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SKYLAB M551 METALS MELTING EXPERIMENT

By R. M. Poorman
Materials and Processes Laboratory

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16. ABSTRACT

The objectives of the M551 Metals Melting Experiment were to (a) study behavior of molten metal, (b) characterize metals melted and solidified in the low gravity space environment compared to one-gravity of earth, and (c) determine feasibility of joining metals in space. The experiment used the electron beam (EB) and chamber of the M512 apparatus to make a dwell puddle and a melt in a rotating disc of varying thickness. Hence, the EB performed cut-through, full and partial penetration melts, in addition to a resolidified button. The three disc materials were aluminum 2219-T87, 304 stainless steel, and pure tantalum to provide a wide range of density and melting conditions. Observations to date include the proof that EB welding, cutting, and melting can be done successfully in low gravity. Earlier, some welding authorities had postulated that without gravity the EB would force the molten puddle out of contact. However, the experiment proved that surface tension forces predominate. From the viewpoint of cast-solidification, small, equiaxed grains in Skylab specimens compared to large, elongated grains in ground-based specimens were observed. The former are thought to be associated with constitutional supercooling and nucleation where the latter are associated with dendritic solidification. In further support of the more equiaxed grain growth in Skylab, symmetric subgrain patterns were frequently observed where there was much less symmetry in ground-based specimens.

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SKYLAB M551 METALS MELTING EXPERIMENT

INTRODUCTION

The M551 Skylab Metals Melting Experiment evolved from an earlier plan for a welding experiment. It was changed and broadened to include melting and solidification of practical metals as speculation about the effect of low gravity on these phenomena increased. In this report the status, background, and history of that development, the final objectives, M512 electron beam apparatus and procedures used in ground studies, aircraft and Skylab are discussed. Emphasis is placed on evaluation of results including a macroview of the welding implications and a micro-structural view of the metallography of solidification in Skylab versus earth-bound experiments.

OBJECTIVES

The objectives of the M551 Metals Melting Experiment were to (a) study behavior of molten metal in low gravity with particular attention to the stability of the molten puddle and its interface with the solidified metal; (b) characterize metals solidified in low gravity with regard to grain size, orientation, and subgrain patterns that may be caused by the difference in convection during solidification; and (c) determine feasibility of joining and casting metals in space.

HISTORY

The M551 Metals Melting Experiment evolved from several closely related lines of study and development work. Its original motiviation came from studies performed in the early 1960's on methods of assembling structures in space. During that period it was expected that construction and maintenance of large orbital space stations would involve assembly of structural members in space, and the consensus of several studies was that electron beam welding would be the best process for performing the necessary joining operations.

Development work on compact electron beam welders was initiated by Marshall Space Flight Center (MSFC) in 1963, and an electron beam welding experiment was proposed for the S-IVB Workshop in the fall of 1964. A portable welder was developed by the Westinghouse Electric Corporation for weld repair, limited weld fabrication, and melting. The experiment was formally approved by the Manned Space Flight Experiments Board (MSFEB) in December 1966, as the M493 Electron Beam Welding experiment.

At about the same time, MSFC began to explore the prospects for possible space materials manufacturing of products for use on Earth. Considerable interest was developed in the idea through contacts with industrial firms and studies performed in-house while development work on the experiment proceeded. As a result of this interest, it was suggested in 1968 that the capabilities of the apparatus should be exploited to perform some preliminary space materials experiments.

Concepts for additional manufacturing experiments were studied, and at the same time the M493 experiment was reassessed to determine its applicability to the new space materials manufacturing discipline. The outcome of these studies was a proposal of concepts for experiments to be performed in a modified version of the M493 apparatus. The concepts included a revision of the original welding experiment to pursue more general objectives under the title, Metals Melting.

Ballistic Trajectory Aircraft

During June and July 1972, three flights were made in an Air Force KC-135 aircraft flying ballistic trajectories to achieve low gravity for a brief period. The M512 apparatus was mounted and specimens were installed to simulate operations in Skylab, albeit for 15-25 seconds only, at a time. While these flights were essential for developing and checking procedures and proving the operation of equipment, they did not provide enough time at low gravity to obtain a complete cycle of melting and solidifying before the aircraft pulled out of the low gravity trajectory and into a high gravity condition. Hence we were not able to make useful metallographic studies of low gravity solidification from this phase of the program.

EQUIPMENT DESCRIPTION

The M551 experiment was performed June 1973 on Skylab I in the M512 Materials Processing Facility. It provided a basic apparatus and a common Saturn Workshop interface for a group of metallic and nonmetallic materials experiments. The facility (Fig. 1) is integrated into the docking adapter and

