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Introduction

1.1 Development and Practical Application of Single-crystal Nickel Alloy

Nickel alloys possess excellent comprehensive properties, such as high-temperature strength, high oxidation resistance, high fatigue resistance, and high thermal stability, and therefore have been employed widely in manufacturing the hot-end components of aeroengines [1, 2]. The development of nickel alloys goes through three generations, e.g., wrought nickel alloy, solidified directionally nickel alloy, and single-crystal nickel alloy (Figure 1.1). The temperature capability is enhanced from generation to generation. For example, compared to directionally solidified nickel alloy, a single-crystal turbine blade allows an operating temperature higher by around 25–50 °C, equivalent to an increase in turbine blade service life by up to 3 times from the aspect of working efficiency.

The turbine inlet temperature has been improved significantly for advanced aeroengines. Using the single-crystal hollow turbine blades can make the turbine inlet temperature reach 2100 K for the F119 aeroengine. At such a high temperature, the polycrystalline turbine blade formed by the conventional casting method can melt and cease to work. However, single-crystal turbine blade works well and is becoming the preferred choice of first-stage turbine blades of aeroengines with a higher thrust-weight ratio of above 10. This is mainly because the whole turbine blade grows from a single grain without any grain boundaries, which often induce defects of micropores and microcracks in polycrystalline nickel alloy (Figure 1.2). Meantime, the elements enhancing grain boundaries as well as decreasing the metal melting point can be reduced effectively (Figure 1.3). Thus, these promote the high temperature resistance of single-crystal nickel alloy. By using the advanced material preparation technique for single-crystal nickel alloy and the double-wall air cooling/casting-in-chill manufacturing technique for single-crystal turbine blade, the turbine inlet temperature can be increased to 2200 K, which makes the extreme machining of single-crystal nickel alloy one of the cutting-edge research topics in fabricating the military and commercial aeroengines.

Grinding of Single-crystal Superalloys: Fundamentals and Technologies, First Edition.
Wenfeng Ding et al.

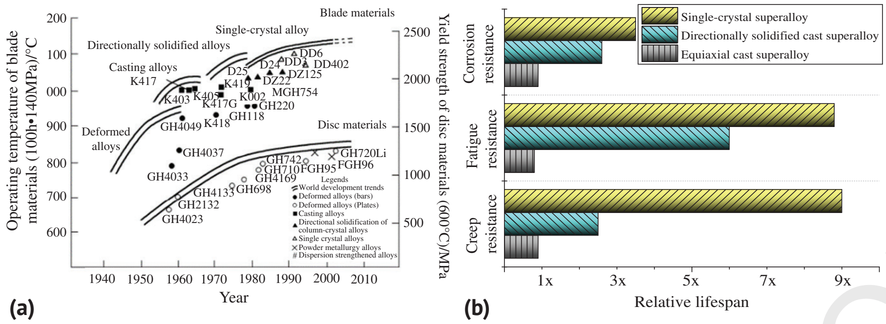


Figure 1.1 Development of (a) temperature capability and (b) mechanical properties of nickel alloys.

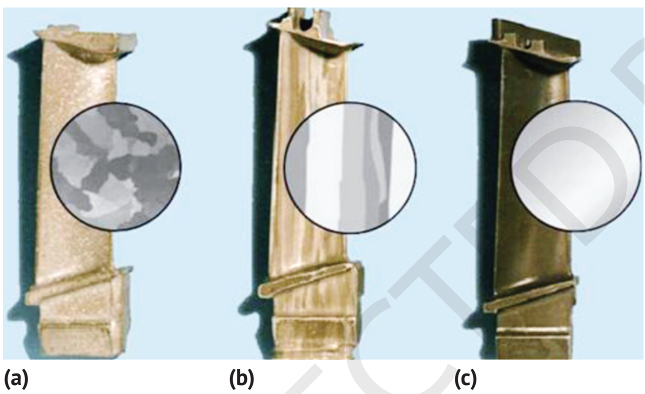


Figure 1.2 Microstructures in different casting nickel alloys: (a) equiaxial cast; (b) directionally solidified cast; and (c) single crystal [2]/Journal of Mechanical Engineering.

