Solidification Mode of Weld Metal in Inconel 718

Optical micrographs revealed bands with dark-etching regions normal to solidification direction. Stratified layers of etch pits within the bonds are due to the retention of crystal defects. Concentration of Fe, Ni, Mn and Cv decreased after crossing the boundaries of the bonds

BY H. YOSHIMURA AND K. WINTERTON

ABSTRACT. The solidification mode of weld metal in Inconel 718 has been investigated by means of optical microscopy, especially using the etch-pit technique, transmission electron microscopy and electron-microprobe analysis.

It was found that the weld metal shows bands with dark edges, these bands being normal to the direction of solidification. There are two kinds of relationships between the dendritic structure and this banding: one involves the growth of dendrites through the banding, and the other the nucleation and growth of new dendrites when the old dendrite enters a new band. Using the etch-pit technique, many etch pits were observed at the dark edges of the bands because of the high dislocation density there. According to the results of electron-microprobe analysis, there was some microsegregation at the dark edges of the bands showing that the iron, nickel, manganese and chromium contents decreased and the molybdenum, titanium and niobium contents increased.

The occurrence of banding is a direct indication of variation in the growth rate of solidification in weld metal.

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Introduction

The solidification of weld metal starts from the weld/plate interface towards the center top surface of the weld metal and the growth of dendrites in single-pass welds can generally be considered as columnar dendritic growth composed of roughly parallel rows of dendrites. Therefore, the weld metal can be considered as solidifying like a casting. Although the usual solidification phenomena have already been clearly described by Chalmers et al[1] few investigations on the solidification mechanism of weld metal under rapid cooling conditions have been reported.

The mechanical and chemical properties of weld metal depend upon features of the structure such as grain size, segregation, cracking, porosity and crystallographic anisotropy; these in turn depend upon the solidification mechanism. Therefore, it is important to investigate the solidification mode in welding as has been done for conventional casting.

In a previous account of the solidification phenomena of weld metal, Savage et al[2] have pointed out that the grains in the base metal at the fusion boundary were continuous across the interface into the weld metal. This phenomenon is called "epitaxial

Table 1—Chemical Composition of Inconel 718 Plate and Wire

	Composition, percent											
	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	Mo	Nb + Ta
Plate Material	0.05	0.07	19.50	0.007	0.18	0.07	51.10	19.03	0.57	1.06	3.02	5.24
Filler wire	0.05	0.16	18.95	0.007	0.31	0.04	52.27	18.48	0.42	0.90	3.13	5.25

Table 2—Welding Condition

Welding process	Condition	Wire	Electrode size in.	Arc length, in.	Current amp	Potential volts	Welding speed ipm	Gas flow cfh
GTA	Bead on plate	No filler	—	3/16	250～260	11～13	16	Ar60
		Filler	3/16	3/16	250～260	11～13	16	Ar60
GMA	Bead on plate	Filler	3/16	3/16	260～280	13～16	20	Ar50 He5

