FAILURE ANALYSIS OF RADIOISOTOPIC HEAT SOURCE
CAPSULES TESTED UNDER MULTI-AXIAL CONDITIONS

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ABSTRACT

In order to qualify small radioisotopic heat sources for a 25-yr design life, multi-axial mechanical tests were performed on the structural components of the heat source. The results of these tests indicated that failure predominantly occurred in the middle of the weld ramp-down zone.

Examination of the failure zone by standard metallographic techniques failed to indicate the true cause of failure. A modified technique utilizing chemical etching, scanning electron microscopy, and energy dispersive x-ray analysis was employed and dramatically indicated the true cause of failure, impurity concentration in the ramp-down zone.

As a result of the initial investigation, weld parameters for the heat sources were altered. Example welds made with a pulse arc technique did not have this impurity buildup in the ramp-down zone.

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INTRODUCTION

Radioisotopic thermal generators (RTGs) are designed as long-term, low-wattage power sources. Thermal energy generated by the alpha decay of the radioisotopic fuel ($^{238}\text{PuO}_2$) is converted to electrical energy by thermoelectric conversion.

Containment of the radioisotopic fuel is a major safety factor associated with the use of the RTG. This containment is achieved by encapsulating the fuel in an assembly consisting of three separately welded components. This final product is called a fueled heat source. A cutaway view of a fueled heat source positioned in an RTG is shown in Figure 1. Figure 2 illustrates the components of the fueled heat source. The liner and strength member components are fabricated from T-111 (Ta-8W-2Hf), and the clad components are fabricated from Hastelloy C (Ni-16Cr-16Mo-5Fe-4W).

The strength member is the main structural component of the fueled heat source, and all safety analyses performed to qualify the heat source system call for the strength member to remain intact.

The design life of the current heat source is 25 yr and during this time helium is being generated by the alpha decay of the $^{238}\text{PuO}_2$ fuel. This gas remains in the closed volume of the strength member, since it is assumed that the inner liner may be compromised sometime during the 25-yr period.

At the end of the 25-yr life of the heat source, an incident can be postulated in which the heat source can be exposed to an elevated temperature (1273 K) for 1 hr. During this thermal excursion, the pressure within the strength member can increase to 37.92 MPa. The strength member must remain integral during this period.

To demonstrate this integrity, a multi-axial mechanical test is performed on typical strength members. The test specimen (Figure 3) is filled with a known volume of helium through the high-pressure tantalum tubing. After the capsule is filled with helium, the fill tube is crimped and welded closed. The crimp fixtures on the tubing not only aid in making the closure weld, but also prevent closure weld failure during the test.

After the fill tube is sealed, the test specimen is heated to 1273 K in a vacuum furnace. This produces internal pressures in excess of 41.37 MPa in the test capsules. The strength member remains on test until failure.

Once the strength member is at test temperature, the helium atmosphere inside the vacuum furnace is monitored with a helium leak detector. During the test, the helium leak rate is normally 2×10^{-8} std. $\text{cm}^3 \text{ sec}^{-1}$. When it increases to a value in excess of 2×10^{-6} std. $\text{cm}^3 \text{ sec}^{-1}$, the test specimen is considered a

failure and an alarm circuit is activated. The circuit stops a test clock and turns off the furnace power.

Although most of the test specimens fail above what would be considered design minimum, the failure zone is rather peculiar. Rather than fail by a random creep failure in the weld-body - heat-affected-zone (HAZ) interface, which should be typical for this design, most capsules failed because a "blow hole" occurred in the ramp-down area of the weld bead. Because of this unusual failure, a study was initiated to try to pinpoint the cause of the "blow hole" failure.

POST-TEST EXAMINATION

Optical microscopy was initially used as the major investigative process. Samples of tested capsules were mounted both perpendicular and parallel to the weld bead. The mounted specimens were then ground toward the point of failure. At various times during this procedure, the specimens were examined in both the as-polished and etched condition. This study did not provide any data which would explain why the failure occurred in approximately the same zone in each tested specimen even though the specimens were examined at the point of failure as well as the regions before and after the point of failure.

