

Deformation behavior of as-cast Ni-based superalloy under wide temperature range with low strain rates

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Abstract: The mechanical behavior of superalloys during cooling is crucial for understanding crack formation in casting. Tensile tests with different strain rates were conducted on as-cast nickel-based superalloy Mar-M247LC across 25 °C to 1,250 °C. Results show that yield strength increases with strain rates at constant temperature but decreases with temperatures at constant strain rate. Ultimate tensile strength (UTS) peaks at about 1,400 MPa between 600 °C and 800 °C before declining, and it is notable that UTS shows small differences across three strain rates below 950 °C. Strain rate sensitivity coefficient generally increases with temperature, reaching 0.2472 at 1,250 °C. The fracture morphology is jointly governed by temperature and strain rate. Intergranular fracture is dominated by brittle phases, prevailed at 25 °C and 600 °C. A transition to dimple rupture occurs between 800 °C and 950 °C, with dimple density increasing as the strain rate decreases. At 1,100 °C, an intergranular fracture mode is presented. At the extreme temperature of 1,250 °C, γ' phase melting exacerbates brittleness under high strain rates, while promoting lamellar intergranular fracture via grain boundary segregation under low strain rates. During directional solidification above 1,100 °C, uniform cooling of the casting is essential, and it mitigates thermal shrinkage stress by narrowing temperature gradients, thus preventing stress concentrations arising from uneven cooling rates. Below 1,100 °C, the alloy shows relatively high strength under different strain rates, with small differences. Thus, the cooling rate can be increased appropriately, which improves production efficiency.

Keywords: Ni-based superalloy; as-cast alloy; tensile deformation; strain rate sensitivity; fracture morphology

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1 Introduction

Nickel-based superalloys are widely used in heavy-duty gas turbine blades due to their excellent creep strength and surface stability^[1-3]. The columnar crystal blades are prepared by the directional solidification process,

which eliminates the transverse grain boundaries, leading to improved mechanical properties^[4-6]. The actual alloy shrinkage process is often subjected to various resistances from the structures of shell^[7], core^[8], casting and gating system^[9], leading to tensile stress generated inside the casting. If the stress exceeds the strength of the alloy at that temperature, cracks will form^[10, 11]. Studying the mechanical behavior of alloys in a wide temperature range during casting, especially tensile deformation and fracture mechanisms, can enhance the understanding of solid-state deformation during the casting process of superalloys.

Many researchers have conducted studies on the tensile process and deformation behavior of columnar crystal superalloys in the past few decades. Lin et al.^[12] studied the tensile deformation behavior of a typical

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superalloy with solution treatment in the temperature range of 920 to 1,040 °C and the strain rate range of 0.001 to 0.01 s⁻¹, and pointed out that the combined effect of local necking and micropore aggregation led to fracture, and δ phase (Ni₃Nb) and carbides are the nucleus for the formation of microvoids. Choi et al.^[13] found that the tensile properties of solution-and-aging treated CM247LC superalloy are closely related to temperature and dislocation structure. As the test temperature increases, the dislocation density within the γ' phase of tensile specimens decreases, while that in the γ matrix increases. The alloy exhibits the highest tensile strength at 750 °C and the best plasticity at 649 °C. Guo et al.^[14] observed that during the tensile testing of heat-treated DZ51G at 760 °C, the γ' phase was strengthened, and the dislocation motion mechanism gradually transformed from shearing γ' particles at low temperatures to Orowan looping around the γ' phase at high temperatures. Concurrently, the fracture mode transitioned from brittle to ductile. Cui et al.^[15] studied the tensile properties of the heat treated M951G alloy within the temperature range of 20 °C to 1,100 °C and explained the temperature dependence of the alloy's deformation. Zhang et al.^[16] investigated the differences in fracture surfaces of CMSX-4 under two strain rates of 5×10⁻⁴ s⁻¹ and 5×10⁻³ s⁻¹ at room temperature, revealing that the fracture morphology of tensile samples is strongly correlated with strain rate. The size of cleavage planes and dimples increases with increasing strain rate.

However, most researchers have focused on the service performance of heat-treated alloys^[12-15, 17-19], while few studies on the as-cast alloys^[20]. Investigating the deformation behavior of as-cast alloys under different temperatures and strain rates benefits to predict their deformation characteristics during casting cooling. Furthermore, during cooling, the shrinkage rate is directly related to the cooling process, showing that

a faster cooling rate leads to greater shrinkage deformation of the alloy. In this study, different strain rates were used to reflect the influence of different cooling rates. Considering the actual slow cooling process, the deformation behavior under low strain rates was mainly studies.

Specifically, the tensile deformation behavior of as-cast nickel-based superalloy MAR-M247LC at the temperature range of 25 to 1,250 °C and strain rates from 10⁻⁴ s⁻¹ (quasi-static) to 10⁻² s⁻¹ was investigated. It aims to clarify the deformation and fracture behavior under the coupling effect of wide temperature ranges and low strain rates, and to elucidate the strain rate sensitivity and solid-state fracture characteristics of nickel-based superalloy.