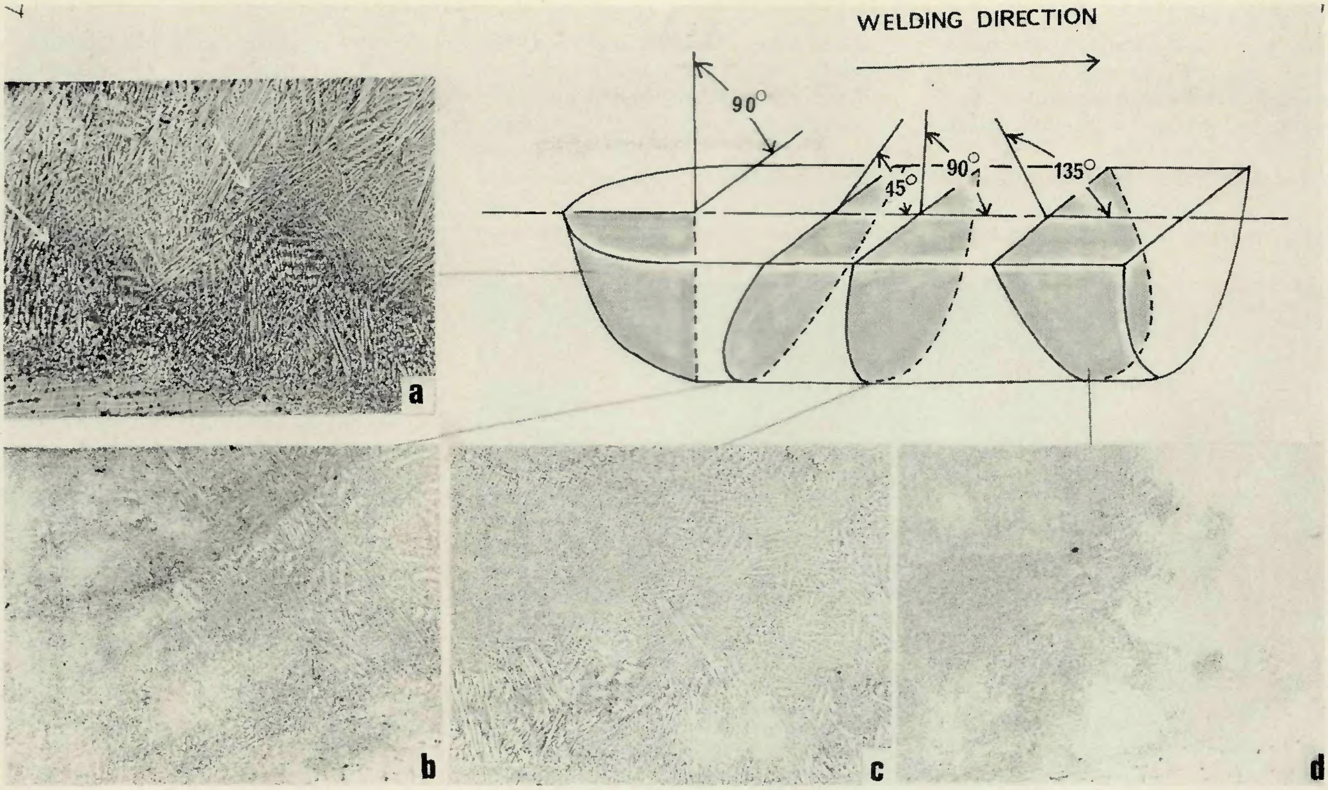


Fig. 1—Optical micrographs of various sections of weld metal showing typical banding. GTA process without filler. Mag: 50X

growth." D'Annessa[3] and Jesnitzer[4] have suggested that "transverse banding" was caused by variations in growth rate resulting from thermal fluctuations in the weld pool and Garland[5] has shown that a similar structure may be caused by cyclic variations from the welding power source. Downs[6] has shown by transmission electron microscopy that weld metal possesses a "creep-like substructure" due to thermal stresses.

To study the mode of solidification in welding, the present work comprises a study of the basic phenomena involved, notably morphology, crystallographic characteristics and segregation; this has been accomplished by means of optical microscopy, etch-pit techniques, transmission electron microscopy and electron-microprobe micro-analysis.

Inconel 718 was the test material because this alloy is convenient for analysis of solidification structure since it remains as single-phase austenite from its melting point to room temperature. Moreover, this material has shown good potential as a heat resisting superalloy and will probably see increasing use.

Materials

The as-received material (1-in. thick plate) had been annealed at 1700C; $^{3}/_{16}$-in. wire was used as filler. The chemical composition of the plate and wire is shown in Table 1.

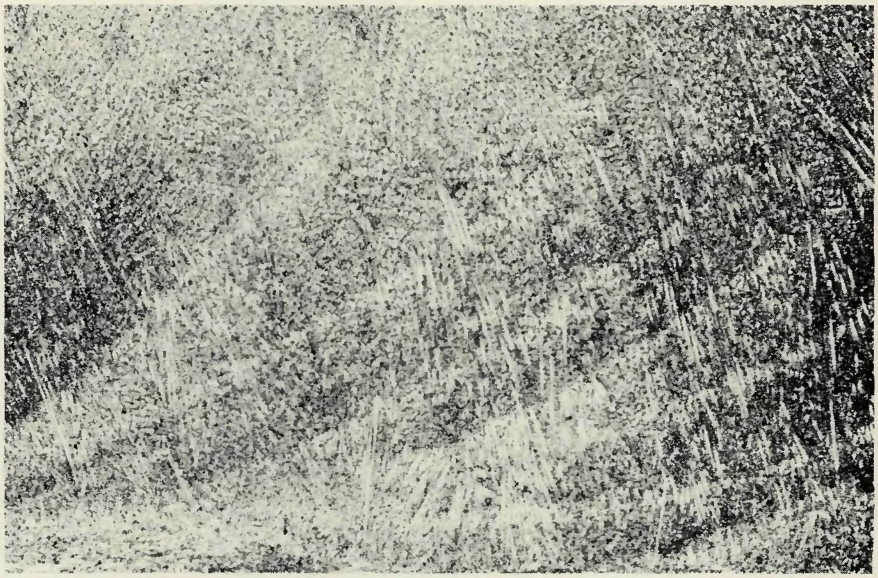


Fig. 2—Optical micrograph of longitudinal section of weld metal. GTA process with filler. Mag: 50X

Test blocks (1 x 3 x 10 in.) were cut from the annealed plate for the bead-on-plate welding tests.