The next step in the evaluation process involved the use of the scanning electron microscope (SEM). With this instrument, it was possible to confirm the "blow hole" fracture zone (Figure 4) as well as identify the cause of the peculiar type of failure.

During the SEM examination of as-tested specimens, the ancillary energy dispersive x-ray (EDX) system detected high concentrations of iron in the "blow hole" regions.

In an attempt to identify the source of the iron signal, it was decided to chemically etch the as-tested specimens and examine them after various times in the etchant bath. This technique had previously been successfully applied to identify inclusions present in the as-received T-111 sheet material.

With an etchant consisting of 70% HNO₃ and 30% HF by volume, a material removal rate of 0.15 to 0.20 mm/min was possible. The first specimen underwent a violent localized etching in the failure zone and at several isolated areas in the body HAZ.

SEM examination of this specimen after the initial etch showed that a foreign material was concentrated in the ramp-down zone of the weld (Figure 5 a and b), as well as in the body HAZ (Figure 6). In fact, in every area that had etched violently, a concentration of foreign material was found beneath the original surface. Since it was spherical in shape, this material had evidently been molten, presumably during the weld operation. The impurity was not found

in any area of the weld head other than the ramp-down zone. EDX analysis indicated that the material consisted of iron, silicon, tantalum, and some minor constituents.

Examination of other strength members that failed in the same manner indicated similar impurity concentration in the ramp-down zone. The shape of the inclusions varied somewhat from capsule to capsule (Figures 7 and 8), but the elemental composition remained essentially the same with iron and silicon as the major constituents with tantalum, and trace amounts of molybdenum, copper, and zinc also detected.

DISCUSSION

As stated earlier, the chemical etching/SEM evaluation technique was used to identify the presence of inclusions in the starting T-111 sheet material.

Three basic types of inclusions were found in the starting material (Figures 9, 10, and 11). The inclusions of the type in Figure 9 are primarily iron and silicon, and those in Figures 10 and 11 consist of silicon, iron, molybdenum, copper, zinc, and potassium. The difference between the inclusions in Figures 10 and 11 is their orientation with respect to the rolling direction. The inclusion in Figure 10 lies parallel to the rolling direction, whereas the one in Figure 11 lies perpendicular. The inclusion in Figure 11 extended approximately 0.25 mm into the sheet material.

The distribution of these inclusions was random with only the iron-silicon type (shown in Figure 9) found in clusters.

Once it was established that the inclusions were randomly dispersed throughout the starting material and the composition of the inclusions found in the welded capsule was determined, it was possible to postulate the mechanism by which included material became concentrated in the ramp-down area of the strength member assemblies.

A continuous radial gas-tungsten arc (GTA) weld was used to attach the end cap to the strength member body. During the weld cycle, the molten "weld puddle" picked up all the inclusions in its path. These impurities were transported radially around the weld bead. In the ramp-down zone, the weld area where penetration decreased as power was reduced, the impurities precipitated as a concentrated mass. In each capsule examined, this mass varied in size, physical appearance, and composition. These variables depended upon the number and type of inclusions which were originally present in the weld zone. However, the effect on the mechanical integrity of the strength members was the same. After an initial circumferential crack was formed at the weld/body HAZ at the outset of the test, several crack paths could be initiated, and as soon as

one reached the included zone, it progressed rapidly through the zone and resulted in a linear crack path through the weld. This path terminated in a "blow hole" failure on the outside of the weld bead.

FUTURE WORK

To prevent "blow hole" failures from occurring in the future and possibly increase the life of the strength member, a study was initiated involving a pulse arc welding technique to effect the closure weld. This technique pulses the weld arc through a programmed current range at the rate of two pulses every second. The pulsing should prevent the accumulation of included material in the weld ramp-down area. Another benefit of this type of weld is that the heat-affected zone is minimized.