2 Materials and methods

Alloys were prepared using an ALD directional solidification furnace, with the nickel-based superalloy MAR-M247LC. Its nominal chemical composition is listed in Table 1. The pouring temperature was 1,550 °C, followed by a holding time of 2 min. Then, downward withdrawal was conducted at a rate of 4 mm·min⁻¹, yielding alloy ingots with dimensions of 100 mm×20 mm×200 mm, where the 200 mm dimension corresponds to the withdrawal direction. Differential scanning calorimetry (DSC) was performed using a Mettler Toledo TGA/DSC 3+ analyzer under high-purity argon (99.99%, flow rate: 100 mL·min⁻¹). The metallic specimens were pulverized into fragments subsequent to hydrogen reduction, and approximately 600 mg of the sample was extracted for examination. The differential thermal flux was recorded during a heating cycle at 20 K·min⁻¹ up to 1,450 °C, held isothermally for 15 min, and then cooled at the same rate. Temperature calibrations were performed using certified reference materials.

Table 1: Chemical compositions of studied Ni-based superalloy (wt.%)

W	Co	Cr	Al	Ta	Hf	C	B	Ni
9.51	9.21	8.17	5.65	3.23	1.43	0.077	0.015	Bal.

The dendritic microstructure of samples was observed using a Zeiss Axio Scope.A1 optical microscope (OM). Metal samples were first ground and polished, and the polished surfaces of the MAR-M247LC alloy were etched with an etchant (5 g CuSO₄+100 mL HCl+5 mL H₂SO₄+80 mL H₂O).

Uniaxial tensile tests were conducted using a Gleeble-3500 thermal simulator at deformation temperatures ranging from 25 to 1,250 °C and strain rates of 10⁻⁴ s⁻¹, 10⁻³ s⁻¹, and 10⁻² s⁻¹. Referencing GB/T228.2-2015 Chinese national standards, tensile specimens with a gauge length of 9.53 mm and a diameter of 4 mm were designed, as shown in Fig. 1. Before loading, the specimens were heated to the test temperature at a rate of 10 °C·s⁻¹ and held for 2 min to stabilize the temperature, with argon gas purging inside the furnace to prevent oxidation. After fracture, the specimens were rapidly cooled by water cooling. The fracture surfaces were observed using a scanning electron microscope (SEM).

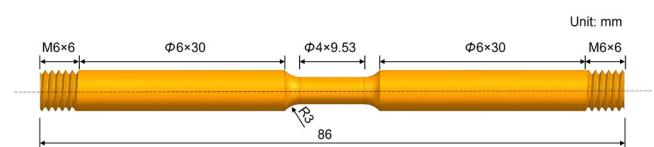


Fig. 1: Schematic diagram of tensile specimen

3 Results and discussion

3.1 Phase transformation and initial microstructure of as-cast superalloy

The DSC thermograms obtained during the heating cycles of the as-cast MAR-M247LC specimens are presented in Fig. 2. The heating profiles reflect the non-equilibrium microstructural state, and the measured transition temperature values are tabulated in Table 2. The initiation of melting appears to overlap with the dissolution of the γ' phase. During

heating, the onset temperature of melting was determined via the extrapolation method. A distinct deviation in the heat flow curve prior to melting is attributed to the dissolution of carbide phases. Figure 2 also displays the thermograms acquired during slow cooling and solidification processes in the DSC. The temperatures corresponding to the liquidus (T_L), carbide precipitation (T_{MC}), solidification completion (T_S), and γ' phase formation ($T_{\gamma'}$) are all determined. A prominent eutectic reaction at 1,267.7 °C (T_{Eut}) is evident, likely involving the γ , γ' , and carbide phases^[21].

Figure 3 shows the initial microstructure of the directionally solidified MAR-M247LC superalloy, which contains numerous

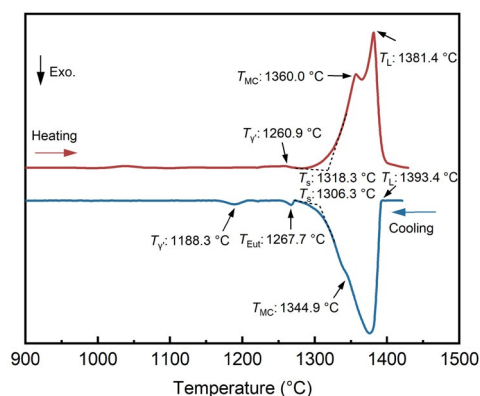


Fig. 2: DSC curves of as-cast MAR-M247LC

Table 2: Phase transition temperatures of as-cast MAR-M247LC

	γ' phase	Solidus	MC carbide	Liquidus	Eutectic
Heating (°C)	1,260.9	1,318.3	1,360.0	1,381.4	\
Cooling (°C)	1,188.3	1,306.3	1,344.9	1,393.4	1,267.7

defective structures such as microcracks and microporosity. These defects arise from inclusions, segregation, and improper matching of ceramic mold during the casting process^[22, 23].

3.2 Tensile deformation behavior

3.2.1 Yield strength and ultimate tensile strength

Figure 4 presents the true stress-true strain tensile curves of as-cast Ni-based superalloy MAR-M247LC under various temperatures and strain rates. All curves exhibit both elastic and plastic deformation stages. Brittle fracture characteristics are observed in the curves from 25 to 800 °C, whereas from 950 to 1,250 °C, the tensile curves also display certain steady-state flow stress and flow softening features. The flow softening behavior at last stage of tension indicates that ductile fracture may occur within this temperature range.

Comparative analysis reveals that true stress-true strain behavior is significantly influenced by temperature when comparing curves at the same strain rate across different temperatures. Similarly, when analyzing curves at three different strain rates at the same temperature, the impact of strain rate on stress curves becomes evident. Notably, the combined effect of temperature and strain rate is particularly pronounced above 800 °C, while the differences among curves under different strain rates are more significant.