Experimental Procedure

Welding Conditions

Inconel 718 alloy was welded by the gas tungsten-arc (GTA) and gas metal-arc (GMA) processes. Typical conditions are given in Table 2. Bead-on-plate welding was by the GTA process, with and without filler, and by the GMA process.

Metallographic Technique

Specimens of Inconel 718 weld metal were prepared for metallographic examination by first grinding on 600A paper, polishing with $^{1}/_{4}$-micron diamond paste and then finally polishing with MgO slurry. Specimens were electrolytically etched using 5% chromic acid. The etch-pit technique was tried to analyze the relationship between structure and crystallographic characteristics. Suitable etch pits were obtained by chemical etching using an etchant composed of copper sulfate, hydrochloric acid and distilled water after the above-mentioned electrolytic etching technique for optical microscopic observation.

Thin foils for transmission electron microscopy were prepared by the following method. Transverse and longitudinal slices between 400 and 500 microns thick were spark-cut from various parts of the weld metal using an Agie-type AB-15K-EDM machine. A disc about 3 mm in diam was almost completely cut from each slice by means of the spark cutter. These discs were thinned for transmission electron microscopy by electropolishing. A solution of 1% (by volume) perchloric acid in methanol was used with an applied potential of 15 volts at a temperature of minus 50C. The structure of these thin foils was directly observed in the electron microscope (Philips Model EM300 operated at 100 kV).

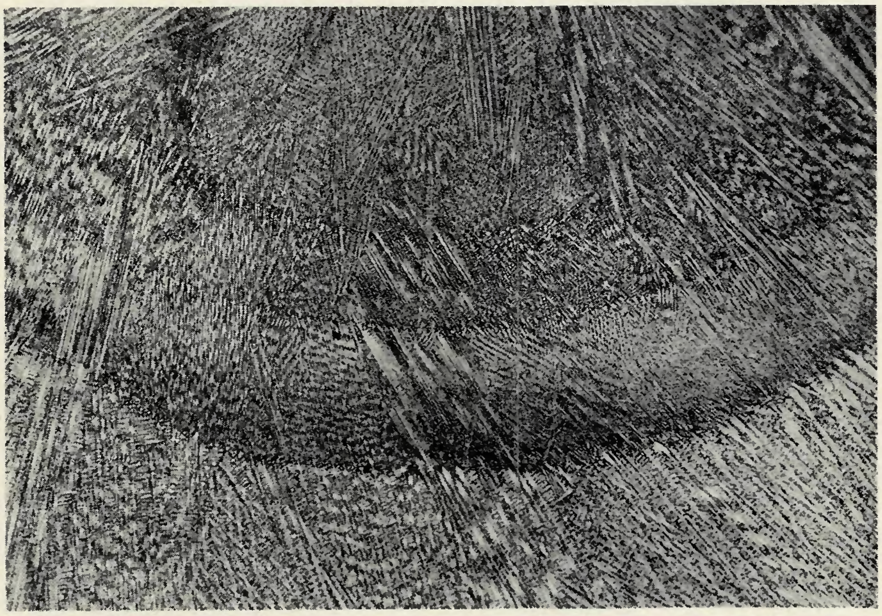


Fig. 3—Optical micrograph of transverse section of weld metal. GMA process. Mag: 50X

Electron Microprobe Analysis

Electron microprobe studies were conducted with a JEM electron microprobe analyzer. The specimens consisted of transverse weld cross sections mounted and prepared by conventional metallographic grinding, polishing and light-etching procedures. In all instances, the microprobe studies were performed on freshly polished surfaces.

The microprobe data are presented as chart-recorder traces obtained from linear scans across the weld metal. The compositional variations in the section should be considered as qualitative only.

