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Mechanical property anisotropy in superalloy EI-929 directionally solidified by an exothermic technique

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Directional solidification of the nickel-based superalloy EI-929 was carried out by employing the exothermic technique for preparing several 150 mm long × 55 mm diameter rods. Specimens machined from the blanks cut at 0°, 45°, 75° and 90° to the chill surface were tensile and stress-rupture tested at different temperatures. The air-melted DS alloy, when loaded parallel to the growth direction, shows considerable improvement in stress–rupture life and tensile ductility as compared with the vacuum induction melted, forged and heat-treated alloy. However, these property advantages rapidly degrade with the increasing deviation of the load axis from the growth direction.

1. Introduction

Although directional solidification (DS) of vacuum-melted nickel-based superalloys is now a well established process for the manufacture of gas turbine components, DS by the exothermic technique has a promising potential for manufacturing cast components from air-melted medium strength superalloys and special steels [1–3]. The present investigation is aimed at extending the scope of the exothermic technique to advanced superalloys which are generally hard to work. Alloys having a higher proportion of refractory elements such as tunsten are also considered difficult to process by DS [4]. EI-929, a Soviet nickel-base superalloy of the nominal composition Ni–14Co–10Cr–5W–3.5Mo–4Al–2Ti–0.5V–0.1C–0.02B (wt %), was found to be a good representative of such alloys for studying their solidification behaviour.

An exothermic mixture developed for Nimocast 90 [5] has been used to cast DS rods of EI-929 in open-bottom investment shells. The temperature dependence of the tensile and stress–rupture properties of the DS alloy specimens made from the material at 0° (transverse). 45°, 75° and 90° (longitudinal) to the chill surface has been evaluated. Fracture surfaces have been examined to correlate the effects of grain orientation with the tensile and stress rupture properties.

2. Experimental procedure

The apparatus used for casting specimens is shown in Fig. 1. Zircon open-bottom investment shells of 5 mm wall thickness held vetically on the water-cooled copper chill were surrounded by loosely packed exothermic mixture.

A 5 kg charge of vacuum induction melted (VIM) master alloy ingot of the nominal chemical composition given in Table I was remelted under a protective slag blanket of calcium silicide in an air induction melting furnace using a magnesia crucible. Extra additions of aluminium and titanium (each 0.5 wt %) were made just before pouring. The exothermic mixture was ignited by heating it to approximately 1373 K and then the molten metal was poured at 1725 K into the investment shell moulds. 10 mm × 10 mm × 55 mm blanks were sliced from the DS rods at 0°, 45°, 75° and 90° inclinations to the chill surface as shown in Fig. 2. These blanks were then machined to prepare tensile specimens (4.06 mm gauge diameter × 25.4 mm gauge length) and stress-rupture specimens (4.50 mm gauge diameter × 20.0 mm gauge length). Tensile testing was done at ambient and elevated temperature in air at a cross-head speed of 1 mm min^{-1}. Stress rupture tests were carried out at 1075 K/432 MPa, 1175 K/216 MPa and 1175 K/245 MPa. Fractured surfaces of the tested specimens were examined using optical and scanning electron microscopy.

3. Results and discussion

3.1. Alloy chemistry

The chemical compositions of the VIM ingot and air-melted DS alloy are given in Table I. Anticipating

TABLE I Nominal chemical composition of EI-929 (wt %)

	C	Si	Mn	Cr	Co	W	Mo	Al	Ti	V	B	Fe	S	Ni
VIM ingot	0.12	0.15	0.05	10.5	14.5	5.2	4.0	3.8	2.2	0.5	0.015	1.8	0.005	Balance
DS alloy	0.10	0.28	0.08	10.4	14.5	5.0	3.8	4.0	2.1	0.5	0.015	1.9	0.008	Balance