At the same temperature, lower strain rates correspond to lower yield stress and greater elongations. This phenomenon occurs because lower strain rates lead to longer tensile duration, facilitating dislocation slip and thus increasing plastic strain. In contrast, within the temperature range of room temperature to 800 °C, strain rate has a relatively minor effect on peak stress.

The tensile properties of as-cast MAR-M247LC superalloy under different conditions are exhibited in Fig. 5. Figure 5(a) shows the yield strength of as-cast MAR-M247LC superalloy under various tensile conditions. Due to the indistinct yield

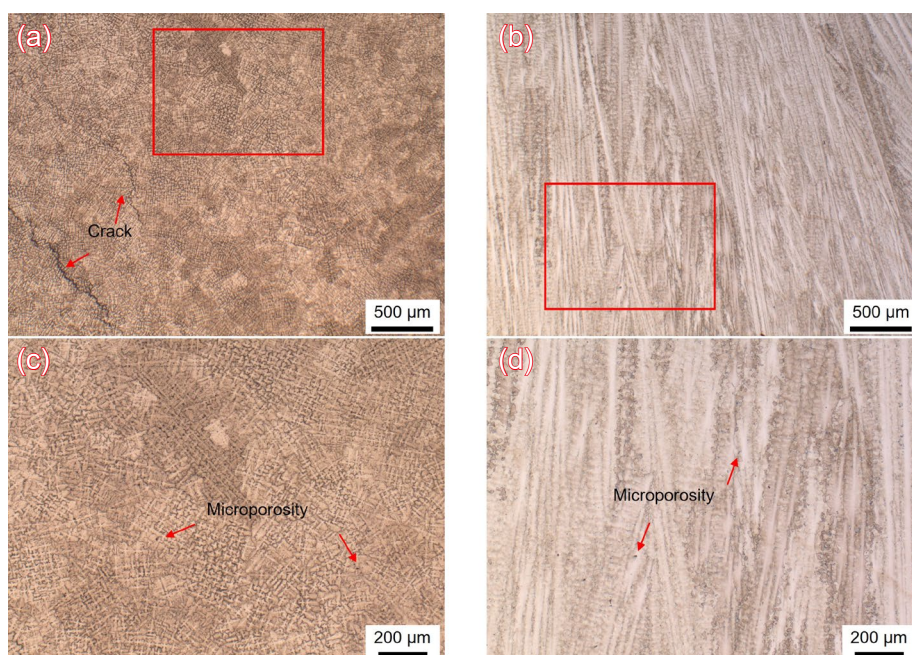


Fig. 3: Initial microstructure of directionally solidified MAR-M247LC superalloy: (a) radial section; (b) axial section; (c) a detailed view of (a); (d) a detailed view of (b)

phenomenon in the stress-strain curves, the specified plastic elongation strength (proof stress at specified plastic elongation, $R_{p0.2}$) was used for statistical analysis. At a constant temperature, the yield strength consistently increases with the strain rate increases, as observed under all test temperatures. This behavior is attributed to the accelerated dislocation

multiplication rate and intensified dislocation pile-up during the elastic stage at higher strain rates, which necessitate higher energy to initiate dislocation slip^[14]. Conversely, at a constant strain rate, the yield strength decreases with increasing deformation temperature, as elevated temperatures reduce the free energy barrier for dislocation motion^[24].