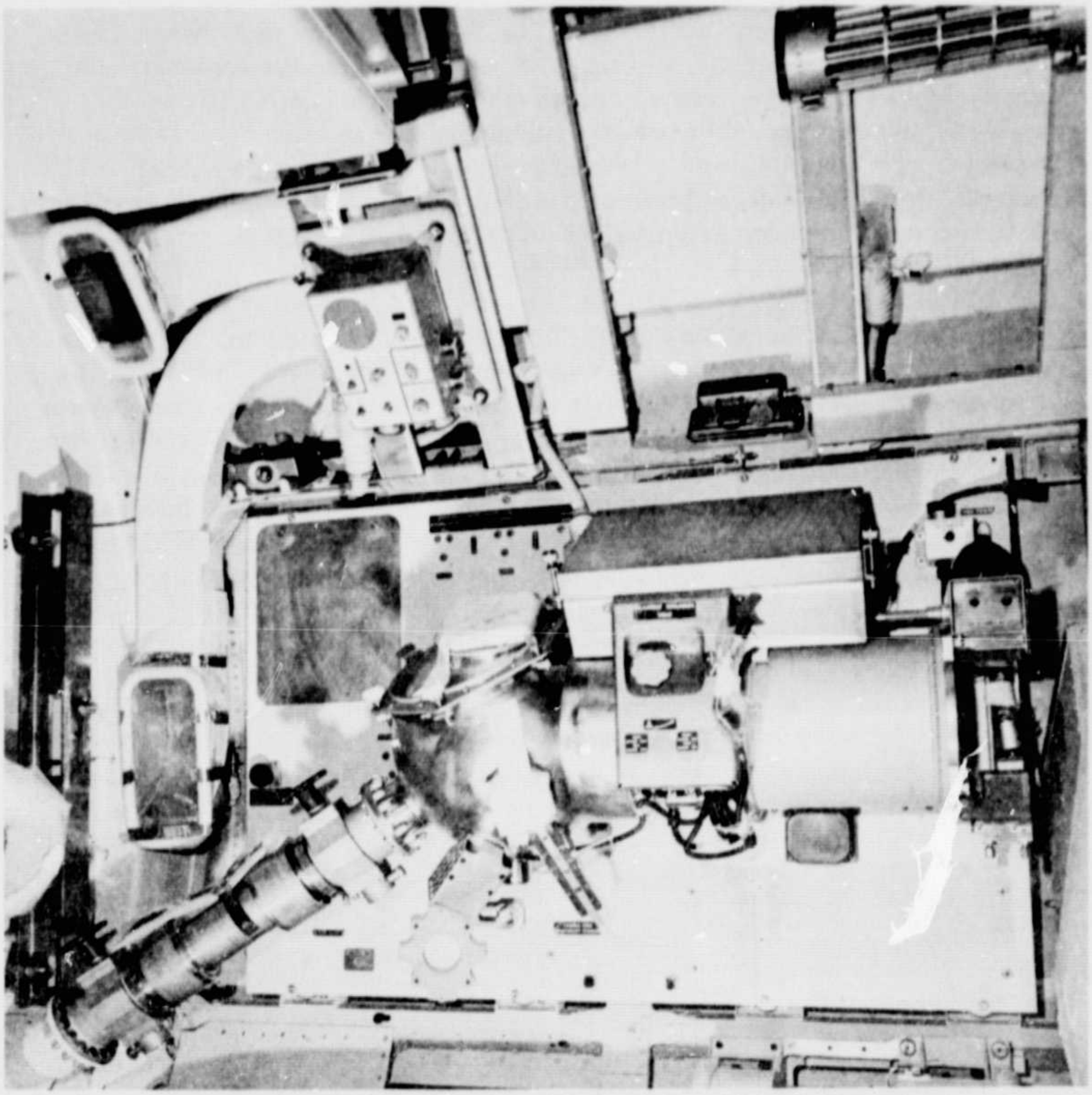

Figure 1. Materials processing in space facility installed in docking adapter.

consists of a vacuum work chamber with associated mechanical and electrical controls. The vacuum chamber is a 40 cm sphere with a hinged access hatch. It is connected to the space environment by a 102-mm diameter, 1-m-long line containing two manual valves in series. The chamber contains an electron beam subsystem which operates normally at 20 kV and 80 mA. It has focusing and deflection coils that are operated from the control panel. Electric power for the electron beam and exothermic experiments is supplied by a self-contained battery. Other experiments performed in the facility obtain their power from the laboratory power system. A cylindrical well accommodates a small electric furnace used in another series of experiments. A mounting fixture is incorporated to accommodate each experiment module in turn. The fixture also doubles as a heat sink with a predetermined and calibrated thermal impedance. Ports for a floodlight, a 16-mm data acquisition camera, a vacuum cleaner, and a water spray are provided in the work chamber.

The control panel (Fig. 2) contains the gages to monitor the pressure in the chamber, the voltage and current of the electron beam gun, and certain temperatures. In addition, switches and potentiometers located here operate and control the individual experiments except the multipurpose electric furnace series. This series was approved late in the program (June 1972) and has its own controls. It uses the work chamber only as a location and vacuum source for its furnace. The facility has electrical, mechanical, and other integration interfaces with the docking adapter. Beyond this, it is a self-contained facility for the crewmen to use to perform the different materials processing experiments.

The facility was operated during all three manned periods. The Metals Melting, Exothermic Brazing, and Sphere Forming experiments were performed during the first period; the multipurpose electric furnace series of experiments was performed during the second and third; and the zero gravity flammability experiment was performed during the third.

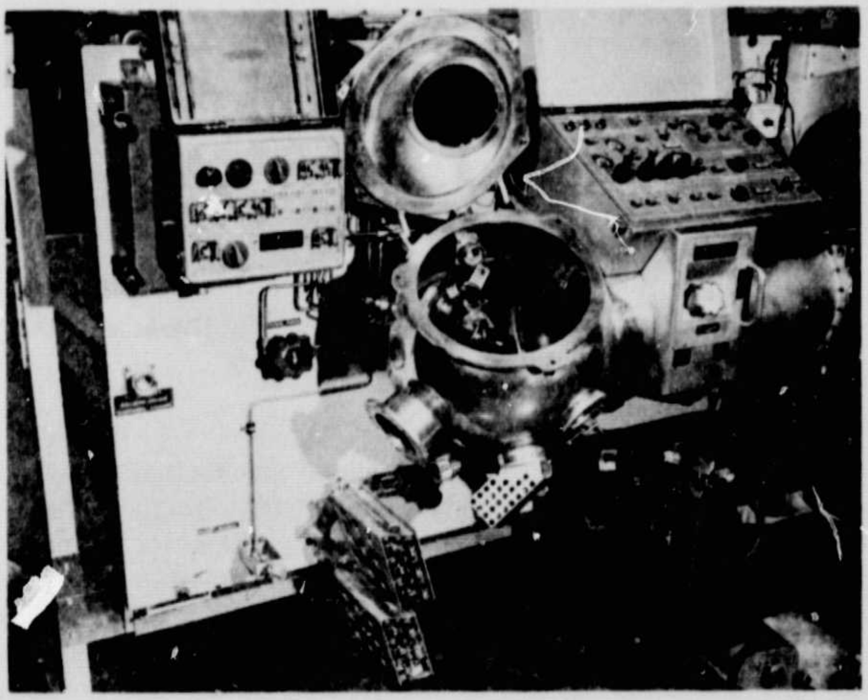

Figure 2. Materials processing in space facility components.

The basic equipment used for the Metals Melting experiment is shown in Figure 3; it consists of an electric motor drive mechanism which is attached to a three-legged mounting base and carries the disc-shaped experiment specimens as shown. The motor is a nominal 24 V 1760 rpm dc motor, and the gear reduction in the drive mechanism is 300:1; in order to arrive at the output shaft speed of 2.6 rpm required for the experiment, the motor armature speed is reduced by running at an actual input voltage of only 12 V. Power for the motor is supplied through the cable connector shown on the end of the assembly. The melting path to be traversed by the electron beam is visible along the junction between the specimen's inner disc and outer ring.

Figure 4 is a sectional scale drawing of the M512 facility's work chamber with the Metals Melting fixture mounted in it. In this drawing the electron beam port is directly behind the specimen, and the beam direction is perpendicular to the plane of the figure. The sample is mounted at a distance of 38 mm from the beam port.

The mounting base of the fixture is attached by captive screws at three points around the opening of the heat sink well in the side of the work chamber. Electric power is led from the zero-g connector at the top of the chamber by a cable to the motor and is controlled by a switch on the facility's control panel. The same switch initiates photographic recording by the sequencing camera during runs of the experiment.