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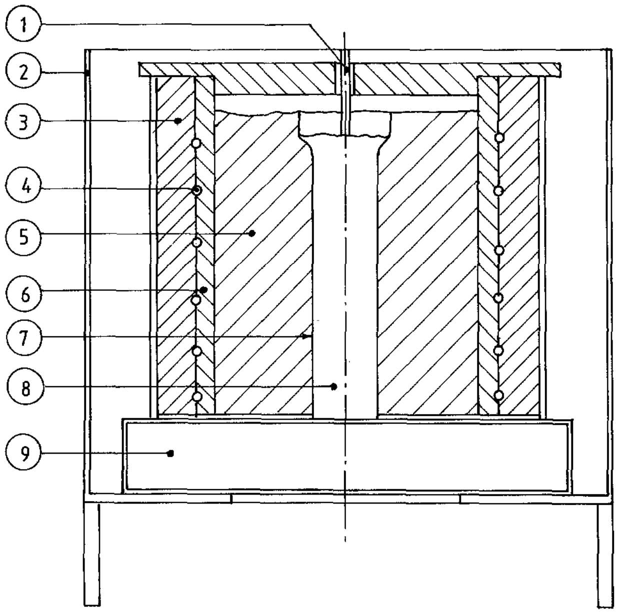


Figure 1 Schematic cross section of apparatus used for exothermic DS process. 1, Alumina tube; 2, metallic case; 3, insulator; 4, heating element; 5, exothermic compound; 6, magnesia crucible; 7, investment shell mould; 8, molten metal; 9, water-cooled copper chill.

some carbon loss during air-melting, the carbon content was kept slightly higher while preparing the remelt stock. As expected, the extra additions of titanium and aluminium were helpful in maintaining the alloy chemistry within the specified range.

3.2. Microstructure

A longitudinal section of the DS ingot (Fig. 3) shows that the grains are aligned in the growth direction except in a region near the top, where equiaxed grains have formed due to the non-availability of the positive temperature gradient in the liquid metal ahead of the solidifying interface. The dendrite arm spacings are known to depend upon the local soldification time [6].

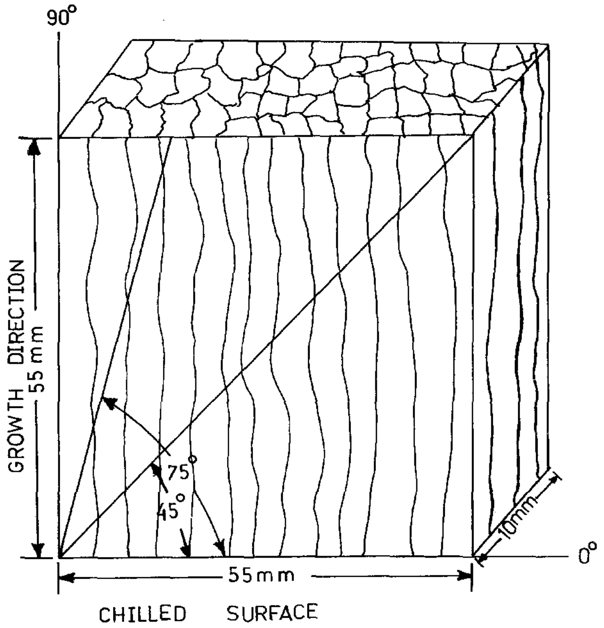


Figure 2 Schematic arrangement showing the location of tensile and stress–rupture test specimens machined from the DS ingot of EI 929.