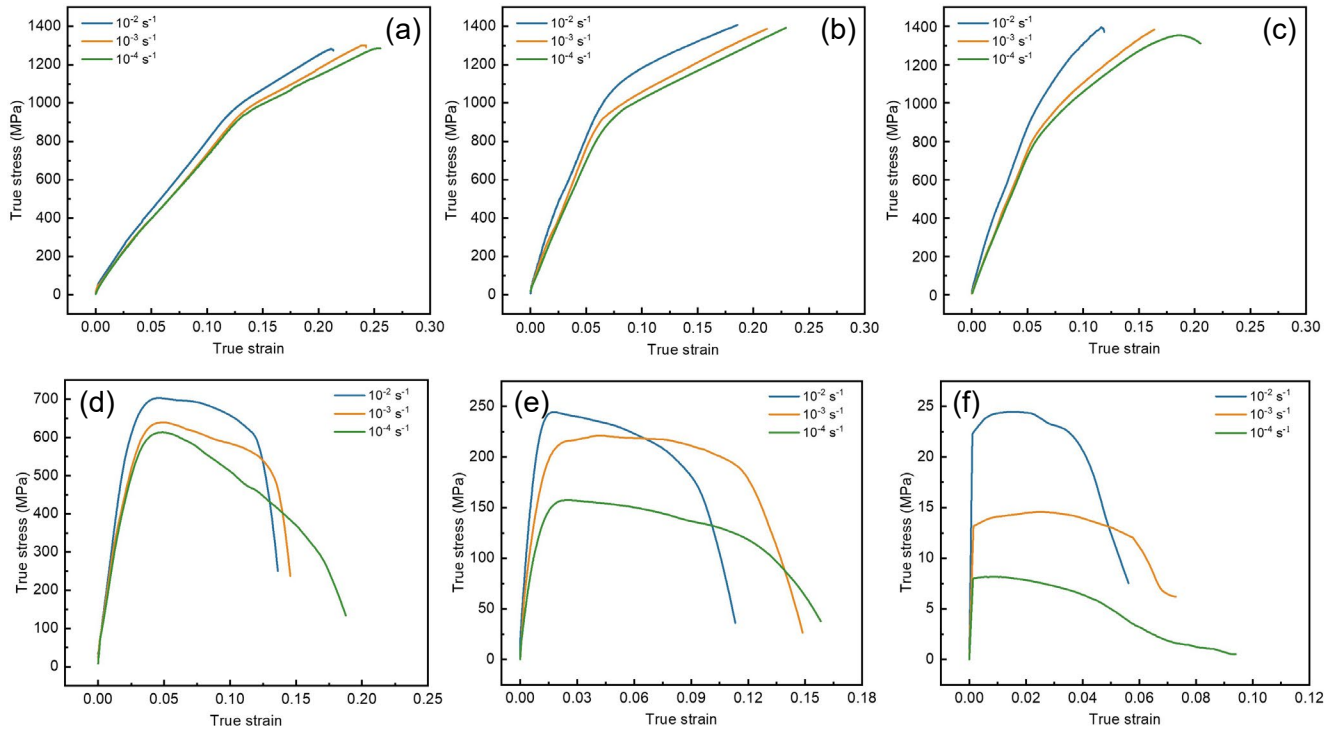


Fig. 4: True stress-true strain curves of MAR-M247LC superalloy under different deformation temperatures and deformation rates: (a) 25 °C; (b) 600 °C; (c) 800 °C; (d) 950 °C; (e) 1,100 °C; (f) 1,250 °C

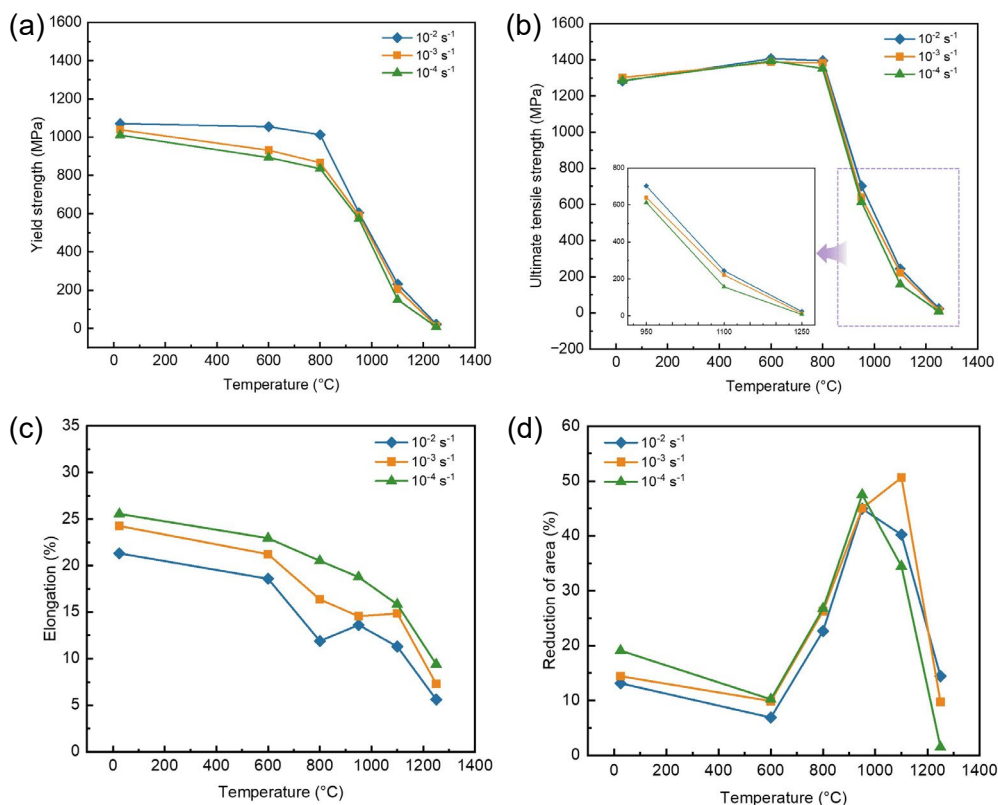


Fig. 5: Tensile properties of as-cast MAR-M247LC alloy under different conditions: (a) yield strength; (b) ultimate tensile strength; (c) elongation; (d) reduction of area

Figure 5(b) shows the ultimate tensile strength (UTS) of as-cast MAR-M247LC superalloy under various tensile conditions. The UTS first increases and then decreases with rising temperature, peaking between 600 °C and 800 °C. The coefficient of variation^[25] (C_v) was used to quantify data dispersion, where σ represents the standard deviation and μ represents the mean.

$$C_v = \frac{\sigma}{\mu} \quad (1)$$

All C_v values below 950 °C are less than 2%, whereas significant increases are observed at 950 °C, 1,100 °C, and 1,250 °C (Table 3). This indicates that the UTS becomes highly sensitive to strain rate at elevated temperatures, while showing negligible dependence at lower temperatures.