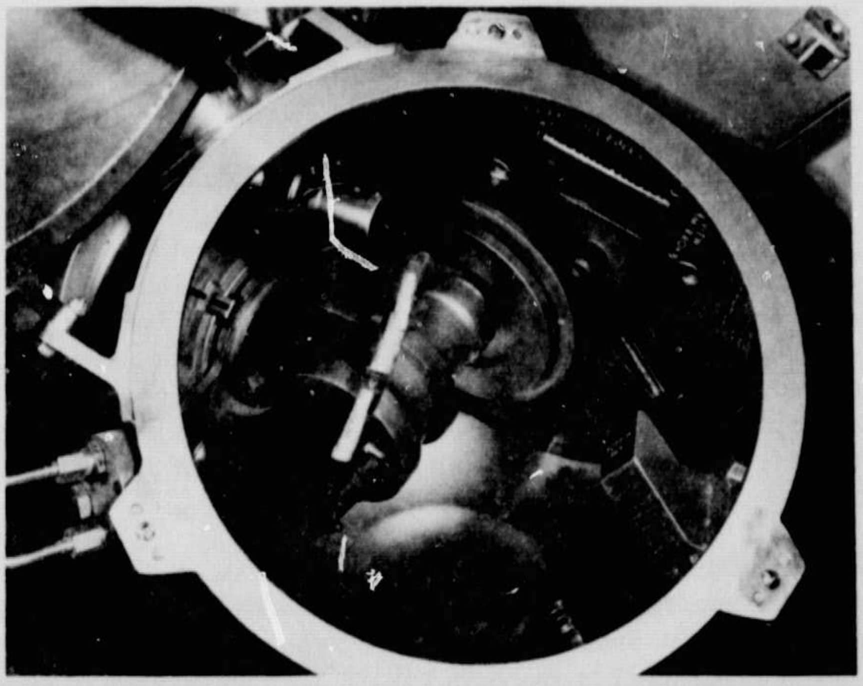

Figure 3. Metals Melting experiment installed in work chamber.

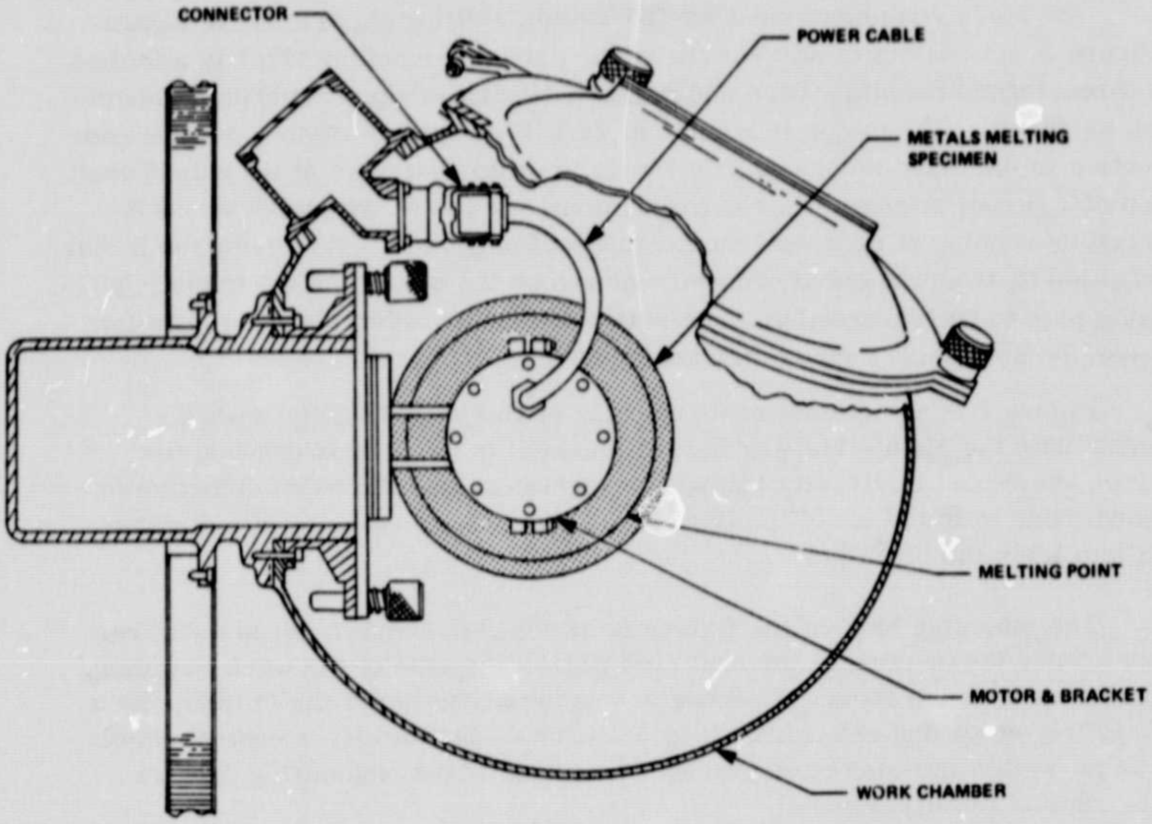

Figure 4. Installation of Metals Melting assembly in Skylab.

The work chamber' s camera port is in the lower hemisphere, and inside the chamber it is covered by an aluminum housing containing a diagonal mirror. A second mirror is just above the port, mounted in a recess in the flange surrounding the electron beam port, which is at the upper right inside the chamber. These two mirrors reflect the image of the beam impingement area on the specimen to the camera mounted outside the chamber. A third mirror mounted above the electron beam port permits the operator to view the face of the sample through the viewport in the cover of the working chamber. Light for this is provided by a small lamp in the recess to the left of the electron beam port.

The disc mounted on the drive mechanism is one of the specimens. The sample thickness required for the experiment is provided by milling channels to different depths in the back of the plate. A schematic drawing of the specimen used in the experiment is shown in Figure 5. Photographs of an actual specimen are shown in Figures 6 and 7. Materials are listed in Table 1.