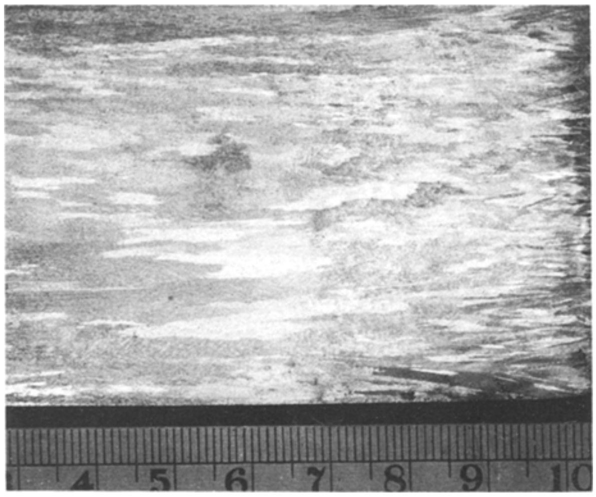
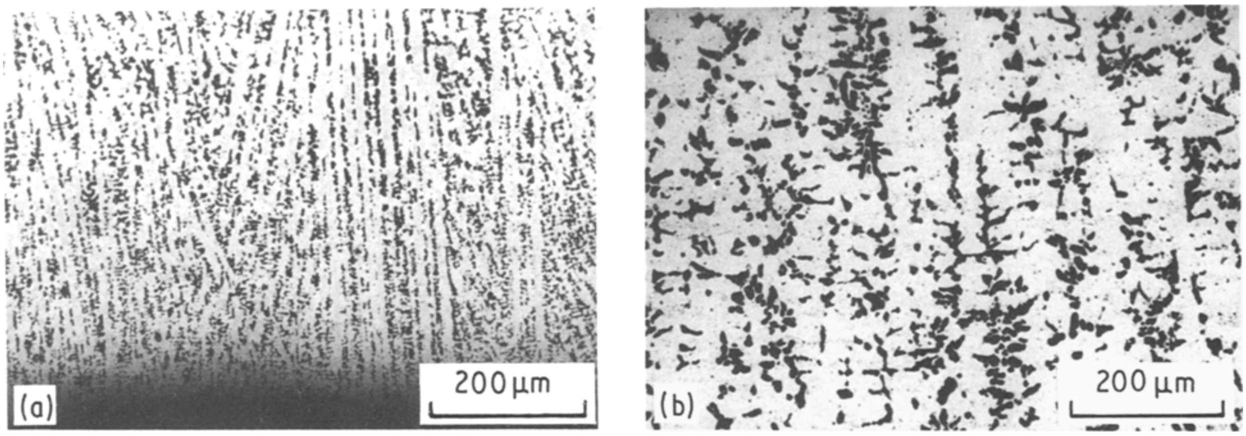


Figure 3 Longitudinal section of the DS ingot showing alignment of grains in the growth direction.

As shown in Fig. 4a, the dendritic spacings are very fine ($\simeq 20\,\mu$m) near the chilled surface. As solidification front moves away from the chilled surface in the course of further growth, a gradual fanning out of the dendritic arms and increasing spacings ($\simeq 170\,\mu$m) result (Fig. 4b). A typical microstructure on a surface transverse to the growth direction at a height approximating the gauge section location is shown in Fig. 4c.

3.3. Tensile properties

Table II shows a comparison of the tensile properties of the DS and heat-treated wrought alloy at various temperatures. The DS alloy, being in the as-cast condition, possesses a lower yield strength (YS) and ultimate tensile strength at all temperatures as compared with its wrought counterpart, which has been prepared by vacuum induction melting followed by forging and a three-stage heat treatment [7]. However, the tensile ductility of the DS alloy (longitudinal) is found to be higher, especially at higher temperatures possibly because of the absence of grain boundaries perpendicular to the loading direction. The tensile ductility decreases with the increasing deviation of the loading axis from the growth direction. It is, however, interesting to note that this ductility drop at elevated temperature is serious only beyond an inclination of 45°. The DS alloy, when subjected to a suitable solutionizing and reprecipitating treatment, is expected to be superior or equivalent to its VIM wrought counterpart for loading directions up to 45° away from the growth axis. Fractographic examination carried out on the room-temperature tensile-tested longitudinal specimens showed that the fracture has taken place in a transgranular fashion (Fig. 5a). Decohesion along the interfaces of dendritic arms following a considerable amount of plastic deformation is evident at higher magnification (Fig. 5b). However, in the case of transverse specimens, the fracture was along the grain boundaries without significant plastic deformation. Fracture was a combination of both the intergranular as well as transgranular mode in the specimens tested at 45° and 15° to the growth direction (Figs 5c and d).