Experimental Results and Discussion

Optical Micrograph

Banding. The solidification structure of a bead-on-plate weld using the

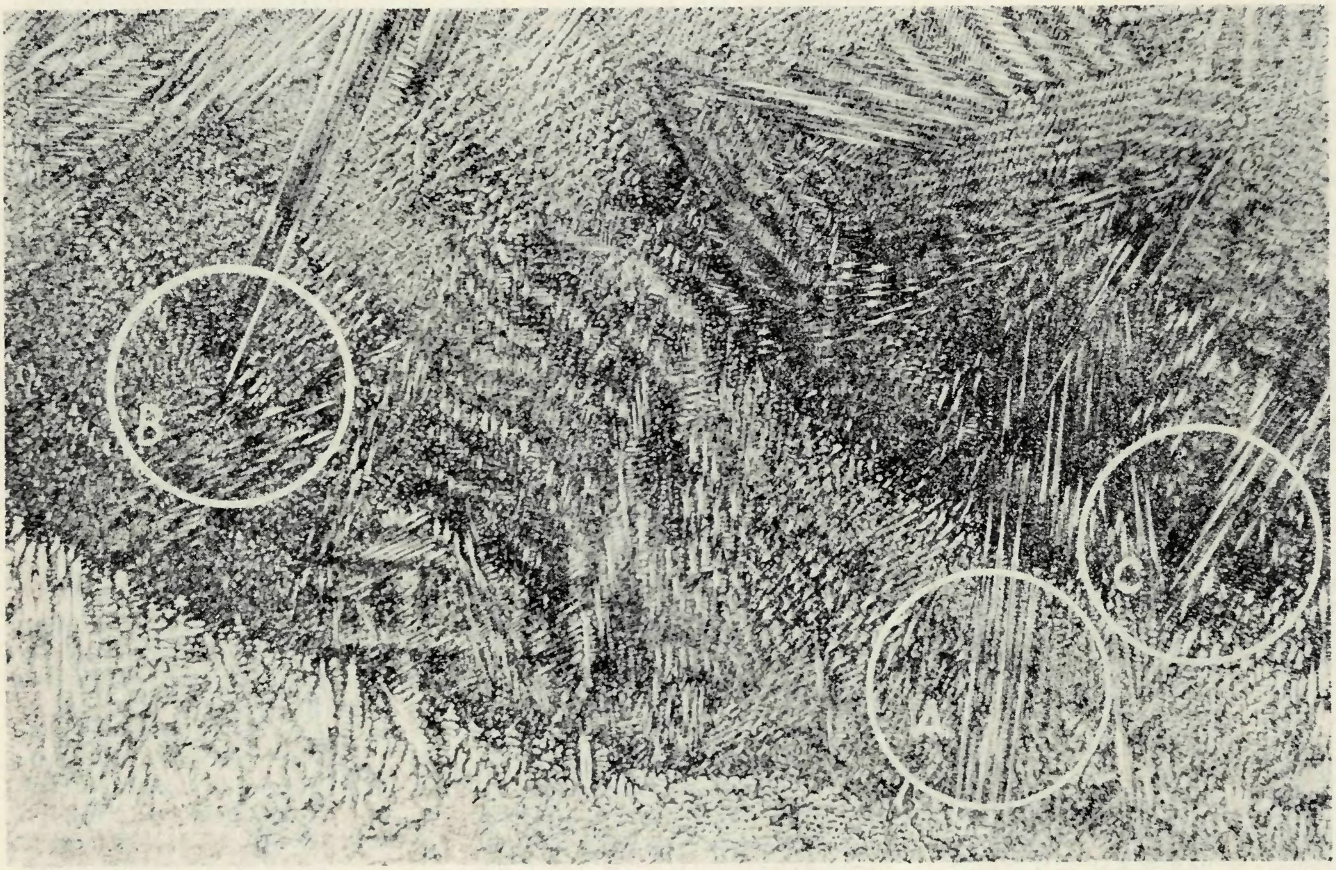


Fig. 4—Optical micrograph of longitudinal section of weld metal showing two kinds of relationships between dendrites and banding (A, B, C). Mag: 50X

GTA process without filler was first examined. This proved to be a suitable method with respect to the analysis of the phenomena of melting and solidification in welding. Optical micrographs of various sections of weld metal are shown in Fig. 1.

The growth of dendrites oriented at about 45 deg to the direction of welding was observed on the sections illustrated in Fig. 1a and 1b. Bands with dark edges can be seen normal to the growth direction of the dendrites which is also the direction of solidification. Similar bands were observed normal to the growth direction of various sections of weld metal as shown in Fig. 1c and 1d and in single-pass welds using GTA welding with filler wire and GMA welding as shown in Fig. 2 and 3, respectively.

A typical micrograph from the section illustrated in Fig. 1a is shown in Fig. 4.