While no strength member test specimens have been tested yet, several example welds have been made and examined. Some of the immediate benefits derived from this new technique were a more uniform weld bead on the interior of the capsule and a smaller, less-pronounced heat-affected zone.

SEM examination of the weld zones also showed that the included material was randomly dispersed throughout the weld beads and not concentrated in the ramp-down area. Figure 12 shows the interior surface of a typical pulse arc weld bead. Included material is shown frozen to the bead. Approximately 0.18 mm into the weld bead inclusions are randomly dispersed (Figure 13) as they are in the starting material. In fact, several of the inclusions seem to have suffered very little effect from the welding process (Figure 14).

In its ability to prevent a buildup of impurity material in the weld ramp-down zone, the pulse arc weld seems to be successful. Also, it provides a more uniform weld bead and a smaller heat-affected zone. This should result in a strength member that is structurally stronger than those previously tested.

On the basis of this initial examination, it appears that pulse arc welded capsules should be better than those previously tested.

CONCLUSION

This study has shown that inclusions present in the parent material were carried along the weld puddle during normal GTA welding and precipitated out during weld ramp-down. This concentration of impurities provided an easy crack growth path that resulted in "blow hole" failures of strength member capsules being tested under multi-axial test conditions.

In an attempt to eliminate the concentration of impurities in the ramp-down zone, a study involving the use of pulse arc welding has been initiated. An examination of the weld development capsules indicate that the impurity concentration has been eliminated, the interior weld bead is more uniform, and the heat-affected zone is smaller and less distinct. These features should be beneficial to maintaining the integrity of the strength member.

LIST OF ILLUSTRATIONS

- Figure 1: This cutaway view shows the radioisotopically fueled heat source as it is positioned in the RTG.
- Figure 2: The heat source consists of three individual capsules. The strength member is the structural component. The liner acts as a barrier between the fuel and strength member to prevent adverse strength member/fuel reactions. The clad prevents compatibility problems with the strength member and RTG components.
- Figure 3: The multi-axial test specimens are filled with a known volume of helium by means of a fill tube which is welded to the strength member cap. The fill tube is sealed by welding and the crimp fixtures prevent fill tube failure during test.
- Figure 4: The failure of test specimens occurred when the internal volume of helium was lost through these "blow holes" which were located in the center of the weld ramp-down zone.
- Figure 5: The concentration of inclusions located in the weld ramp-down zone provided a path by which a linear crack could proceed through the weld and result in capsule failure. The included material was molten during welding and assumed a spherical shape when it solidified.
- Figure 6: Included material which was present in the capsule body heat-affected zone was also molten during welding and as a consequence assumed a spherical shape on solidifying.
- Figure 7: Included material which was slightly different in composition from that observed in Figure 5 assumed a different shape as it concentrated in the weld ramp-down zone of another tested specimen.
- Figure 8: Material of a third composition assumed a shape completely different from that observed in Figures 5 and 7.
- Figure 9: Included material consisting of only iron and silicon was found in clusters in the starting sheet material.
- Figure 10: Elongated inclusions lying parallel to the rolling direction were also found in the starting sheet material. In addition to iron and silicon, these inclusions also contained tantalum, molybdenum, copper, zinc, and potassium.

- Figure 11: Inclusions located perpendicular to the rolling direction were also found in the starting sheet material. These inclusions had silicon as the major constituent with iron and zinc also present. This particular inclusion extended approximately 0.25 mm into the sheet material.
- Figure 12: Pulse arc welding of the strength members resulted in the freezing of some of the included material on the weld bead surface. This material on the surface of the weld should have no effect on the mechanical integrity of the capsule.
- Figure 13: Approximately 0.18 mm into the pulse arc bead, the included material is still randomly dispersed.
- Figure 14: Some of the included material found in the interior of the pulse arc weld bead still retained an elongated shape similar to that found in the starting material.