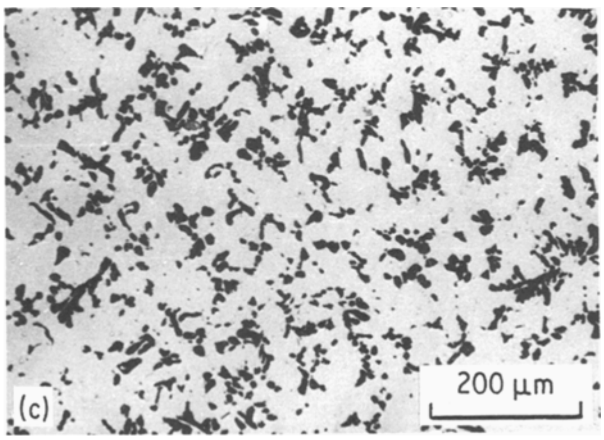


Figure 4 Microstructures of specimens taken at varying distances from the chill surface of DS ingot: (a) bottom; (b) top; and (c) cross section at 80 mm above the chill surface.

4. Stress–rupture properties

The stress–rupture properties of the DS alloy (all four directions) are compared with those of the wrought alloy in Table III. The DS alloy has a significantly improved stress–rupture life and ductility when tested parallel to the growth axis as compared to its heat-treated wrought version. However, for all the other inclinations examined (15° and beyond from the growth axis) the stress–rupture properties are considerably inferior. Heat treatment of the DS alloy is not expected to be of much help in improving this property anisotropy.

Examination of longitudinal sections through the fracture surface (Fig. 6) illustrates the rôle of grain boundaries which are perpendicular to the stress axis in reducing the stress–rupture life of the DS alloy. For the specimens loaded parallel to the growth direction, the interdendritic carbides provide the crack nucleation sites. The cracks also initiate on areas of the grain boundaries, which are perpendicular to the load axis, thus resulting in a transgranular type of fracture (Fig. 6a). However, for all other orientations the cracks are mostly intergranular and interdendritic in nature (Figs 6b, c and d).

5. Conclusions

The exothermic DS technique can be employed for making castings even from those superalloys which have a high proportion of refractory and reactive elements, such as EI-929. Maximum tensile and stress rupture property advantage is obtained when loading is parallel to the growth direction. Tensile properties degrade significantly beyond 45° off axiality, whereas the stress–rupture properties degrade even at 15° away from the growth axis.

TABLE II Tensile properties of EI-929 (DS–directionally solidified in air, W–vacuum induced melted, forged and heat treated)

Test temperature (K)	Alloy condition	Inclination to chill	0.2% YS (MPa)	UTS (MPa)	Elongation (%)
300	DS	90°	730, 742	912, 933	12, 13
	DS	75°	716	868	8
	DS	45°	828	883	5
	DS	0°	774	803	2
	W	–	852	1177	11
1075	DS	90°	609	660	10
	DS	75°	692	789	6
	DS	45°	686	700	6
	DS	0°	758	775	2
	W	–	817	901	4
1175	DS	90°	379	413	9
	DS	75°	458	542	6
	DS	45°	410	468	7
	DS	0°	482	520	1
	W	–	541, 569	569, 581	7, 8

