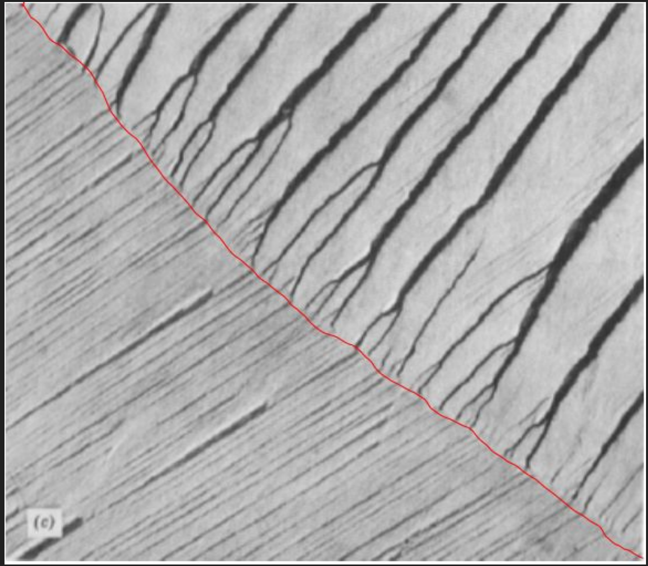

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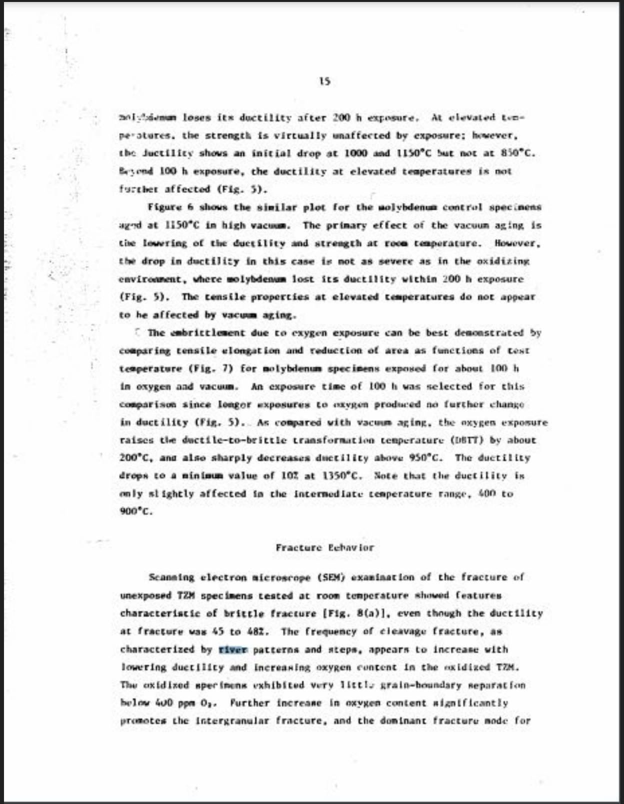

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molybdenum loses its ductility after 200 h exposure. At elevated temperatures, the strength is virtually unaffected by exposure; however, the ductility shows an initial drop at 1000 and 1150°C but not at 850°C. Beyond 100 h exposure, the ductility at elevated temperatures is not further affected (Fig. 5).

Figure 6 shows the similar plot for the molybdenum control specimens aged at 1150°C in high vacuum. The primary effect of the vacuum aging is the lowering of the ductility and strength at room temperature. However, the drop in ductility in this case is not as severe as in the oxidizing environment, where molybdenum lost its ductility within 200 h exposure (Fig. 5). The tensile properties at elevated temperatures do not appear to be affected by vacuum aging.