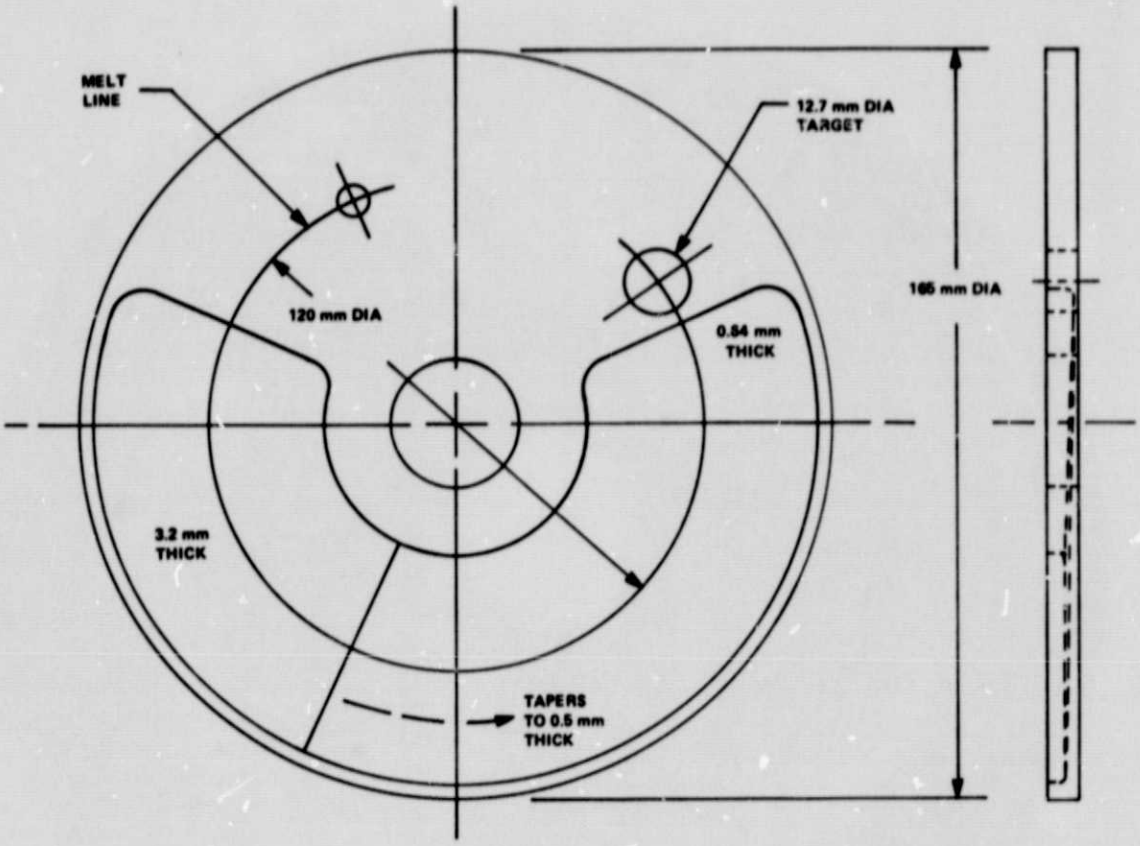

Figure 5. Metals Melting specimen.

PROCEDURES

Three discs of varying thicknesses were processed in space by the electron beam welder: The first was 304 type stainless steel, the second 2219-T87 aluminum, and the third pure tantalum. Singularly, each disc was placed in a work chamber, and the work chamber was vented overboard to space vacuum conditions. The electron beam was initiated in sharp focus on the target area of the disc, and the beam was adjusted and held at 80 mA and 20 kV. Each disc was then rotated to provide 89 cm/min travel speed on an 120 mm diameter. The specimens were designed with a thin section as the travel started. This provided a cutting action by the beam for 45 deg of rotation. Here, the thickness gradually increased over 90 deg of rotation to a value which provided a normal penetration of the electron beam weld. After 90 deg more

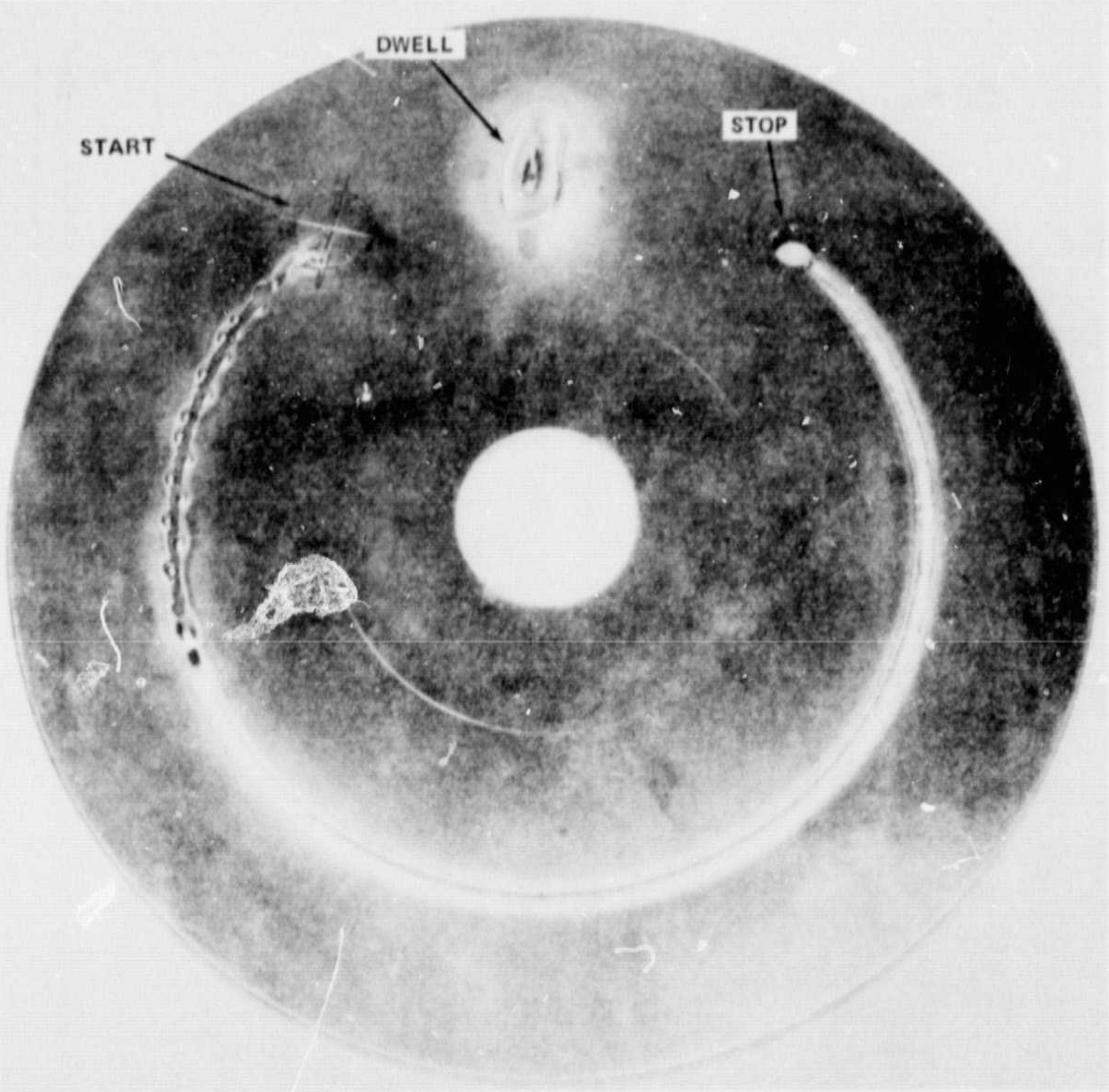

Figure 6. Skylab 304 stainless steel sample S/N 106 (front).

of rotation the thickness step increased to provide a partial penetration melt for 45 deg. Here, at a 6.4-mm-diameter hole, the beam was terminated. The disc was rotated another 22 deg and was stopped at the dwell area. The electron beam was defocused and reinitiated for the dwell portion of the test. On the stainless steel and aluminum discs, dwell times were 15 sec, while the dwell on the tantalum disc was 45 sec. Thus, a large molten pool formed and solidified.