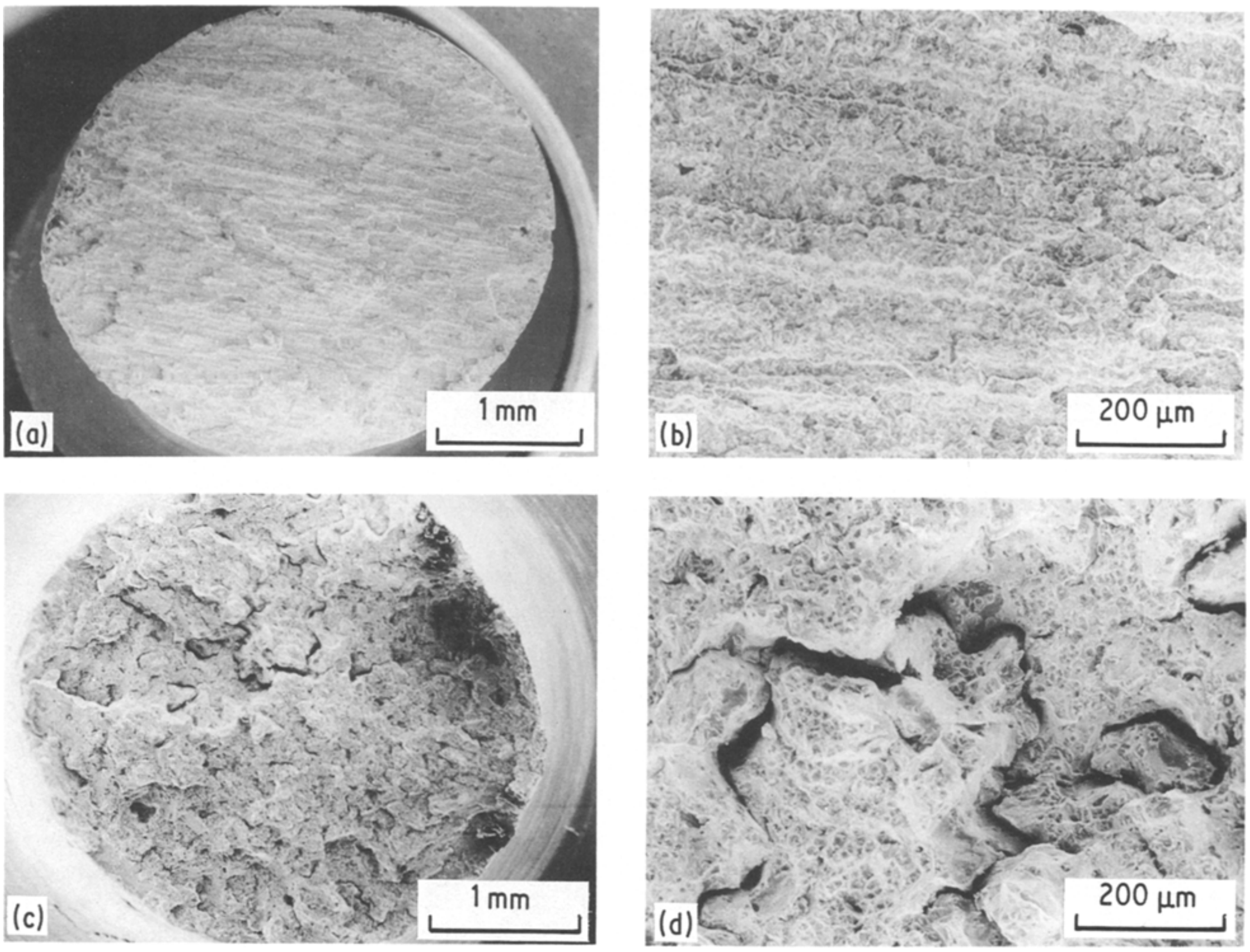


Figure 5 Fracture morphology of room-temperature tensile-tested specimens from different orientations of the directionally solidified EI 9292 ingot: (a), (b) parallel to growth direction; (c), (d) 15° to growth direction.