Table 3: Value of C_v at different temperatures

Temperature (°C)	C_v
25	0.81%
600	0.75%
800	1.60%
950	7.07%
1,100	21.69%
1,250	52.13%

3.2.2 Elongation and reduction of area

As shown in Fig. 5(c), temperature acts as the primary variable here, at the same strain rate, the elongation to fracture generally tends to decrease with increasing temperature. This is because higher temperatures weaken grain boundaries by enhancing atomic diffusion^[26] and thus promoting the formation of defects such as voids and cracks. During tension, these grain boundary defects easily act as crack initiation sites and propagate, causing premature fracture and reduced elongation. An exception occurs at a strain rate of 10^{-2} s^{-1} and 800 °C, where the effect of strain rate on deformation behavior is significantly amplified: dislocations rapidly accumulate at grain boundaries. This accumulation hinders effective deformation coordination across boundaries. Consequently,

stress concentration is exacerbated. This promotes crack initiation and propagation. Ultimately, it leads to abnormally low elongation. At lower strain rates (10^{-3} s^{-1} and 10^{-4} s^{-1}), dislocations have more time for climb and cross-slip to coordinate grain boundary deformation, avoiding this issue^[27].

For as-cast MAR-M247LC, the reduction of area first decreases, then increases, and finally decreases again as temperature rises [Fig. 5(d)]. Below 1,100 °C, reduction of area slightly increases with decreasing strain rate, but this trend is disrupted at 1,100 °C and 1,250 °C. It is indicated that within this temperature range, phase transformations of strengthening phases or abnormal grain growth may occur in the superalloy, complicating deformation conditions. This will be further analyzed and discussed with fracture surface observations.

3.2.3 Strain rate sensitivity

During tensile deformation, the strain rate sensitivity of metals or alloys influences necking or strain localization phenomena^[28]. The strain rate sensitivity coefficient (m)^[29] is employed to evaluate the degree of stress discrepancy at different strain rates under the same temperature (T) and strain (ϵ) during the tensile process. This coefficient is calculated by the slope of the $\ln\sigma$ - $\ln\dot{\epsilon}$ ^[30].

$$m = \left. \frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}} \right|_{\epsilon, T} \quad (2)$$

Figure 6 illustrates the strain rate sensitivity at different temperatures, evaluated within the middle range of plastic true strain for each temperature (the specific true strain values used are 0.175 at 25 °C, 0.15 at 600 °C, 0.075 at 800 °C and 950 °C, 0.03 at 1,100 °C, and 0.02 at 1,250 °C). As shown in Fig. 6(a), the differences in $\ln\sigma$ are relatively small at 25 °C, 600 °C, and 800 °C, whereas more pronounced variations are observed at 950 °C, 1,100 °C, and 1,250 °C. Generally, when the value of m is lower than 0.05, it indicates that the material behavior is insensitive to the strain rate^[31]. In Fig. 6(b), the strain rate sensitivity coefficient is the lowest at 25 °C ($m=0.0186$), indicating that low strain rate changes have minimal impact on the true stress-true strain curves at this temperature. At 800 °C and 950 °C, the sensitivity coefficients (0.0432 and 0.0402, respectively) show little difference. Due to sufficient energy for dislocation motion and

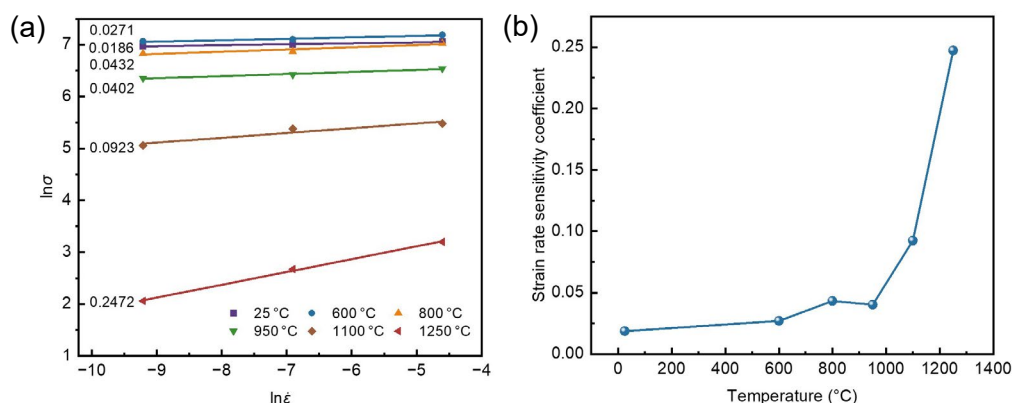


Fig. 6: $\ln\sigma$ - $\ln\dot{\epsilon}$ slope curve (a) and strain rate sensitivity coefficient (b) at different temperatures

high dislocation density within this temperature range, which distinguishes them from lower-temperature behaviors. Notably, at 1,100 °C and 1,250 °C, the m values increase to 0.0923 and 0.2472 respectively, demonstrating significant strain rate sensitivity. Overall, for as-cast MAR-M247LC superalloy, the strain rate sensitivity coefficient increases with temperature, exhibiting relatively comparable sensitivity characteristics at intermediate temperatures (800 to 950 °C), and the high strain rate sensitivity at 1,250 °C indicates that near the alloy solidification temperature, sufficiently slow deformation rates may lead to significant plastic deformation and even crack formation under low stress conditions.

In the directional solidification cooling process, due to the complexity of the casting structure, there are significant differences in deformation rates between different regions under the same temperature field. At the same temperature, the high-strain-rate region develops high stress, which generates a stress-strain gradient. When this gradient is transmitted to the low-strain-rate region within the same temperature field, it readily induces the initiation and propagation of solid-state cracks. Therefore, in the high-temperature cooling range ($\geq 1,100$ °C), the withdrawal rate needs to be reduced to coordinate the deformation of different regions, thereby weakening the stress-strain gradient and reducing the risk of solid-state cracks. In the medium and low temperature ranges, the strain rate sensitivity of the material is low, and the cooling rate can be appropriately increased to shorten the production cycle and optimize process efficiency.

