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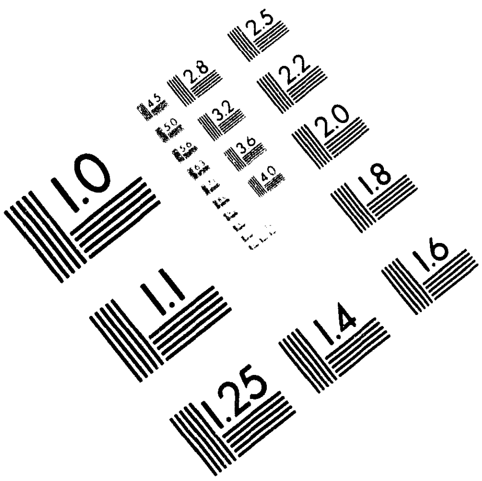

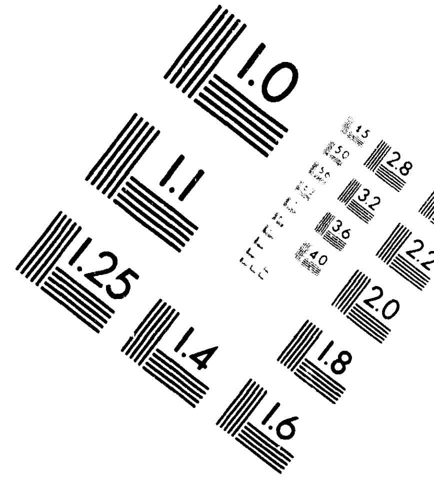

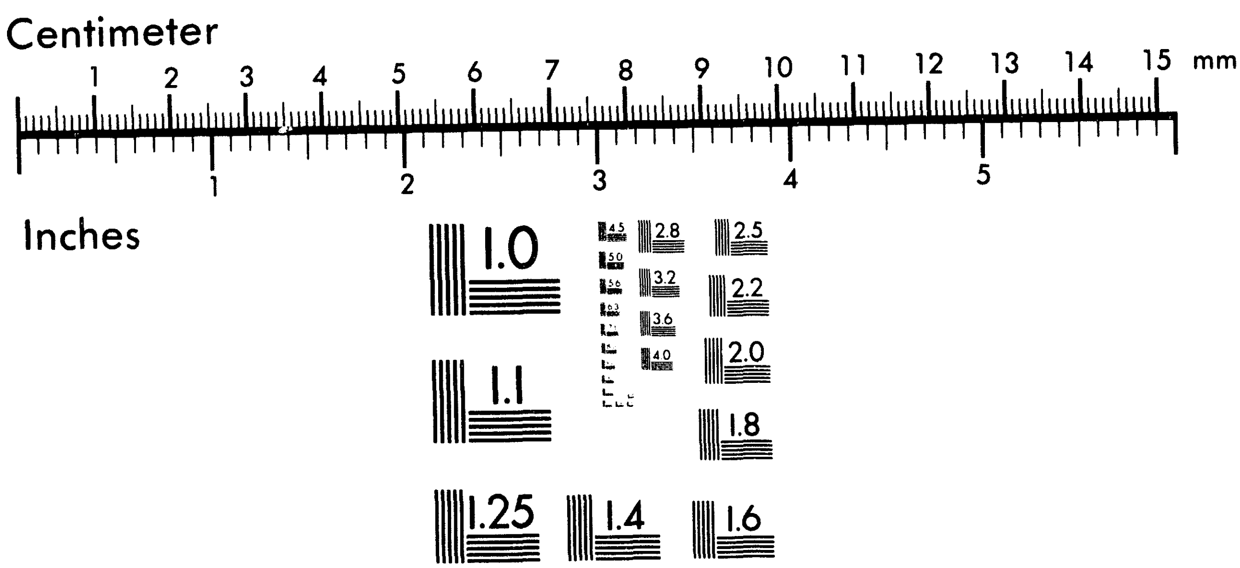

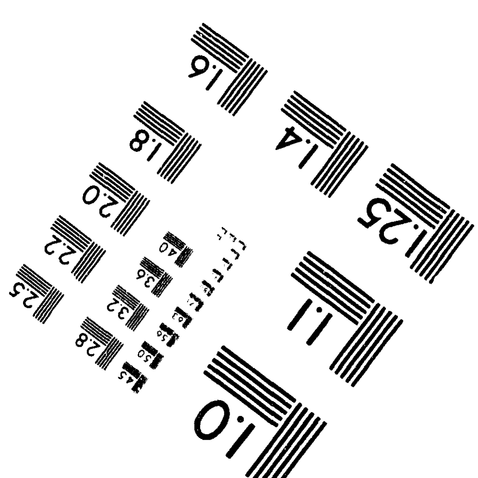

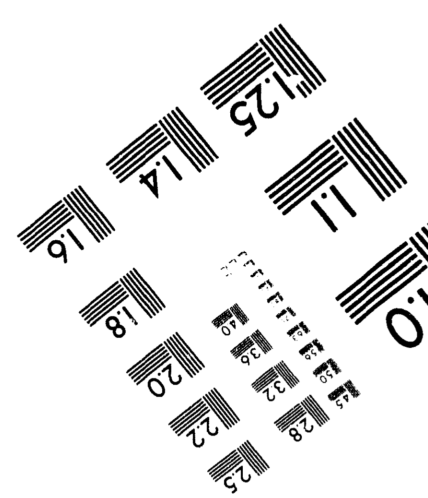

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Gravitational Effects on the Development of Weld-Pool and Solidification Microstructures*

L. A. Boatner and S. A. David
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

and

G. Workman
Johnson Research Center, University of Alabama
Huntsville, Alabama

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RESEARCH REPORT

GRAVITATIONAL EFFECTS ON THE DEVELOPMENT OF WELD-POOL AND SOLIDIFICATION MICROSTRUCTURES

L. A. Boatner and S. A. David
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
and
G. L. Workman
Johnson Research Center, University of Alabama-Huntsville
Huntsville, Alabama 35899

This research effort has as its objective the development of a quantitative understanding of the effects of both low- and high-g environments on the solidification microstructures and morphologies that are produced in alloy single crystals during a variety of melting and solidification processes. The overall goal of the effort is to delineate the nature of the roles played by natural convection, surface-tension-driven convection, and mass transport effects due to interactions associated with various heating methods that are used to form melt pools in practical, commercially important alloy systems. The experimental and theoretical investigations comprising this effort encompass the study of configurations in which stationary heat sources are employed as well as melt pools formed by moving heat sources like those frequently used in fusion-welding processes.

The present research effort is being carried out through an extension of our previously developed experimental techniques in which large, alloy single crystals have been utilized in the study and quantification of solidification microstructures that were produced in melt pools formed primarily by moving electron-beam and laser heat sources.[1-8] These previous investigations of the solidification microstructures formed in alloy single crystals have provided detailed microstructural information which cannot be obtained from polycrystalline specimens, and the resulting quantifiable microstructural properties have, in turn, led to the development of new analytical techniques for modeling and predicting solidification-cell structures.[1-8]

