Communication

A Phenomenological Analysis of Freckling in Directional Solidification of Ni-Base Superalloy: The Role of Edge and Curvature in Casting Components

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The geometrical factor in freckle formation has rarely been taken into account. In this work, freckle formation in superalloy components is examined. It is found that freckle formation is subject to the effects of the edge and curvature. In polygonal casting sections, freckles are formed preferably on the convex edges. In the components with a curved contour, freckles are exclusively formed on the outward-curving surface having positive curvature.

<https://doi.org/10.1007/s11661-019-05513-5>

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Freckles remain as one of main casting defects in single-crystal (SC) or directionally solidified (DS) Ni-base components.^[1–4] They appear to be long trails of equiaxed grains aligning roughly parallel to the direction of gravity and are often found on the surface of SC or DS superalloy castings.^[5–7] It is generally acknowledged that freckles are formed as a consequence of thermosolutal convection, which is driven by density inversion in the mushy zone.^[1,8–11] The interdendritic liquid in the mushy zone tends to “jet” upward from the mush zone. Along the way, these jets erode dendrites and break them apart. Thereafter, the eroded dendrites re-dissolve into the liquid or act as nuclei for equiaxed grains.^[12–17]

Apart from chemistry segregation,^[18–20] solidification parameters and casting size also play significant roles with respect to freckle formation in Ni-base superalloy casting.^[1,2,21–25] During solidification, convective flow in

the mushy zone can be accelerated by a lower temperature gradient (G) or solidification velocity (V), resulting in larger dendrite spacing and higher permeability. Hence, freckles are preferentially formed under such conditions. To prevent the formation of freckles, high temperature gradients or high solidification velocities are required.

- Above a critical thermal gradient, the mushy zone becomes too small to accommodate the convective currents for freckles to form.
- With an increasing solidification velocity, the local solidification time will be shorter than the minimum one required to form freckles, resulting in a freckle-free structure.
- In addition, larger casting size leads to severe freckling.^[1, 4, 5, 26–28] This is because an increased cross section of a casting has a wider mushy zone, providing a sufficient reservoir for the interdendritic convection, and the convection favors the freckle formation.^[29–32] In contrast, freckles are normally not found in components with small cross-sectional area.^[1] This is commonly referred to as the size effect of freckle formation.

In recent work,^[16,24–27] a series of SC and DS experiments with a relatively complex geometry was carried out under industrial conditions, and a number of interesting phenomena related to freckle formation were observed, such as the shadow,^[33] step,^[33,34] orientation,^[35] slopping^[23] and edge effects.^[33,36]

Recently, we observed that freckles prefer to form on the edges of components instead of on the plane surface despite the higher cooling rate on the edges, which is unfavorable for freckle formation. In this article, the edge and curvature effect on freckle formation will be reported.

Compositions of Ni-base superalloy CMSX4 involved in this article are provided in Table I. The components were cast at 1500 °C. The pulling velocities were 1 mm/min for bars and 3 mm/min for real blades, respectively. Sixteen trails were carried out for casting bars and over 20 trails for blades. The geometries of casting components involve the rectangular and cylindrical cross section.

As shown in Figure 1, freckles are commonly located on the edge of the sample in either the simple geometries or real blades of the superalloy. This so-called “edge effect” phenomenon contradicts our current understanding of freckle formation; freckles form at lower cooling rates. A higher solidification rate results in an unfavorable thermal condition for freckle formation in the edges. Therefore, it is usually believed that freckles arise preferentially on the smooth surfaces of the thicker parts of the components.

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Manuscript submitted June 13, 2019.

Article published online November 1, 2019

Table I. Compositions of Ni-Base Superalloy CMSX-4 (Wt Pct)

	Co	Cr	Mo	W	Al	Ti	Ta	Hf	Re	C
CMSX-4	9.0	6.5	0.6	6.0	5.6	1.0	6.5	0.1	3.0	0.12

Fig. 1—A rectangular component exhibiting freckles on the edges (a) and a turbine blade showing freckles on the trailing edge (b).

Further details of the geometrical effect on the freckle formation are shown in Figure 2, which presents an incomplete cast blade consisting of four parts with respect to the side surface, *i.e.*, convex side A, concave side B, leading edge C and trailing edge D. Freckle chains can be observed on both leading and trailing edges indicating the edge effect on freckle formation. In addition to freckles forming on the leading and trailing edge C and D, most of the freckles occurred on the convex side A of the blade body compared with concave side B where the blade surface was totally freckle free. Moreover, the freckle appearance became very pronounced, especially in the middle part of the convex side where the surface curvature and local thickness were the largest.

A solidified structure is revealed in the decanted mushy zone because of the insufficient feeding. The decanted mushy zone can be easily recognized as the dark zone ahead of the fully solidified solid zone, which appears much brighter, as shown in convex blade side A in Figure 2. In the exposed freckling channels in the mushy zone, growing dendrite and broken dendrite arms can be observed. At the locations corresponding to the freckling channels, the mushy zone is wider because of the delayed solidification processing. Under each channel in the mushy zone, a freckle chain can be found in the solid zone. It is then evidently confirmed that the freckle formation resulted from the channel-shaped segregation and convection in the mushy zone. The molten alloy in the freckling channels was seriously

segregated, significantly lowering the solidus temperature. As a result, the residual melt in the channels was exhausted by the neighboring dendrites, leaving open grooves on the surface of convex side A.