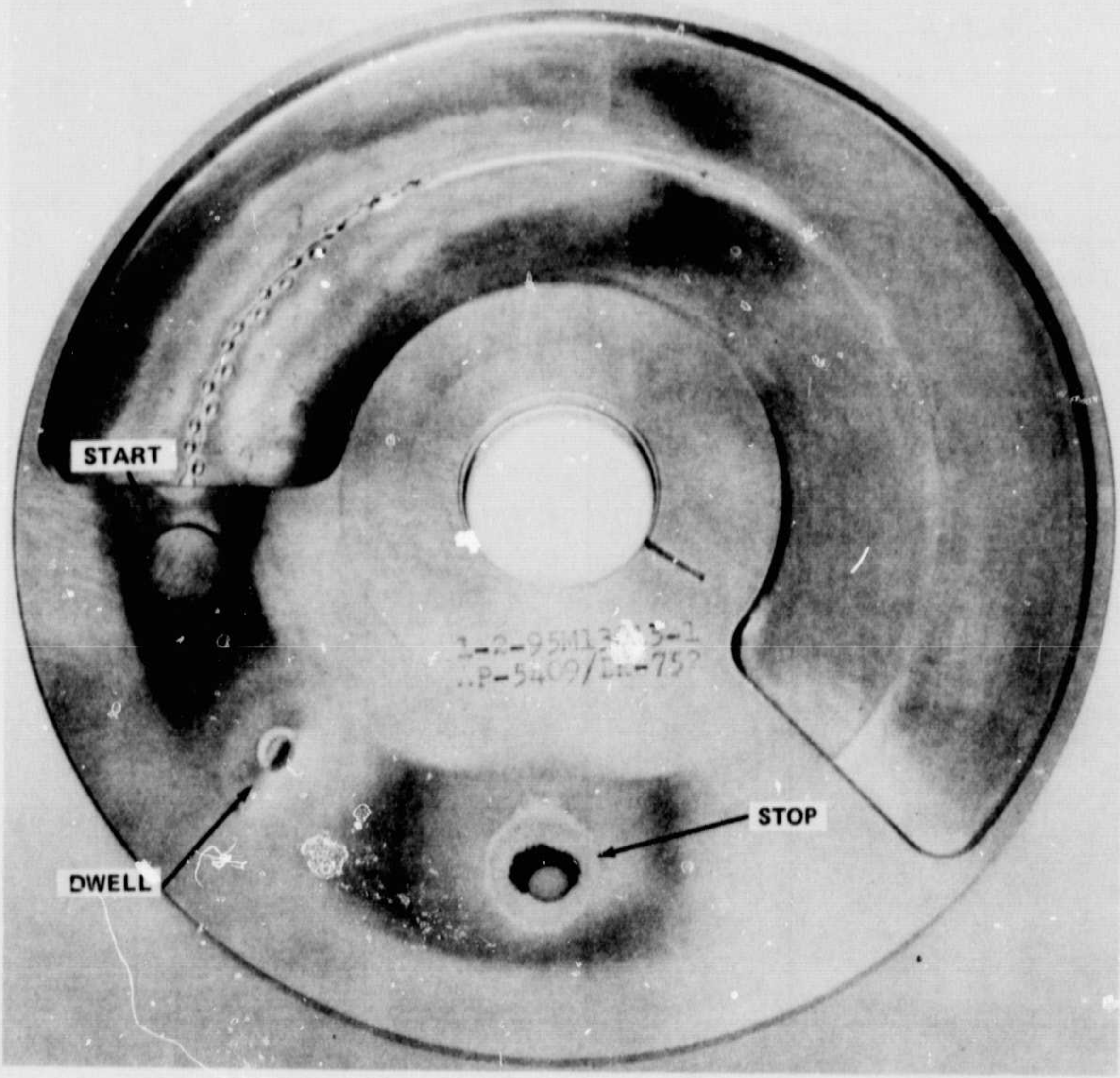

Figure 7. Skylab 304 stainless steel sample S/N 106 (rear).

All discs were processed the same except that the tantalum melt used 70 mA beam current. Thickness on the stainless steel and aluminum ranged from 0.64 to 6.4 mm. The tantalum values were 0.43 to 1.57 mm.

TABLE 1. MATERIALS USED IN EXPERIMENT M551 METALS MELTING

Identification	Aluminum 2219-T87		Stainless Steel 304		Com. Pure Tantalum	
Density, g/cc		2.83		8.03		26.6
Melting Point, °C		638		1442		2996
Thermal Conductivity cal/cm/sec/°C		0.6		0.38		0.13
Composition, %	Cu	6.2	C	0.05	Ta	99.5
	Mn	0.3	Mn	1.5	Cb	0.1
	Ti	0.15	Si	0.75		
	Mg	0.02	P	0.04		
	Fe	0.25	S	0.03		
	Si	0.15	Cr	19.0		
	Zn	0.10	Ni	8.5		
	Al	bal	Mo	0.5		
			Cu	0.5		
			Fe	bal		

With each specimen the work chamber was vented overboard for 2 hours and, even so, the vacuum level during melting was only approximately 10^{-4} torr. Astronaut Pete Conrad performed the following steps in accomplishing the M551 Experiment:

a. Verify and check the M512 control panel.

b. Mount the first metals melting sample in the M512 vacuum chamber.

c. Establish vacuum.

d. Perform the melt cycle and make motion pictures at 24 f/ sec of the traversing beam.

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	Ti	0.15	Si	0.75		
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	Fe	0.25	S	0.03		
	Si	0.15	Cr	19.0		
	Zn	0.10	Ni	8.5		
	Al	bal	Mo	0.5		
			Cu	0.5		
			Fe	bal		

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d. Perform the melt cycle and make motion pictures at 24 f/ sec of the traversing beam.

e. Allow sample to cool (approximately 2.5 hours).

f. Pressure equalize the M512 vacuum chamber.

g. Remove and stow the Metals Melting sample.

h. Repeat steps b through g for the remaining two Metals Melting samples.

During the Metals Melting experiment the vacuum conditions in the work chamber were reported as abnormal by the astronauts. Close examination of all flight data indicated vacuum sequencing was normal. The absolute pressure in the work chamber was somewhat higher than expected but within the normal operating limits of the experiment. The absolute pressure outside the Skylab was somewhat higher than expected. Hence, work chamber vent time to vacuum was greater than expected.

An extensive review of vacuum pressures and vent time by the Astronautics Laboratory at MSFC shows all pressures and systems were normal. Values were within our operating range. No anomalies are believed to be related to the vacuum systems in the metals melting facility M512.

CHARACTERIZATION PLAN

After receiving specimens, both ground-based and Skylab flight, personnel at MSFC photographed them for identification, measured distortions, and weighed each one of them. R. E. Monroe at Battelle Memorial Institute radiographed, sectioned, and sent designated pieces back to MSFC and others. Both groups did metallographic analyses and provided data to the researchers for their analyses (Table 2). At this time MSFC is still involved in discussions of the implications of the microstructures presented here. The differences in interpretation, particularly with regard to the evidence of probable types and levels of convection, indicate that there is still much to be done to recap the full benefit of the experimental evidence from Skylab.

The data packages included ground-base data, flight and ground-base film of M551 experimental sequence, and flight data. Members of the consultant team have been in constant contact with each other for experiment definition, plan, and data analysis.