3.3 Fracture characteristics

3.3.1 Fracture morphology after tensile tests

Figure 7 shows the sectional fracture morphologies of the failed specimens at deformation temperatures ranging from 25 to 800 °C under strain rates of 10^{-2} s $^{-1}$, 10^{-3} s $^{-1}$, and 10^{-4} s $^{-1}$. At low deformation temperatures (25 to 800 °C), the fracture surfaces exhibit irregular undulating regions. The fracture morphology at 25 °C reveals distinct carbide particles and eutectic phases [(Figs. 7(a)–(c)], with clear grain contours, indicating dominant intergranular fracture. As the strain rate decreases, small amounts of dimples appear [Fig. 7(c)], slightly improving plasticity, though cleavage facets remain predominant. Similarly, at 600 °C, intergranular fracture remains the primary failure mode, characterized by pronounced surface undulations and cleavage steps at the fracture edges. The presence of short, dense secondary cracks [Figs. 7(d)–(f)] suggests a strong brittle tendency under these conditions. At 800 °C, dimples form across all strain rates, and the reduction of area at 800 °C is significantly higher than at 600 °C under the same strain rate. Notably, at the strain rate of 10^{-4} s $^{-1}$, localized necking is observed, evident in both Fig. 5(d) and Fig. 7(i), indicating improved plasticity of the alloy at low strain rates.

Figure 8 shows the fracture morphologies of specimens deformed at temperatures ranging from 950 to 1,250 °C under strain rates of 10^{-2} s $^{-1}$, 10^{-3} s $^{-1}$, and 10^{-4} s $^{-1}$. At 950 °C and 1,100 °C, obvious necking occurs on the fracture surfaces. Due to the

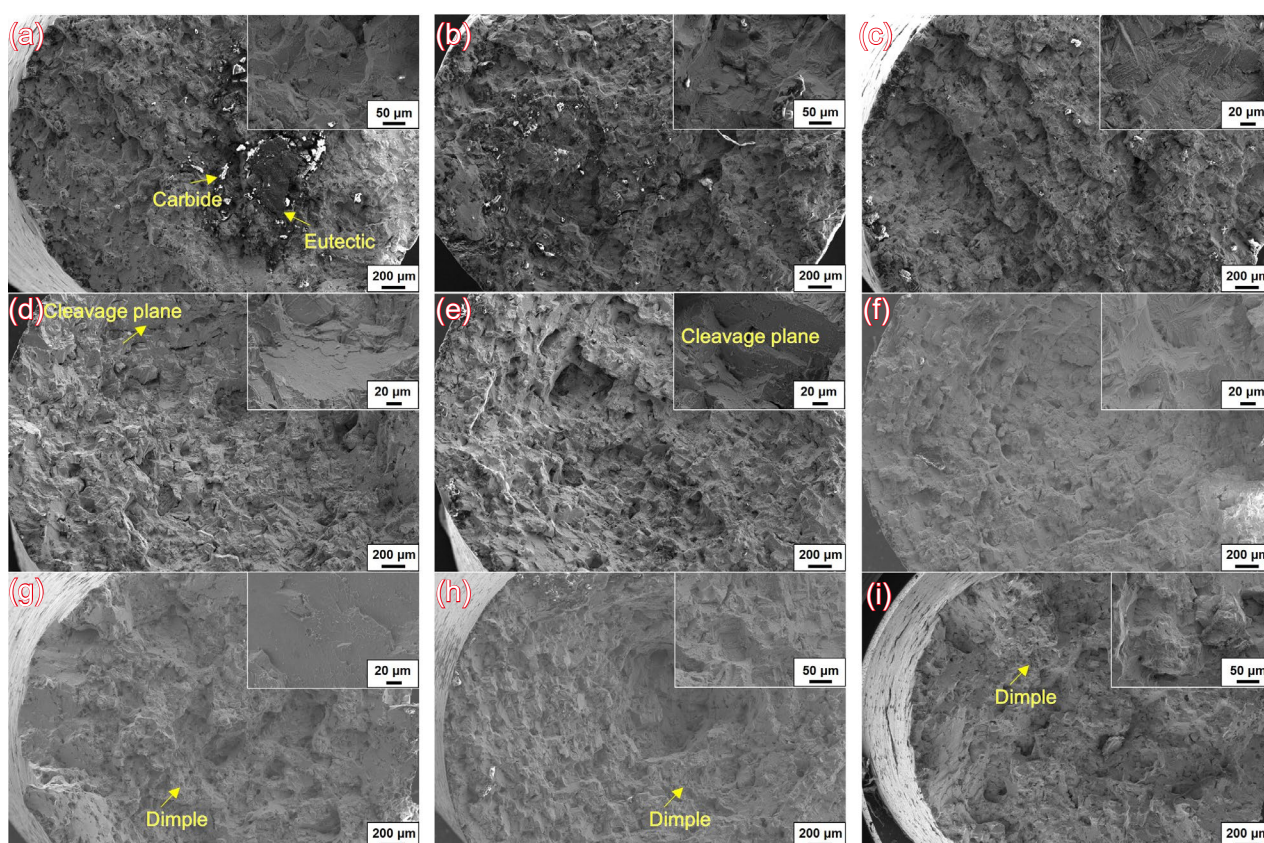


Fig. 7: SEM images of fracture surface at 25 to 800 °C with different strain rates: (a) 25 °C- 10^{-2} s $^{-1}$; (b) 25 °C- 10^{-3} s $^{-1}$; (c) 25 °C- 10^{-4} s $^{-1}$; (d) 600 °C- 10^{-2} s $^{-1}$; (e) 600 °C- 10^{-3} s $^{-1}$; (f) 600 °C- 10^{-4} s $^{-1}$; (g) 800 °C- 10^{-2} s $^{-1}$; (h) 800 °C- 10^{-3} s $^{-1}$; (i) 800 °C- 10^{-4} s $^{-1}$