This illustration shows that there are two kinds of relationship between the dendritic structure and the banding. One involves the growth of dendrites through the banding. It may be noted that traces of the original banded structure show also on the continuous dendrites in terms of depth of etching (see location A, Fig. 4). The other involves the nucleation and growth of new dendrites when a dendrite enters a new band, as shown in the locations marked B and C in Fig. 4.

These two kinds of structure were observed throughout the material.

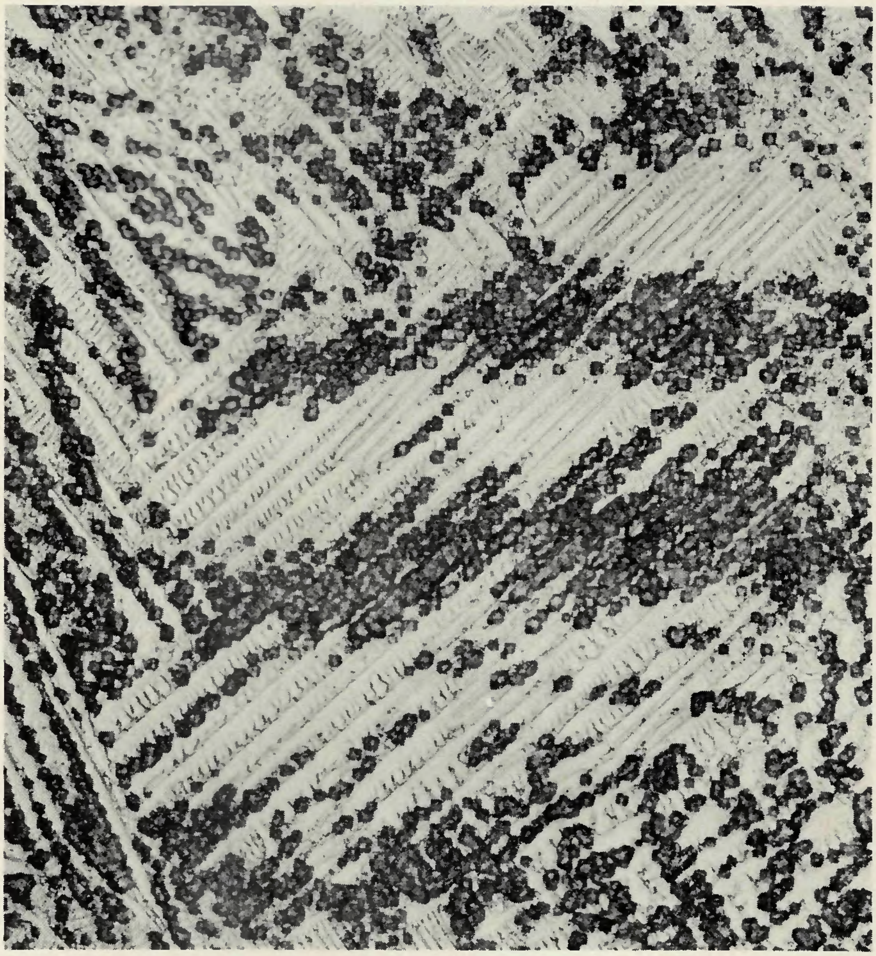


Fig. 5—Optical micrograph of weld metal showing stratified etch pits. Mag: 100X

Etch-Pit Technique. Analysis by means of the etch-pit technique has been used to study the relationship between optical microstructure and crystallography. The etch-pit structure exhibited layers of etch pits within the bands, lying normal to the direction of solidification as shown in Fig. 5.

Etch pits are generally supposed to correspond to crystal defects such as dislocations. Therefore, this result suggests that crystal defects are stratified to remain normal to the direction of solidification.

Transmission Electron Micrography

A transmission electron micrograph of an area observed in the optical micrograph as the dark edge of a band is shown in Fig. 6. Many dislocations are observed. The dislocation density is about 2×10^8 per cm^2 which is higher than previously reported[7] values of 10^6 to 10^7 per cm^2. The arrangement of dislocations is different from those found in deformed metals in that helical dislocation lines and dislocation loops are observed as shown in Fig. 6a and 6b.

Electron Microprobe Analysis

One of the aims of this study was to determine solute segregation modes within the banding in order to determine the existence of any characteristic solidification mode.

The data in the form of linear electron microprobe scans for various solute elements are shown in Fig. 7; these are copies of chart recorder traces obtained from linear microprobe scans across the banding as shown in Fig. 8.