TABLE 2. M551 METALS MELTING TEAM

Name	Affiliation	Specialty
Mr. Robert Monroe	Battelle Memorial Institute	Joining Research-Metals
Prof. C. M. Adams, Jr.	University of Wisconsin	Joining Research-Metals
Prof. Koichi Masubuchi	Massachusetts Institute of Technology	Stress Analysis & Thermal Treatment
Dr. Martin Tobin	Westinghouse	Surface Tension
Dr. Philamina Grodzka	Lockheed-Huntsville	Solidification & Convection Physics
Dr. M. R. Brashears	Lockheed-Huntsville	Solidification & Convection Physics
Dr. S. V. Bourgeois, Jr.	Lockheed-Huntsville	Solidification & Convection Physics
Dr. A. A. Smith	British Welding Institute, England	Joining Research-Metals Physical Testing

MELTING ANALYSIS – A MACROVIEW

Gravity effects appear to be small in the weld nugget configuration and puddle control of all three materials when related to typical welding problems. In all cases there was greater puddle sagging in the ground-base specimen with one gravity compared to the Skylab specimen with low gravity. This was particularly true for the melt dwell periods of 15 and 45 sec. In the over, full, and partial penetration phases, puddle sag was very slight. Frequency of surface ripple, beading and melt spatter appeared to be somewhat related to gravity. All three were slightly reduced in the Skylab specimens which were melted in low gravity. These parameters are of more interest to a scientific study of solidification than to the practical aspects of welding. Basically, this experiment indicates that molten metal surface tension is the predominant force controlling the melt puddle. In low gravity the melt nugget is more symmetrical. All weld puddling and control techniques that are applicable on Earth would be expected to be useful in welding in a space environment. Hence, this experiment has demonstrated the feasibility of welding in space. This subject is developed in detail in a report by R. E. Monroe of Battelle Memorial Institute [1].

METALLOGRAPHIC ANALYSIS OF MICROSTRUCTURE

A typical cross section, magnified 10 and 100 times, of the aluminum 2219-T87 partial penetration melt is shown in Figure 8. The ground-base melt shows the familiar large grains often seen in weldments and castings with columnar grain growth oriented perpendicular to the solidification front. It also shows heavy banding, the fine, equiax-grained chill zone and the grain growth of the unmelted, heat-affected zone. The large, elongated grains are explained on the basis of dendritic freezing and the finer-grained chill zone is described on the basis of greater super cooling (temperature differential), as described by Chalmers [2] and Reed-Hill [3].

By contrast the Skylab specimen which was solidified in low gravity under otherwise identical conditions shows a major reduction in large, elongated grains; an increased width of the finer-grained chill zone; and almost no banding. This can be explained if there was, as predicted, a reduction in thermal convection which is accompained by a greater temperature differential at the solidifying interface. In addition, the reduced convection would provide less mixing and greater constitutional super cooling which would produce nucleation of many more but smaller grains of varying composition. Constitutional super cooling results when a solid freezes with a composition different from that of the liquid from which it forms [3]. Instability of the freezing interface results in subgrain microsegregation which breaks up the banding seen in the ground-base specimen. Hence, there are differences in the solidified microstructure between one and low (10^{-4}) gravity which may have important implications for obtaining finer-grained castings in space.

Figure 9 shows a cross section (100X) of the solidified aluminum in the full penetration area of the specimen. It clearly shows the differences in the subgrain microsegregation between the ground-base and Skylab specimens. A symmetrical, rosette pattern in the Skylab specimen indicates the lack of a

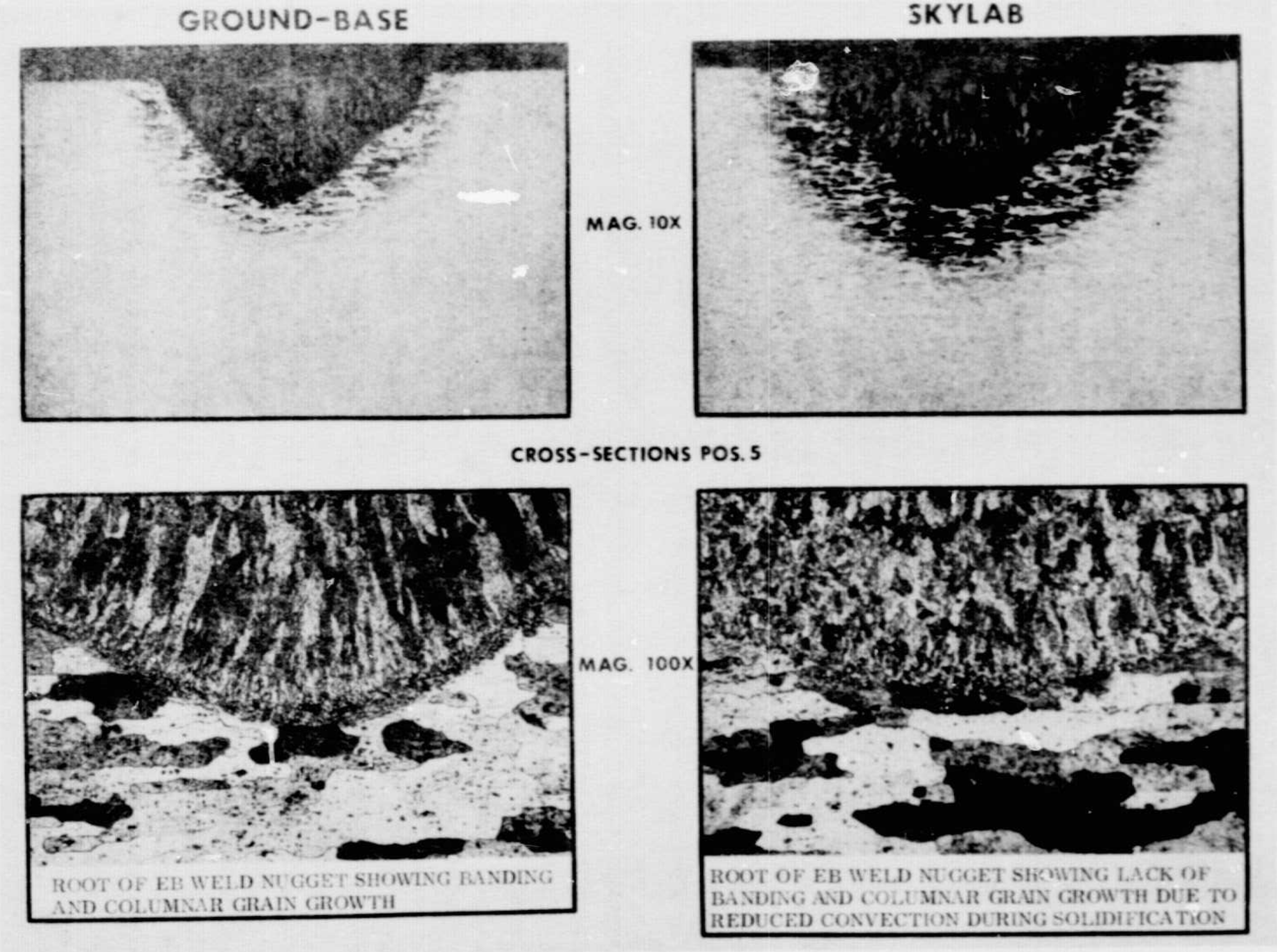

Figure 8. Comparison of ground-base and Skylab EB melts in 2219-T87 aluminum (photographically reduced 12 percent for publication).