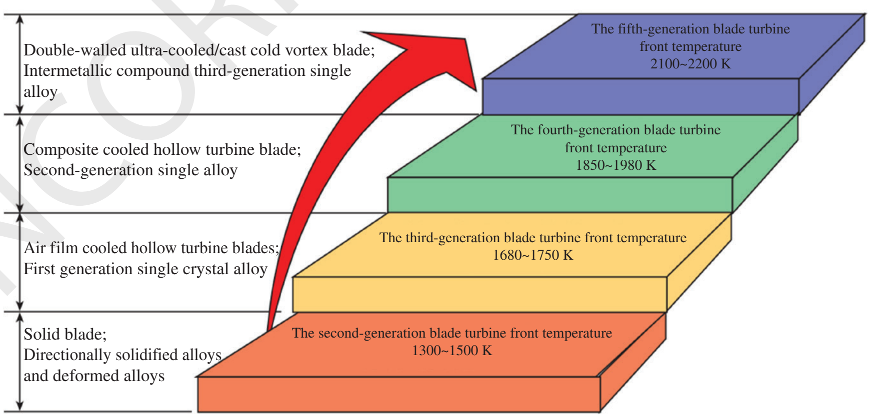


Figure 1.3 Application of single-crystal turbine blades in an advanced aeroengine. Adapted from [3].

1.2 Advantages of Grinding Technology of Single-crystal Nickel Alloy

Relying on the micro-cutting behaviors of thousands of abrasive grains on the wheel surface, the grinding process can fabricate a high-quality surface with low surface roughness, compressive stresses, and high accuracy (Tables 1.1 and 1.2), regardless of workpiece materials. This nature is different from the conventional turning, broaching, and milling methods, which often face major challenges in difficult-to-cut materials (i.e., nickel alloys) because of the rapid tool wear and the huge difficulty in controlling surface integrity and accuracy (Table 1.3). Currently, various grinding techniques have been developed to fulfill the requirements of different practical applications for almost any workpiece material (e.g., nickel alloys and ceramics). For instance, surface grinding is usually employed in manufacturing the automobile components and machine tools with flat surface requirements; profile grinding is usually combined with the creep-feed deep machining method that permits high efficiency in grinding the aeroengine parts with large stock removals and complex shapes; and micro grinding works as one of the effective methods to fabricate the micro features in metals. The common characteristic of the abovementioned grinding techniques is that the grinding process always serves as the final process to guarantee the workpiece surface quality.

In the case of aeroengine manufacturing, the typical features of nickel alloy turbine blades include high machining accuracy, good surface quality, and high fatigue resistance. Though the nontraditional machining methods (e.g., electrochemical

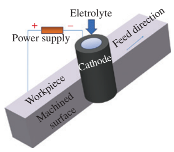
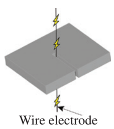
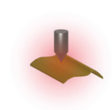
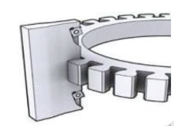
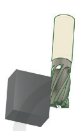
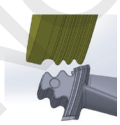
Table 1.1 Material removal rates achieved in the common grinding process.

Contents	Shallow grinding	Creep-feed grinding	High-speed grinding	High-efficiency deep grinding
Grinding depth a_p (mm)	Low 0.001–0.05	High 0.1–30	Low 0.003–0.05	High 0.1–30
Workpiece speed v_w (m/min)	High 1–15	Low 0.05–0.5	High 1–15	High 0.5–10
Grinding speed v_s (m/s)	Low 15–40	Low 15–40	High 60–200	High 60–200
Material removal rate Q_w' ($mm^3/(mm \cdot s)$)	Low 0.05–2	Low 1–10	Medium ≤ 60	High 50–2000

Table 1.2 Surface roughness achieved in the common grinding process.

Grinding methods	Conventional grinding	Precision grinding	Ultraprecision grinding	Mirror grinding
Surface roughness R_a (μm)	0.16–1.25	0.04–0.16	0.01–0.04	≤ 0.01

Table 1.3 Main methods and related characteristics for machining single-crystal nickel alloy components.

Machining method	Machining efficiency	Machining accuracy	Machined surface quality	Other characteristics
 Electrochemical machining (ECM)	High	±50 μm	$R_a \leq 1.6$ μm, with slight/without affected layer	With slight/without electrode wear, suitable for mass production, large initial investment, and not environmentally friendly
 Electrical discharge machining (EDM)	Medium	±5 μm	$0.2 \leq R_a \leq 3.2$ μm, with affected layer and even microcrack	Suitable for any workpiece materials, having electrode wear, suitable for mass production, large initial investment, and not environmentally friendly
 Additive manufacturing	Low	±350 μm	$3.2 \leq R_a \leq 12.5$ μm, easy to deform	Limited workpiece size, difficulty in fixturing and supporting workpiece, and large initial investment
 Broaching	Medium	≤ 10 μm	$0.8 \leq R_a \leq 1.6$ μm	Rapid tool wear and high cost
 Milling	Low	≤ 10 μm	$0.4 \leq R_a \leq 3.2$ μm	Rapid tool wear, limited workpiece size, and low machining efficiency
 Grinding	Medium	≤ 5 μm	$R_a \leq 0.6$ μm, with compressive stresses	Rapid tool wear if using conventional abrasive wheels, good surface quality