The scanning direction from A to B in Fig. 8 is shown from left to right in Fig. 7 and represents a traverse across a boundary between two bands. Solute concentration traces are shown for iron, nickel, manganese, chromium, molybdenum, titanium, niobium and aluminum respectively.

The concentration of the first four of these elements decreases, after crossing the boundary of a new band, whereas molybdenum, titanium, and niobium increase whereas the aluminum remains rather uniform across the banding. An explanation for these differences is presented later in the paper.

Solidification Mode of Weld Metal

It is usually considered that transverse solute banding occurs as the result of periodic changes in growth rate due to periodic changes in the temperature gradient in the liquid[3] or the periodicity of this banding could be due to cyclic variations[5] in the welding power source or to nonuniformity of mixing between the weld metal and the parent metal.[8] These bands appear to be bounded by curved surfaces normal to the direction of solidification. They are formed from regions of solute enrichment due to a sudden increase in growth rate and from regions of solute impoverishment due to a sudden decrease in growth rate. In welding, these bands occur as solidification outlines usually revealed as dark etching contours on polished and electrolytically etched specimens.

The metallographic studies showed that sometimes the growing dendrites crossed the bands without change of direction and, presumably, without change of crystal orientation. In other cases, when a dendrite intercepted a band, a group or family of dendrites