On the middle part of convex side A, as shown in Figure 2, the most serious freckles were observed, although the local curvature effect was relatively small. The thickness of the cross-sectional mold must be an important promoting factor, *i.e.*, the size factor, to provide a sufficient reservoir to support the interdendritic convection and hence the onset of freckling. On the other side, regardless of the favorable size factor and thermal condition of concave side B, no freckles were observed. The interpretation for this important phenomenon is proposed as the curvature effect of the component cross section. The negative curvature of site B diverges and weakens the surface effect compared with positive curvature, which will strengthen the surface effect owing to the overlapping effect.

Based on our recent work,^[37,38] freckles occur not only on the external surfaces, but also inside the castings where a core was inserted. This is also attributed to the above-stated surface effect or wall effect, because both the shell and core wall can provide very high permeability for freckling convection in the mushy zone. Figure 3 shows the cross section of a cylindrical sample with an inserted ceramic tube as core. The external freckles were observed beneath the outside surfaces as indicated with A₁ in Figure 3, revealing the surface effect, *i.e.*, the wall effect, on the freckle formation. Internal freckles were observed only in regions A₂ inside of the core tubes, while region B outside the core tube remained freckle free. This important phenomenon is correlated with the curvature effect on freckle formation. Since convex shapes (regions A₁ and A₂ in Figure 3) have a positive curvature, the combination of the overlapping effect aggravates the formation of freckles. This is similar to the convex side of the blade where the most serious freckles were observed (Figures 2 and 3(a)). For the concave surface in region B, a negative curvature suppresses the freckle formation leading to a freckle-free structure (Figure 2). The schematic diagram summarized in Figure 3(b) indicates the freckling and freckling-free regions contacted the ceramic core. The insertion of the ceramic cores into the superalloy components provides the internal wall to promote freckle formation. However, the freckling consequence is very different because of the curvature effect of the core surface shape.

The favorable locations around the blade contour are schematically illustrated in Figures 4(a) and (b) with shell mold thickness to indicate the local solidification condition. The freckle formed on the leading (C) and trailing edge (D) of the large blade indicates the edge effect—promoting freckle formation. However, this phenomenon appears to contradict the current knowledge about the size effect in which freckles are normally

Fig. 2—View of the decanted solidification front of a large blade and freckle chains formed on the leading edge C and trailing one D and its corresponding detailed views on convex side A showing serious freckles and freckle-free concave side B.

Fig. 3—Cross section of a cylindrical sample showing the freckling region A_1 and A_2 as well as the freckle-free region B (a). Schematic indicating the freckling and freckle-free regions under the curvature effect of external and internal surfaces (b).

not present in small cross sections. Figure 4(b) shows both edges, especially the trailing edges, have very thin mold thickness. Freckle formation should be avoided in these regions because of the faster solidification rate in the component. In addition, the edges in C and D have good cooling conditions due to the thin mold thickness as shown in Figure 4(b). Therefore, relevant locations on blades are assumed to be unfavorable sites for freckle formation. On the other hand, the middle part of concave side B with a thick mold is assumed to have the worst cooling condition and the smallest viewing angle for heat radiation. It was surprising to observe the freckles on side A, which has better cooling conditions. Therefore, there must be other factors influencing the freckle formation apart from the effects of the casting size and cooling rate.

The result of edge and curvature effects on freckle formation is schematically illustrated in Figure 4(c). In the figure the blade contour is simplified as a polygonal section to illustrate the surface effect on freckle formation in complex components. Edges A, C and D are convex edges with different angles, whereas concave edge B presents an angle > 180 deg. Surface effect zones and overlapping zones are marked on Figure 4(c). At edges A, C and D, the surface effect zones of the neighboring sides are overlapped for an angle < 180 deg. As illustrated in the figure, the effect of the convection condition on freckle formation in the overlapping region is doubled compared with the effect at the flat side, leading to the so-called “edge effect” on freckle formation (Figures 1 and 2). To some extent, the overlapping effect of the neighboring sides is more pronounced if the

Fig. 4—Schematic of the blade contour showing the freckling locations (a) and corresponding shell mold thickness (b). Schematic of the surface effect zones and their overlap in a polygonal casting section (c).

included angle becomes smaller according to the observations of freckles on the trailing edges of turbine blades. At concave edge B in Figure 4(c) where an included angle > 180 deg occurs inside of the polygonal, there is a gap in the wedge shape. No freckle forms in concave edge B.

Based on the above results, the following conclusions can be drawn:

- (1) Fluid permeability near the wall is much higher than that inside of the casting, promoting thermal-solutal convection and freckle formation on the component surface.
- (2) On the edges of the components, the surface effects on convection overlap each other, providing a more favorable freckling condition than that on the flat surfaces, leading to the so-called “edge effect,” promoting freckle formation.
- (3) The edge effect can be extended to the curvature effect. The convex side has a positive curvature, and the surface effect can be overlapped and then strengthened, while the concave side has a negative curvature, and the surface effect will diverge and then weaken. Therefore, freckles are observed more frequently on the convex surface than on the concave ones of castings.
- (4) The insertion of ceramic cores into casting components provides an internal wall, which promotes freckle formation on the convex surface.

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