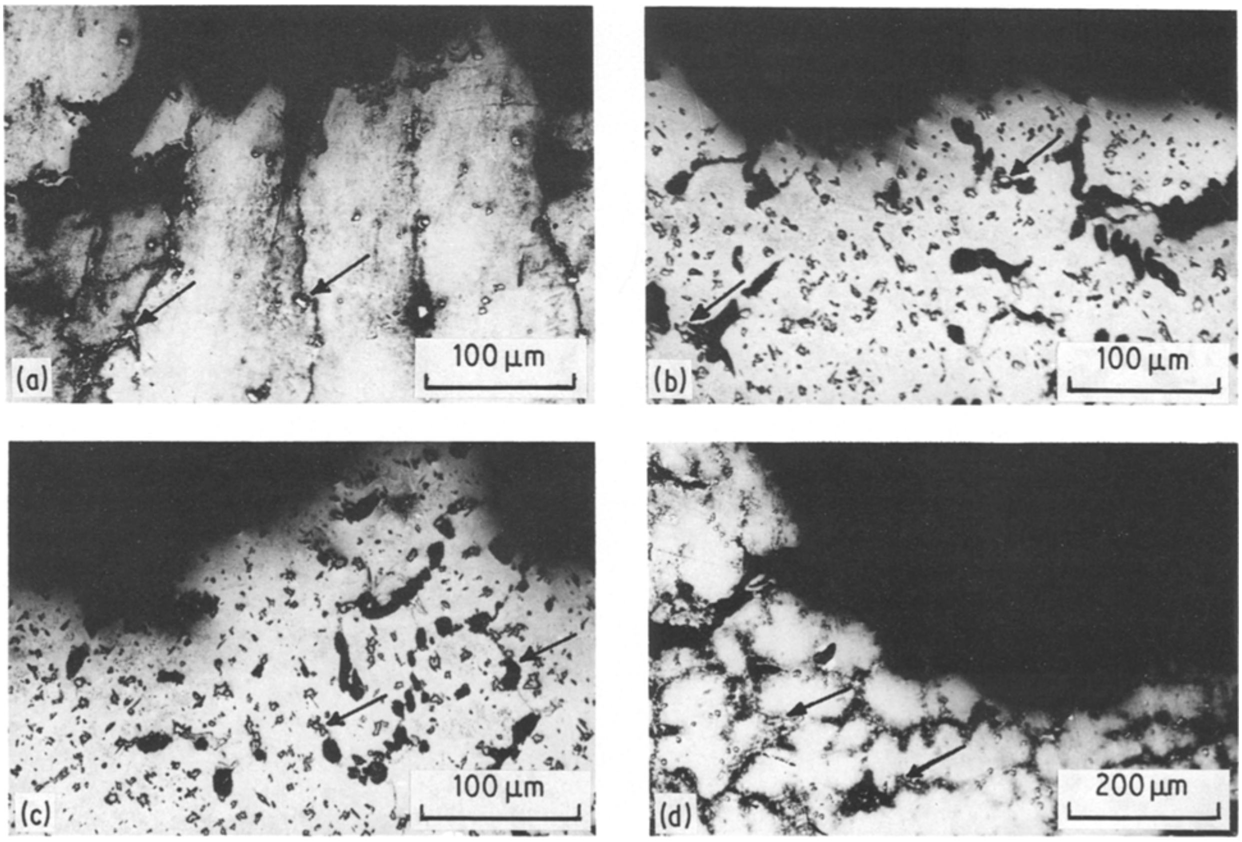


Figure 6 Micrographs showing the fracture behaviour of stress–rupture tested specimens taken from different orientations to the growth direction of the DS EI-929 ingot: (a) parallel to growth direction; (b) 15° to growth direction; (c) 45° to growth direction; (d) transverse to growth direction. Arrows show interdendritic carbides.

TABLE III Stress rupture properties of EI-929 (DS–directionally solidified in air, W–VIM, forged and heat treated)

Temperature/ stress (K/MPa)	Alloy condition and inclination to chill surface	Stress–rupture life (h)	R in A (%)
1075/432	DS/90°	98	13
	DS/75°	17.15	7.7
	DS/45°	12	6
	DS/0°	4	2.5
	W	79	10
1175/216	DS/90°	155, 144	15, 14
	DS/75°	28	7
	DS/45°	31	7
	DS/0°	17, 11	2, 1
	W	72	10
1175/245	DS/90°	52, 50	18, 15

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