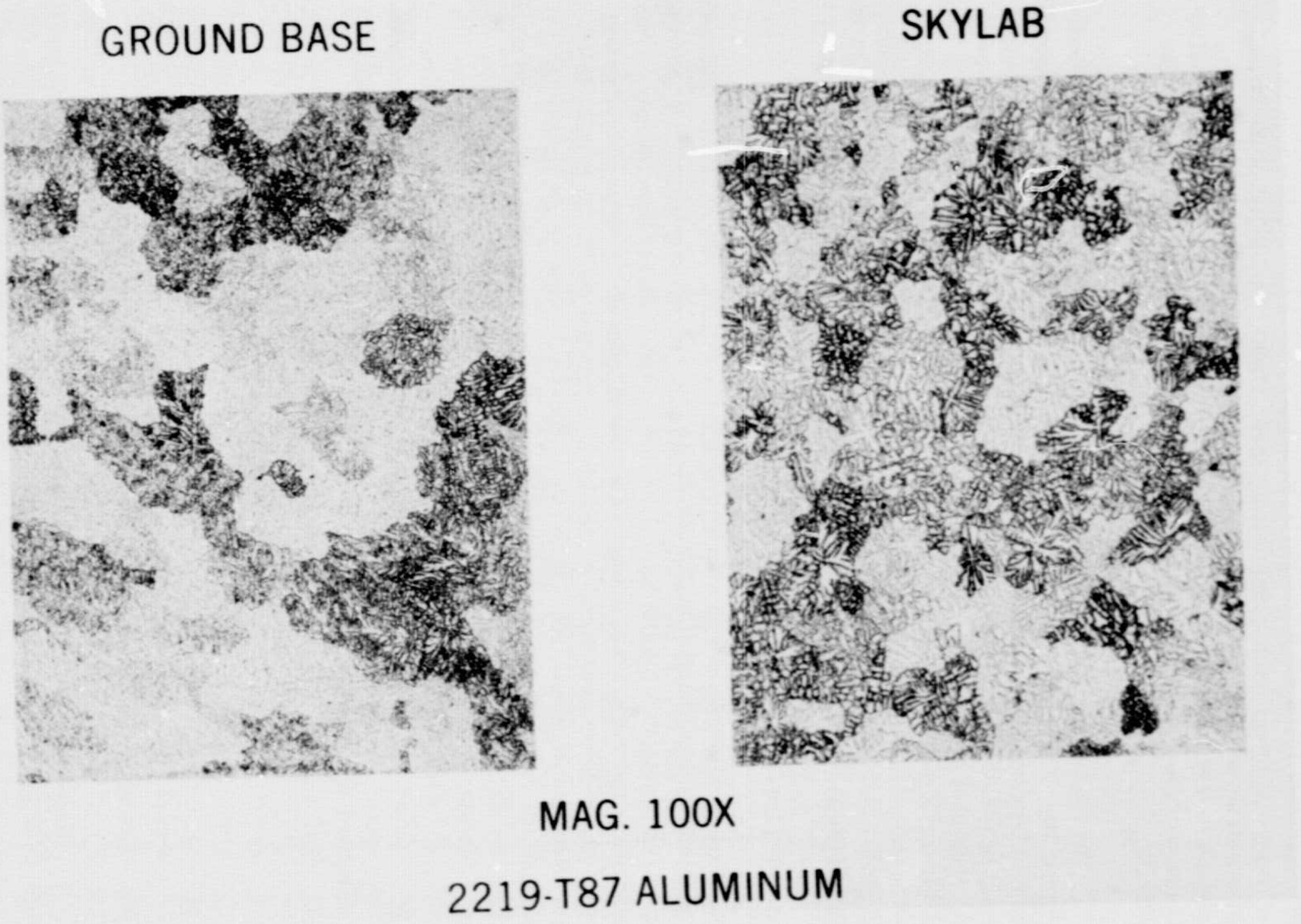

Figure 9. Cast structures in ground-base versus Skylab fusion zones.

directed gravity force when compared to the ground-base specimen in which there is an alignment from upper left to lower right. The more pronounced subgrain structure in the Skylab specimen obtained by an identical etching procedure to that used on the ground-base specimen is another possible indication of increased microsegregation and constitutional super cooling in low gravity.

The partial penetration molten area of the 304 stainless steel is shown in Figure 10. The molten zone is narrower and the interface is sharper than the aluminum because of the lower thermal conductivity. The shape of the spike is a result of the electron beam power profile and beam focus; it is a single-pass weld. The root of the spike is an interesting place to study solidification phenomena. As in the aluminum, large elongated grains perpendicular to the solidification front can be seen in the ground-base specimen compared to the finer grains of the Skylab specimen which solidified at a low gravity. The bands of segregations which are interrupted by some grains appear to have occurred after solidification. These bands are being subjected to further study by microprobe analysis of composition and phase.

Figure 11 shows a cross section and a top view (10X) of a pure tantalum full penetration melt. Being a commercially pure metal with almost no alloying except minor amounts of columbium, there were no complex precipitants during solidification and very large, clean grains were formed. The most interesting observation from the ground-base specimen is that the residual vortices left behind after the electron beam passed were frozen into the grain structure. These occurred because of the rapid cooling rate at the high melting temperature. Although the thermal characteristics and travel speeds were comparable for the Skylab specimens, the residual vortices were erased in the grain structure. This may have been due to the fact that final grain size of the solidified material was smaller in the Skylab specimen compared to the ground-base specimen. The finer grains in the Skylab specimen were observed in all three materials with a wide range of properties.

CONCLUSIONS

1. This experiment demonstrated the feasibility of doing electron beam welding, cutting, and melting in the low-gravity environment of space.

2. Welding in space will not be a major problem related to molten metal behavior or puddle control.

3. Puddle control techniques on Earth should be readily adapted to space environment.

4. Large, elongated grains observed in ground-base specimens where there were smaller, equiazed grains in Skylab specimens indicate that there was a major difference in convection during solidification of three metals with a variety of physical properties.

5. The more equiaxed grain growth in Skylab, with symmetric subgrain patterns, was observed where there was orientation associated with the solidification front in ground-base specimens.