The current research effort consists of both ground-based studies of solidification microstructures and surface morphologies and of studies of the properties of melt pools formed in the low-gravity environment available through the use of the KC-135 aircraft. In contrast to the prior studies noted above, the current research activities are emphasizing investigations of the characteristics of solidification microstructures formed using electric-arc heating or laser heating. These techniques for forming melt pools in alloy single-crystal specimens produce more-symmetric melt pools and avoid the "keyholing" phenomena which are characteristic of electron-beam heating and which generally produce deeper more-complex, elongated, melt pools. Additionally, the existing experimental system which is currently flight qualified for operation on the KC-135 aircraft utilizes laser heating.

In order to carry out the present basic investigations of solidification microstructures in low- and high-g environments, stationary melt pools are produced on oriented principal planes of single crystals of the alloy 70Fe-15Ni-15-Cr. The advantage of employing single-crystal specimens becomes apparent when one considers that during the solidification of melt pools formed in normal polycrystalline alloy systems, the initial epitaxial nucleation at the solid-liquid interface takes place on a multiplicity of randomly oriented grains. The subsequent growth of the solidification cells, therefore, forms complex patterns that are not amenable to quantification or to the development of analytical methods for relating the microstructural development to the initial shape of the melt pool. In the case of melt pools formed on a single-crystal specimen, however, the epitaxial nucleation of all of the solidification cells takes place on one single grain whose orientation can be pre-determined by employing x-ray orientation techniques.