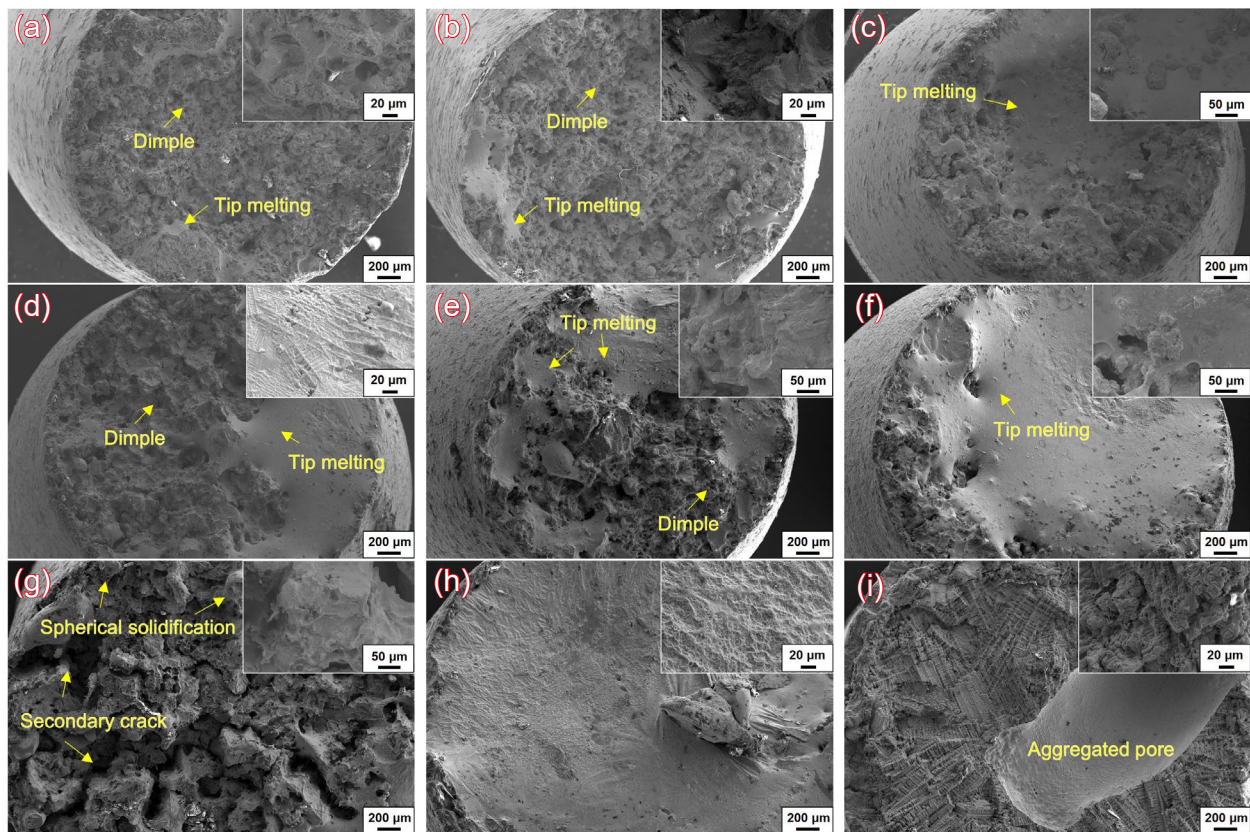


Fig. 8: SEM images of fracture surface at 950 to 1,250 °C with different strain rates: (a) 950 °C- 10^{-2} s $^{-1}$; (b) 950 °C- 10^{-3} s $^{-1}$; (c) 950 °C- 10^{-4} s $^{-1}$; (d) 1,100 °C- 10^{-2} s $^{-1}$; (e) 1,100 °C- 10^{-3} s $^{-1}$; (f) 1,100 °C- 10^{-4} s $^{-1}$; (g) 1,250 °C- 10^{-2} s $^{-1}$; (h) 1,250 °C- 10^{-3} s $^{-1}$; (i) 1,250 °C- 10^{-4} s $^{-1}$

high testing temperature, the experimental equipment still outputs a high current at the moment of necking fracture, resulting in local overheating. This causes melting at the fracture tip, covering part of the fracture characteristics^[32]. As the strain rate decreases, the area of the melted tip region increases, as shown in Figs. 8(a)–(f). At 950 °C, a large number of equiaxed dimples appear on the fracture surface. Compared with those at 800 °C, these dimples are smaller in size, indicating a tendency toward ductile fracture at this temperature. At 1,100 °C, the fracture morphology exhibits intergranular fracture characteristics accompanied by deep dimples [Figs. 8(d) and (e)]. The fracture morphologies at 1,250 °C differ significantly across the three strain rates. Referencing the DSC results (Fig. 2), the melting of γ' phases starts at 1,188.3 °C. The melting of the γ' phase softens the matrix, leading to a sharp decrease in strength and ductility, with a tendency toward brittle fracture. At the high strain rate (0.01 s $^{-1}$), spherical protrusions result from melt cooling shrinkage, with deep and wide intergranular secondary cracks and flow traces formed by tensile shearing of the liquid phase [Fig. 8(g)]. Figure 8(h) shows a micro-porous network and an amorphous glassy layer, likely formed by rapid quenching of molten liquid at grain boundaries; magnification suggests deformation dominated by networked grain boundary sliding. The fracture surface in Fig. 8(i) exhibits layered grain boundary separation: prolonged high-temperature exposure dissolves most of the γ' phases, while impurity segregation at grain boundaries forms brittle phases, leading to brittle

intergranular fracture along columnar grain boundaries and the formation of large aggregated pores.