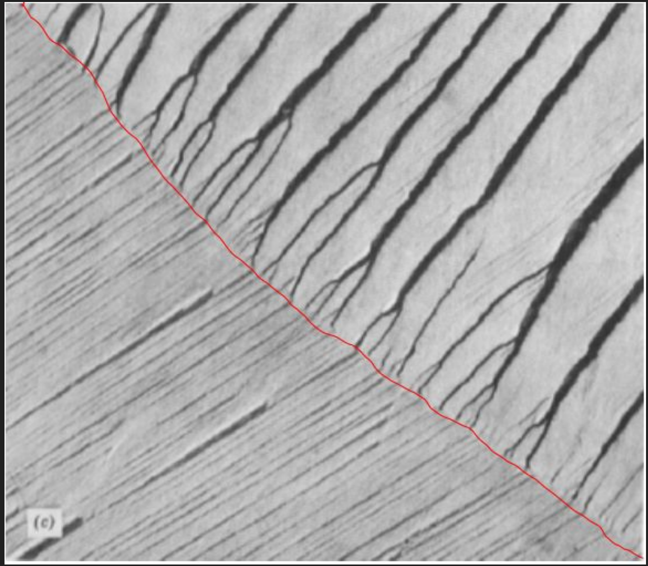
The embrittlement due to oxygen exposure can be best demonstrated by comparing tensile elongation and reduction of area as functions of test temperature (Fig. 7) for molybdenum specimens exposed for about 100 h in oxygen and vacuum. An exposure time of 100 h was selected for this comparison since longer exposures to oxygen produced no further change in ductility (Fig. 5). As compared with vacuum aging, the oxygen exposure raises the ductile-to-brittle transformation temperature (DBTT) by about 200°C, and also sharply decreases ductility above 950°C. The ductility drops to a minimum value of 10% at 1350°C. Note that the ductility is only slightly affected in the intermediate temperature range, 400 to 900°C.

Fracture Behavior

Scanning electron microscope (SEM) examination of the fracture of unexposed TZM specimens tested at room temperature showed features characteristic of brittle fracture [Fig. 8(a)], even though the ductility at fracture was 45 to 48%. The frequency of cleavage fracture, as characterized by river patterns and steps, appears to increase with lowering ductility and increasing oxygen content in the oxidized TZM. The oxidized specimens exhibited very little grain-boundary separation below 400 ppm O_2. Further increase in oxygen content significantly promotes the intergranular fracture, and the dominant fracture mode for

Liu, C., Anderson, S., & Inouye, H. (1978). Effect of oxidizing environment on mechanical properties of molybdenum and tzm. Oak Ridge National Laboratory. doi:10.2172/6580614

What is River Pattern?



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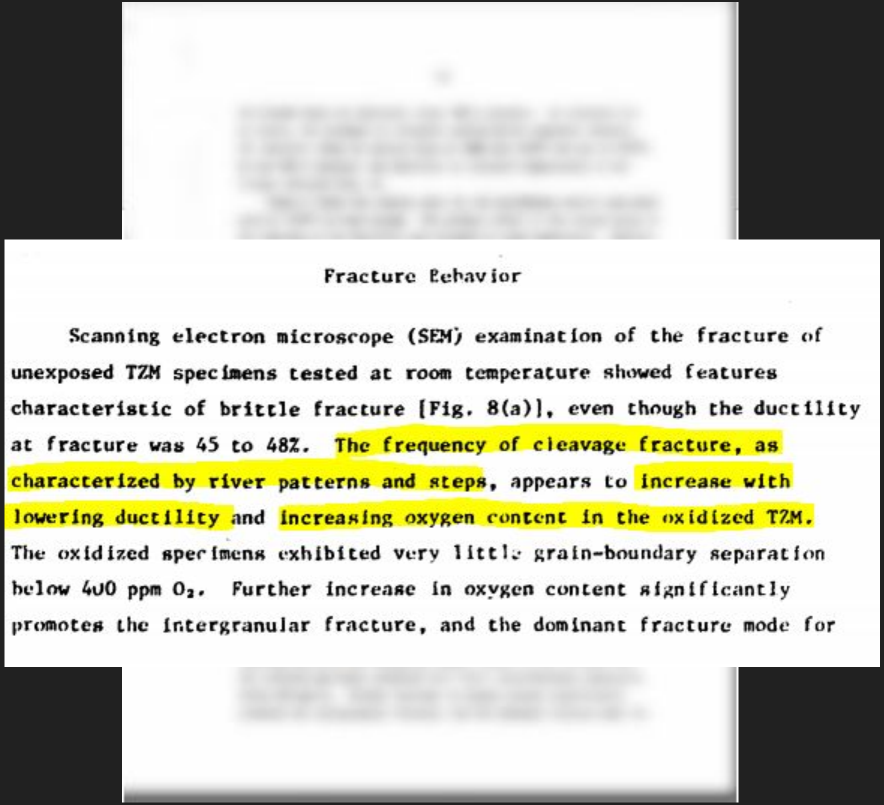

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Claims Against Anticlimax Molybdenum

Anticlimax Molybdenum

1. **Neglected** using the recommended temperatures for thermal processing TZM and continued with higher ranges.