The relatively large 70Fe-15Ni-15Cr alloy single crystals utilized in these investigations were grown by the Czochralski technique using high-purity (5N's) starting material. These crystals were subsequently oriented, and circular specimens approximately 3.0 mm thick were cut from the as-grown boules using electric-arc erosion. The resulting samples were then lapped and the surfaces were finished with a colloidal silica polish (Syton).

In the present investigations, circular melt pools were produced on (100)-, (110)-, and (111)-oriented single-crystal surfaces by electric-arc, laser, and electron-beam melting. In the case of melt pools formed by moving heat sources the direction of the melt trace corresponded to a selected principal crystallographic direction. For the case of stationary melt pools, the principal symmetry directions lying in the major plane of the sample were determined by Laue x-ray back reflection techniques. The solidification microstructures were then determined using metallographic techniques for both horizontal-surfaces and cross sections . Through controlled sectioning of the samples (i.e. along principal symmetry directions of the base crystal), it was possible to carry out a three-dimensional reconstruction of the solidification microstructures for the different crystallographic orientations employed. These results then represent an established quantitative microstructural basis for investigating the effects of both high- and low-g environments on solidification processes in the subject "stainless steel" alloy system.

In order to illustrate the type of microstructural information that can be obtained through the application of alloy single-crystals, the case of a stationary melt pool formed on the (100) surface of an alloy specimen will be considered.[9] A schematic diagram of the experimental configuration employed is shown in Figure 1.

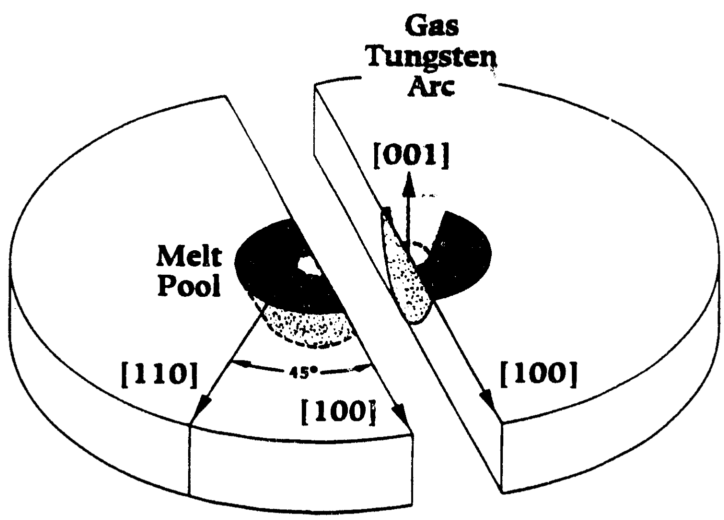

Fig. 1. Experimental configuration employeed in the formation of stationary melt pools on (001)-oriented single crystals of stainless steel. In this case, the melt pool is formed using a gas tungsten arc.

In this case a gas tungsten arc was used to form the stationary melt pool which was subsequently cross sectioned by cutting with an abrasive "wire" saw along the [100] and [110] directions. Melt pools formed using identical melting conditions are also examined by polishing the top surface of the specimen and subsequently lapping the solidified pool in order to reveal the solidification microstructure at various depths. The microstructures observed for the [100] and [110] cross sections anc the transverse (i.e. top view) sections as function of depth can now be combined in order to form the three-dimensional reconstruction of the solidification microstructure as shown in Figure 2. As shown in this reconstruction, the four-fold symmetry of the ((001) plane are clearly manifested in the cellular solidification structure.