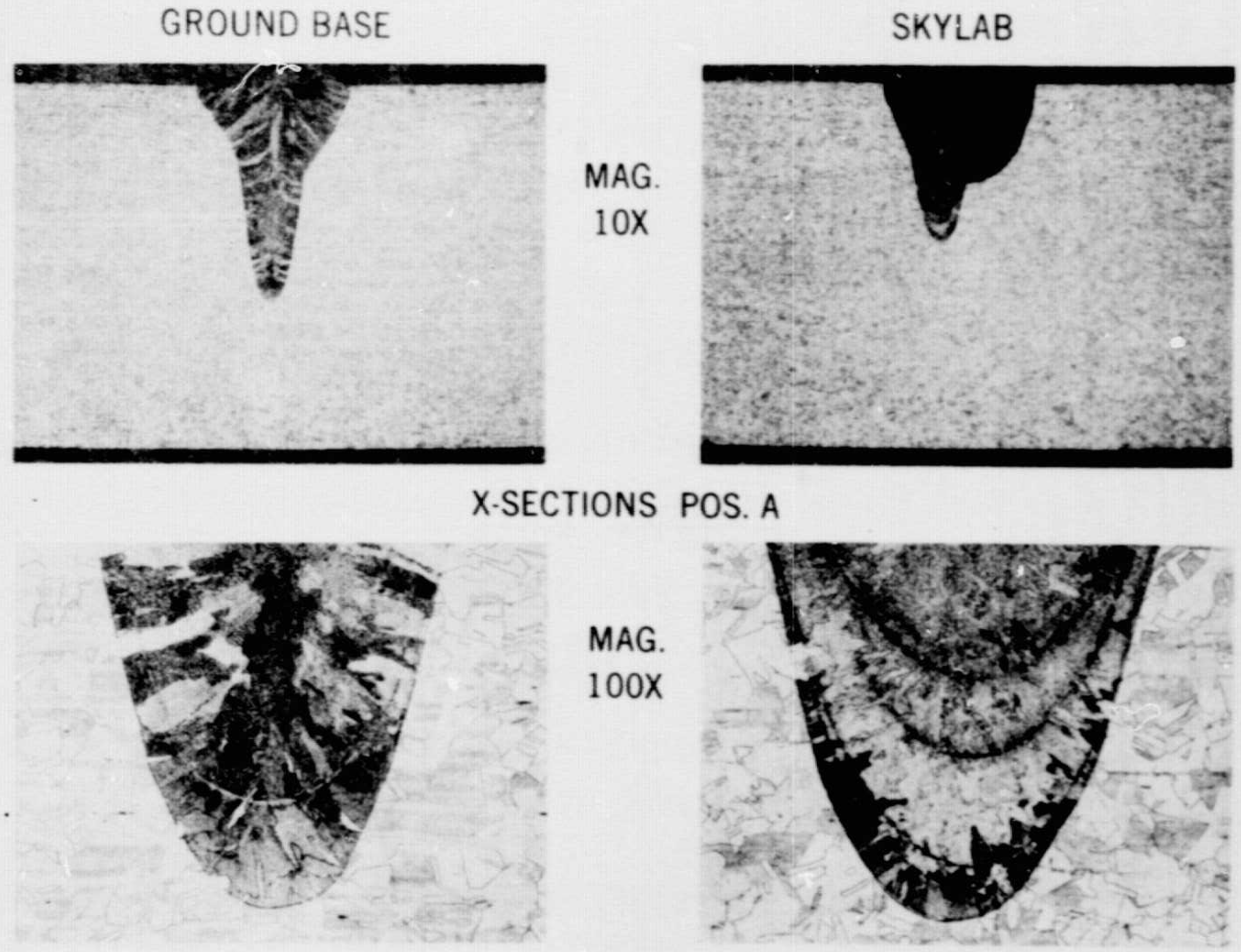

Figure 10. Ground-base and Skylab EB melts in 304 stainless steel (photographically reduced 18 percent for publication).

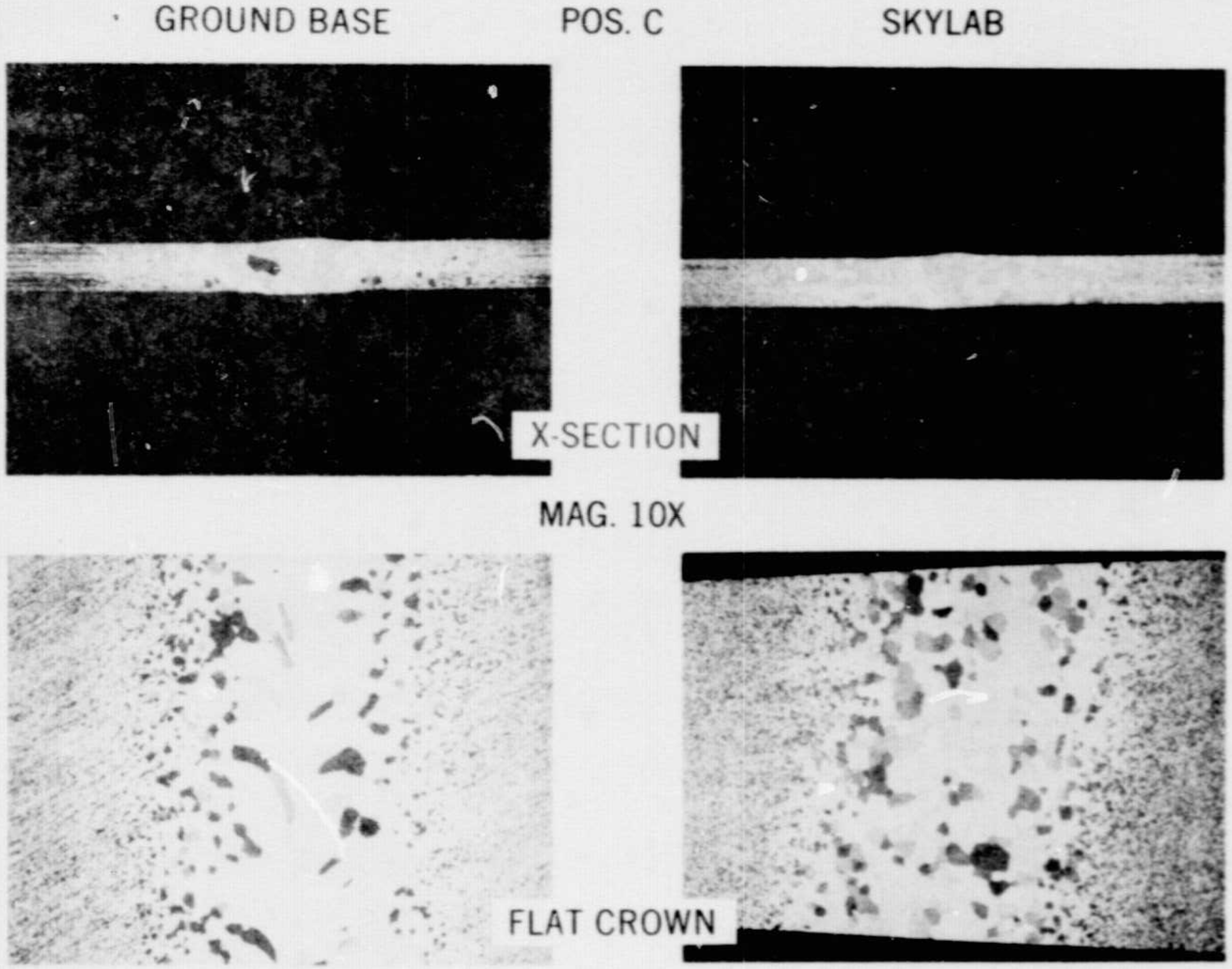

Figure 11. Ground-base and Skylab EB melts in tantalum (photographically reduced 18 percent for publication).

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APPROVAL

SKYLAB M551 METALS MELTING EXPERIMENT

By R. M. Poorman

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

W. J. Franklin

W. J. FRANKLIN
Chief, Process Engineering Division

R. SCHWINGHAMER
Director, Materials and Processes Laboratory

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