2. **Neglected** the extreme pressure and temperature conditions experienced during flight and tested material at one stagnant temperature (room temperature) and did not attempt to contact Drummin Aerospace to warn them of this error.

Provided Evidence

Anticlimax Molybdenum: Material Processing Schedule

Anticlimax Molybdenum

Material Processing Schedule

Material: TZM Molybdenum Alloy

Size: 44 mm dia. Round Bar

1. Vacuum-arc cast into 250 mm dia. ingot
2. Hot extrude (1150°C) to 108 mm dia. bar
3. Anneal at 1500°C/2hrs.
4. Hot rotary forge (1150°C) to 70 mm dia. bar
5. Stress relieve at 925°C/2hrs.
6. Roll to 44 mm dia. bar
7. Stress relieve at 925°C/2hrs.

Guaranteed Minimum Properties at Room Temperature

Yield Strength = 550 MPa

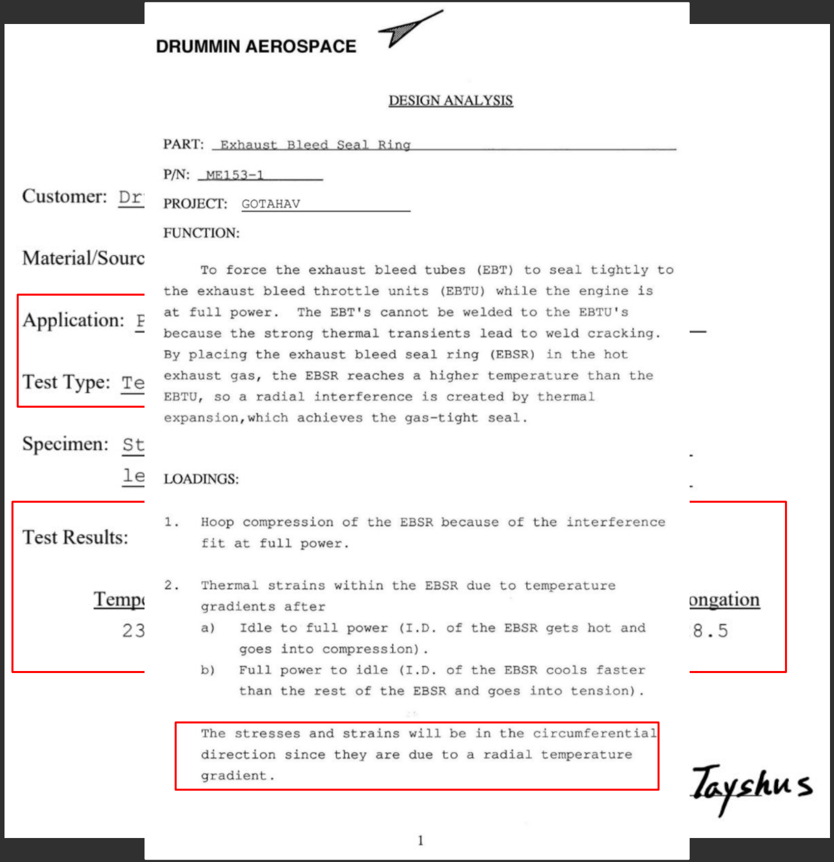
U.T.S. = 600 MPa

% Elongation = 20

Certified by: O. B. Krupt

Provided Evidence

Anticlimax Molybdenum: Material Processing Schedule



DRUMMIN AEROSPACE

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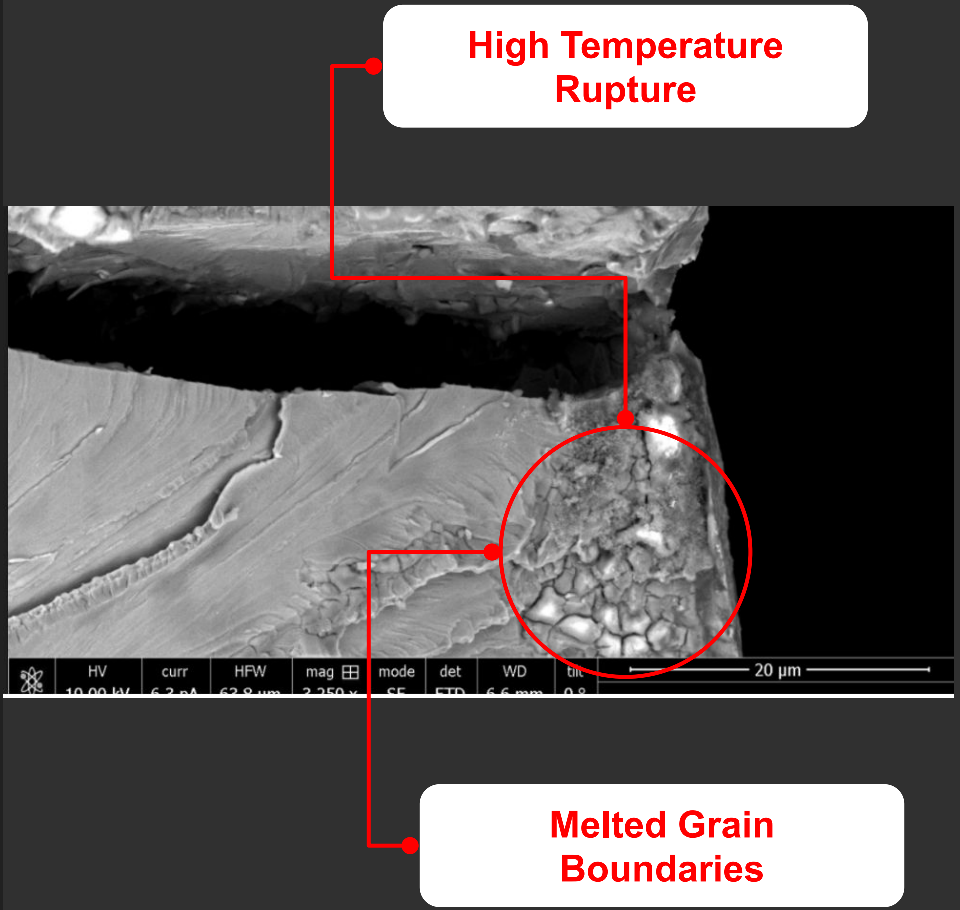
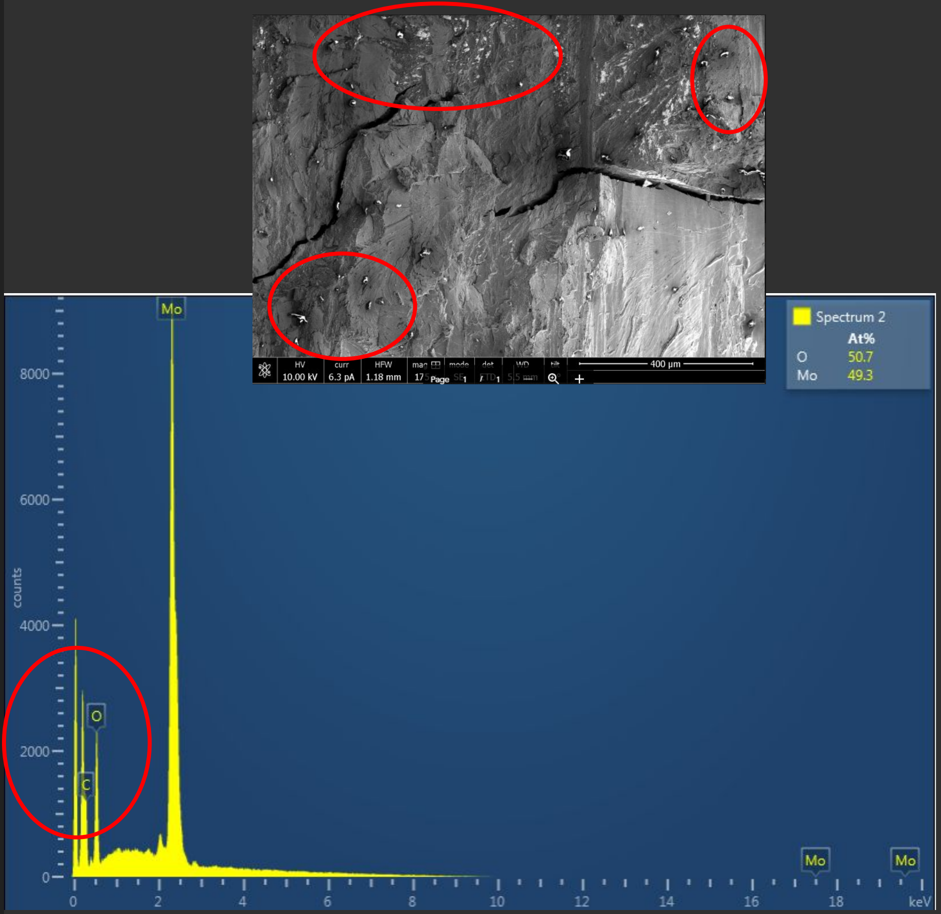
SEM Evidence