3.3.2 Effects of deformation temperature and strain rate

The influence of temperature on fracture morphology exhibits significant regular patterns. In the low to medium temperature range (25 to 600 °C), atomic diffusion capacity is weak, and carbides show lower ductility than the matrix, making them prone to fracture during tensile deformation^[33]. These carbides act as crack initiation sites, leading to dominant intergranular cleavage fracture. As the temperature rises to 800 °C and 950 °C, obvious dimples and necking generally appear, except under the 950 °C- 10^{-4} s $^{-1}$ condition obscured by molten products from Fig. 8(c), marking the transition to ductile fracture. At 1,100 °C, the coupling effect of temperature and stress softens the γ' phase, resulting in a mixed fracture mode with both intergranular fracture characteristics and deep dimples, and the toughness degrades. In the extremely high temperature range (1,250 °C), the γ' phase melts. At high strain rates, brittle characteristics such as solidified melt protrusions and intergranular secondary cracks appear on the fracture surface; while at low strain rates, impurity segregation at grain boundaries leads to complete embrittlement, resulting in layered intergranular separation. The influence of temperature on fracture morphology is relatively complex, which is closely related to the intragranular and intergranular strength of the alloy. Generally, it shows low-temperature brittleness, enhanced toughness at medium and high temperatures, and weakened toughness at extremely high temperatures.

The influence of strain rate on fracture morphology is closely correlated with temperature. At high strain rates, rapid deformation hinders plastic deformation coordination within crystals and reduces grain boundary strength^[34]. At low temperatures, brittle phases at grain boundaries directly initiate intergranular fracture, while at high temperatures (1,250 °C), this accelerates negative effects such as γ' phase melting and grain boundary element segregation, enhancing brittle characteristics. Under moderate strain rates, intergranular fracture remains dominant at low temperatures, though localized small dimples appear; at high temperatures, partial thermal activation promotes micro-void coalescence, resulting in mixed intergranular-ductile fracture features with slightly restored plasticity. At low strain rates, prolonged deformation time mitigates grain boundary cracking. Thermal activation enhances matrix plastic coordination at low temperatures, increasing dimple density and plasticity, while at high temperatures (950 to 1,100 °C), dimple coalescence transforms the fracture surface toward uniform dimple rupture. However, at extreme high temperatures (1,250 °C), grain boundary embrittlement reverts the fracture mode to brittle intergranular separation. Overall, decreasing strain rate tends to shift fracture morphology from brittle intergranular to ductile rupture, though excessively high temperatures disrupt this trend due to grain boundary degradation.

4 Conclusions

The mechanical behavior and fracture modes of as-cast MAR-M247LC influenced by temperatures and strain rates were studied in this research, and the primary findings can be outlined as follows:

(1) At a constant temperature, yield strength increases with the rise in strain rate. Conversely, at a constant strain rate, yield strength decreases with increasing deformation temperature. The ultimate tensile strength first increases and then decreases with temperature, reaching a maximum in the range of 600 to 800 °C. Below 950 °C, the ultimate tensile strengths under the three strain rates show small differences.

(2) The strain rate sensitivity coefficient generally increases with temperature, exhibiting comparable values from 800 to 950 °C. At 1,100 °C and 1,250 °C, the coefficients reach 0.0923 and 0.2472, respectively, indicating that the strain rate has a significant impact on the deformation behavior during high-temperature casting.

(3) Temperature and strain rate jointly affect the fracture morphology. At 25 to 600 °C, intergranular fracture dominated by brittle phases at grain boundaries is observed. With increasing temperature or decreasing strain rate, local dimples appear. At 800 and 950 °C, the fracture mode tends to be dimple rupture, and the number of dimples increases at low strain rates. At 1,100 °C, the fracture exhibits obvious intergranular fracture characteristics. At extreme high temperature (1,250 °C), the γ' phase partially melts. High strain rates exacerbate brittle fracture, while low strain rates lead to layered intergranular fracture due to element segregation at

grain boundaries.

(4) In the directional solidification process, the complex cast structure causes uneven regional deformation under the same temperature field. Based on the research results of strain rate sensitivity, reducing the cooling rate above 1,100 °C can weaken stress-strain gradients and lower the risk of cracks. Meanwhile, increasing the cooling rate in the medium-low temperature range can effectively shorten the production cycle. Additionally, fracture morphologies under different conditions can serve as a reference. They allow deduction of the formation stages of deformation and cracks in actual production. This helps accurately identify key stages for process optimization and improves the overall quality and reliability of castings.

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Conflict of interest

Prof. Qing-yan Xu is an EBM of *CHINA FOUNDRY*. He was not involved in the peer-review or handling of the manuscript. The authors have no other competing interests to disclose.

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