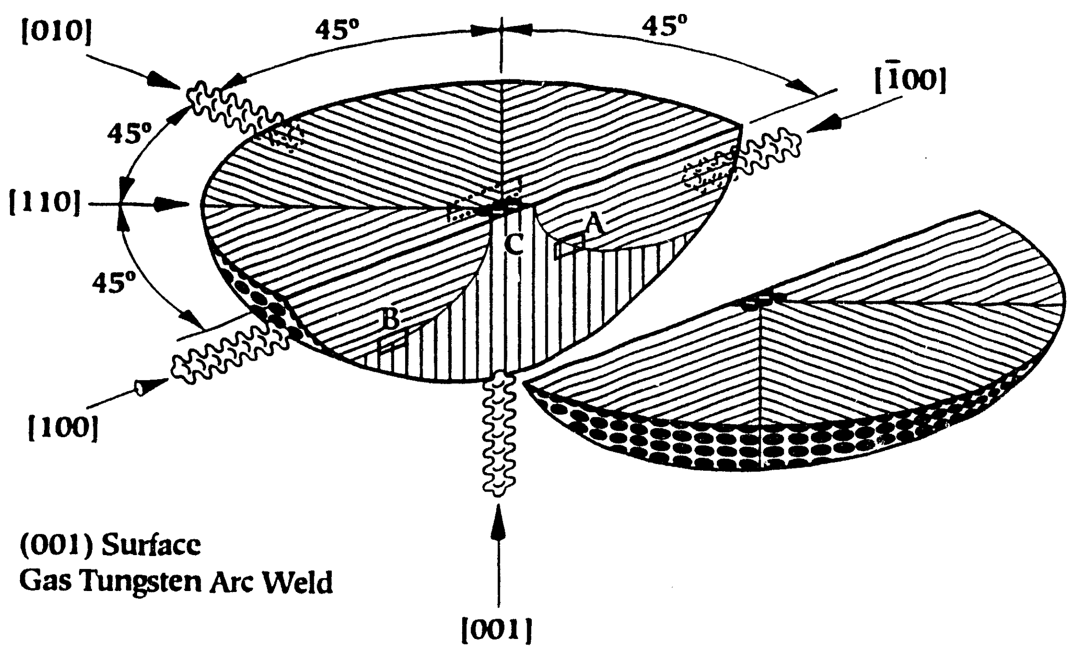

Fig. 2. **Three-dimensional reconstruction of the solidification microstructure formed in a stationary melt pool produced on the surface of a (001)-oriented stainless steel single crystal.**

The well-defined characteristics of the microstructures obtained through the use of single-crystal base material are illustrated by high-magnification views of those portions of the solidified melt pool denoted by the region marked B and of the dotted top-surface region lying just above the region marked C in Figure 2.

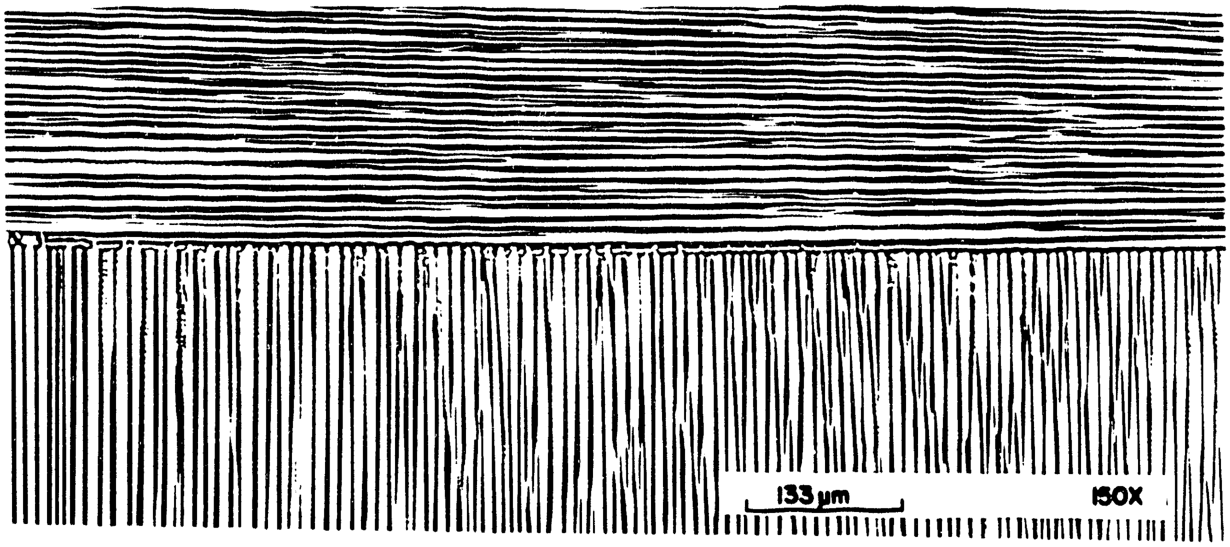

Fig. 3. High-magnification view of the cellular dendritic structure in the cross-sectional area labeled "B" in Fig. 2.

Figure 3 illustrates the cellular dendritic structure in the region marked B in Fig. 2 and shows the intersection of the vertical solidification cells which nucleated epitaxially on the bottom portion of the melt pool and which subsequently grew vertically until they were intersected by the horizontal cells which nucleated and grew horizontally along the [100] "easy growth" directions.