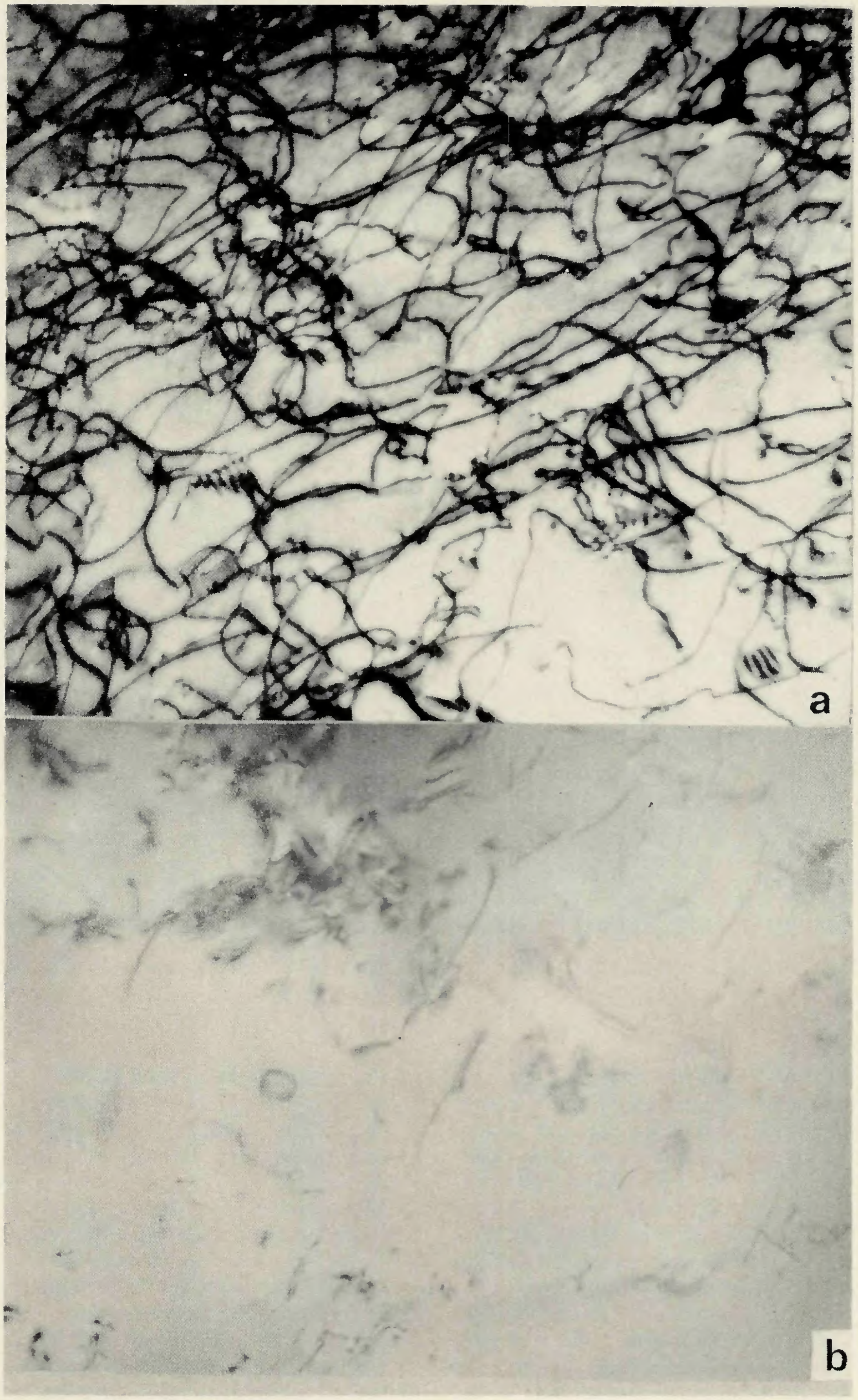


Fig. 6—Transmission electron micrographs of weld metal showing (a) bent helical dislocation and (b) dislocation loops. Mag: (a) 50,000X; (b) 100,000X

seemed to have been initiated within the band. These dendrite groups may, at least sometimes, bear a twin relation to the parent dendrite. So, at least, are the indications from etch-pit examination. To prove this point and to inquire further into this phenomenon would require the application of more refined techniques.

The periodicity of growth rate may result in the production of many crystal defects. The defects will be arranged normal to the direction of solidification, especially under the influence of a sudden increase in growth rate.

It is probable that there are a number of ways in which dislocations can be introduced during solidification. Since dislocations are a nonequilibrium type of defect they can be formed only as a result of nonequilibrium conditions during solidification—for example in welding. There are various kinds of disturbance during solidification that can be effective in producing dislocations: (a) condensation of vacancies; (b) local stresses due to concentration gradients and (c) stress of thermal origin.

It has been clearly demonstrated on theoretical grounds that the vacancy content of a crystal immediately after solidification cannot be appreciably greater than the equilibrium content for that temperature. Because the equilibrium vacancy content decreases as the temperature falls, the excess vacancies will be trapped where cooling is fast enough to prevent the diffusion of the vacancies to sinks such as locations within the weld metal bands where a sudden increase in solidification rate occurs. This may result in the aggregation of vacancies into clusters which can have a significant effect on the subsequent motion of dislocations within the bands of weld metal.

The result of the collapse of a single layer of vacancies could be a ring of complete dislocation with no stacking faults, see Fig. 6b. A dislocation ring can grow by climbing and move by slipping.

Tiller[9] has discussed a mechanism whereby dislocations are formed to compensate for the atomic misfit caused by lattice parameter variations in regions of steep concentration gradients. This author[9] found that dislocation densities of up to 10^7 per cm^2 could be produced by concentration gradients associated with impurity cell structures. Dislocations can also be produced, during cooling, by the stresses set up between neighbouring regions having different concentrations and therefore different thermal expansion coefficients.[10] It therefore appears that dislocations are produced by the stresses caused by the concentration gradient associated with banding and produced by a change in solidification rate.