Anticlimax Molybdenum



EDS Evidence

Anticlimax Molybdenum



2 μm

(c)

Fig. 4—Scanning electron photomicrographs of the fracture surface of a transversely-oriented tensile-tested Mo sample of 44 mm diameter bar stock. (*a*) The origin of fracture can be traced from cleavage patterns, (*b*) grain boundary (showing subgrain facets) at the origin, and (*c*) fractured carbide-crack stringers at the grain boundary.

4. *Auger electron spectroscopy examination of in situ fracture surfaces*

It has long been recognized that oxygen can severely embrittle Mo by segregation to grain boundaries.[25] The recent work by Kumar and Eyre,[3] briefly discussed earlier, has emphasized this point. In their work, it was shown that carbon is effective in reducing the driving force for oxygen

10 μm

Fig. 5—Scanning electron photomicrographs showing the origin of fracture in a transversely-oriented Mo sample from an extrudate (108 mm diameter). Massive fractured carbide-crack stringers are observed at this grain boundary origin.

segregation to grain boundaries. In this manner, carbon promotes ductile behavior. By varying the amount of carbon (from 0.6 to 320 at. parts per million) with respect to an approximately constant oxygen level (about 6 to 8 at. ppm), Kumar and Eyre[3] showed that at C:O atomic ratios of over about 2:1, oxygen segregation was severely limited during recrystallization or slow cooling from elevated temperatures. Alternatively, they were also able to show that as little as 6 at. ppm of O can totally embrittle Mo grain boundaries if C is very low (*e.g.*, 0.4 at. ppm). In the case of commercial Mo, this atomic ratio of C:O is 4.4:1 if the alloy contains the maximum allowable C and O levels. However, the more typical ratio is greater than this (often about 6:1) although for the cases where O is high and C is low, atomic ratios of as low as 2:1 can be encountered. For the case of TZM the situation is more complicated because of the pres-

Wadsworth, J., Packer, C. M., Chewey, P. M., & Coons, W. C. (1984). A microstructural investigation of the origin of brittle behavior in the TRANSVERSE direction in MO-BASED alloy bars. Metallurgical Transactions A, 15(9), 1741-1752. doi:10.1007/bf02666357

Concluding Remarks

Marathon Manufacturing's machining schedule for the exhaust seal ring did not affect the seal under the extreme conditions experienced during flight because of company neglect.

Both **Drummin Aerospace** and **Anticlimax Molybdenum** neglected the design and stress analysis, material choice, and material processing that led to the failure of the seal ring and ultimately, the Mr. B. Moore's death.

For the justice of Mr. B Moore and his family, both **Drummin Aerospace** and **Anticlimax Molybdenum** should be charged the 75/25 on the basis of neglect.