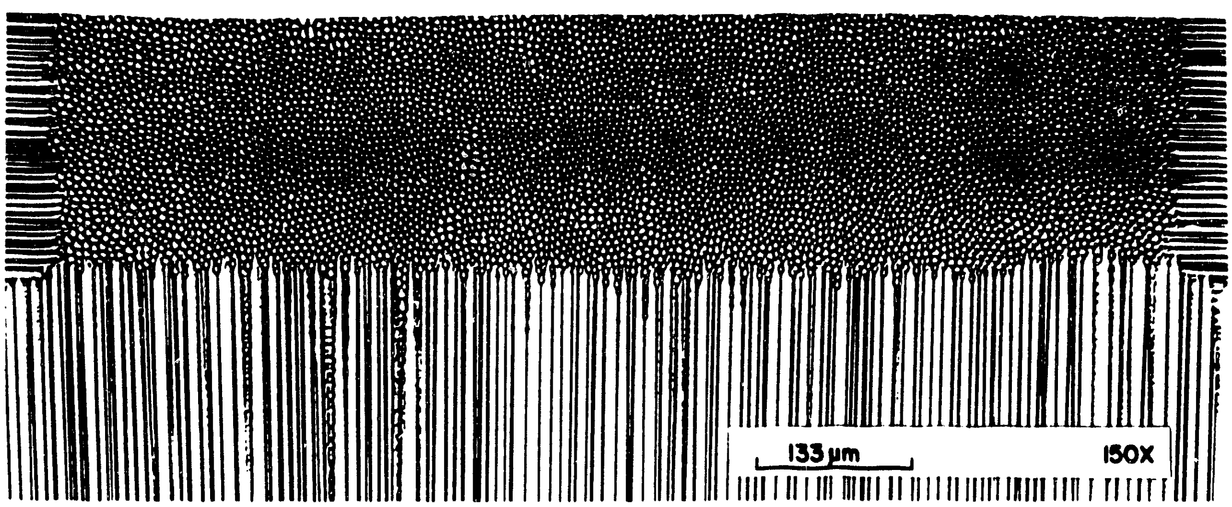

Fig. 4. Top surface view of the cellular dendritic microstructure located in the dotted area just above the letter "C" in Fig. 2.

Figure 4 illustrates a high-magnification view of the central region of the top surface of the sample and shows the dendritic cells which nucleated on the side of the melt pool and subsequently grew horizontally along the perpendicular easy growth directions toward the center of the pool. In this specimen the sample has been lapped slightly so that the cross sections of the dendritic cells which nucleated on the bottom portion of the melt pool and then grew vertically are visible in the center of the micrograph. These [001] dendrites form a "square" pattern in the center of the full transverse view of the solidified area.

Results similar to those outlined above have now been obtained for solidification microstructures formed in the case of [110]- and [111]-oriented specimens and for melt pools formed using electron-beam as well as gas-tungsten-arc heating. Preliminary results have also been obtained using laser heating provided by the KC-135 flight qualified system.

The austenitic stainless steel single crystals described above are also being applied to the development of techniques for the study of convection-flow patterns in both stationary and transient melt pools. These investigations are proceeding through the addition of a tracer element which is introduced after the melt pool has been formed. After sectioning the specimen, the location of the tracer element can be determined and "mapped" by employing back-scattered electron microscopy. Although these investigations are in a preliminary stage of development, promising results have already been obtained, and it appears that this technique can lead to a better understanding of the physical phenomena associated with mass transport and heat and fluid flow in this practical and important alloy system.

Finally, it should be noted that in the course of these investigations, a very interesting phenomenon has recently come to light. This effect consists of the formation of well-defined, oscillatory undulations which appear on the solidified surface as the solidification process takes place. Experiments are presently underway in order to obtain additional information regarding the physical parameters (including gravitational interactions) which control this intriguing process.

The long-term objective of this research effort is to carry out both ground-based and KC-135 low-g experiments in order to provide a basis for the development of a series of solidification experiments for future deployment on the Space Shuttle and ultimately on Spacestation Freedom. In addressing this goal, the research effort is directed, in particular, toward increasing our basic understanding of gravitational, surface tension, natural-convection, and other mass transport effects on solidification processes in general and on fusion-welding processes specifically.

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