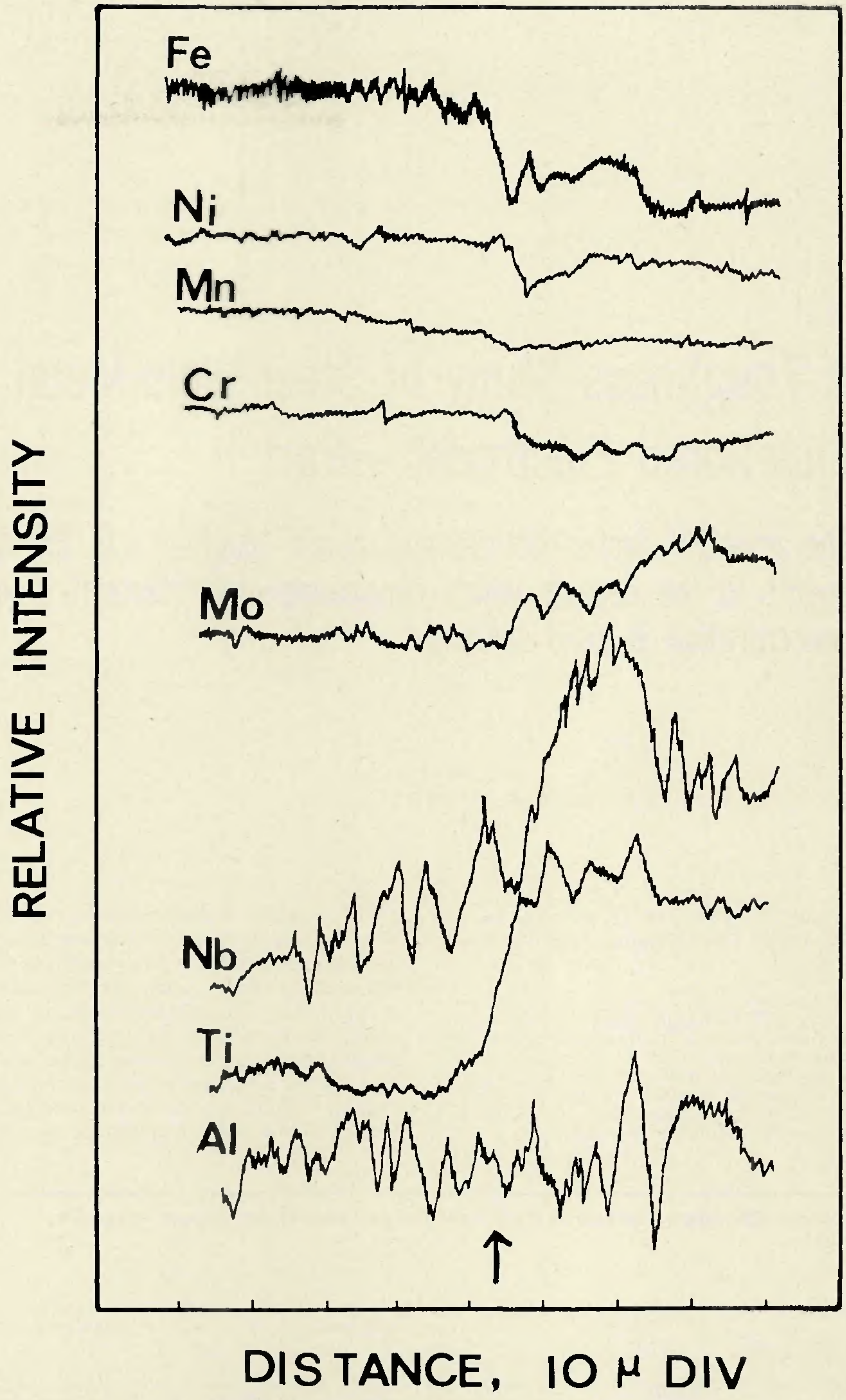
Because of the foregoing considerations, the authors regard the periodicity of growth rate as an important feature of the solidification mode of weld metal.

Summary

The solidification mode of weld metal (Inconel 718) was examined by means of optical and transmission electron microscopy and by electron microprobe analysis. The results obtained are summarized as follows:

1. Optical micrographs showed bands with dark etching regions normal to the direction of solidification. According to examination using the etch-pit technique, there are stratified layers of etch pits within the bands probably due to the retention of many crystal defects.

Fig. 7—Electron microprobe trace of various elements in weld metal. Arrow shows the position of edge of band



2. Transmission electron micrographs showed that the dark-etching region of bands in weld metal had high dislocation densities; dislocation loops may be formed from vacancy clusters which may be caused by the characteristic periodicity in growth rate.

3. Electron microprobe analysis showed that the concentrations of iron, nickel, manganese and chromium decreased after crossing the boundaries of the bands, whereas the molybdenum, titanium and niobium contents increased and the aluminum content remained rather uniform across the banding.

These phenomena may be considered the result of periodic changes in the solidification rate.

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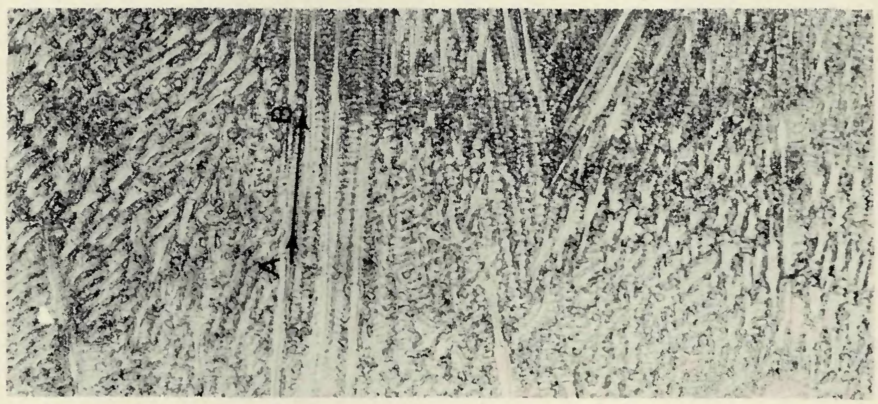

Fig. 8—Optical micrograph of weld metal. Arrow shows the trace of scanning of electron microprobe analyzer. Mag: 100X