Materials Science Forum
ISSN: 1662-9752, Vol. 1134, pp 67-72
doi:10.4028/p-29oBjP

Submitted: 2024-11-01
Accepted: 2024-11-03
Online: 2024-12-11

Microstructure Analysis of the Alloy 625-nTiC Metal-Matrix-Composites Produced by Suction Casting

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Keywords: Composite, nickel, nanoparticle, microstructure, MMC.

Abstract. Alloy 625 is a Ni-based superalloy with the main alloying elements being Nb, Cr, and Mo. It is known for its excellent corrosion resistance, good weldability, both high heat and creep resistance, and good strength. The current work presents the microstructure of Alloy 625-nTiC metal matrix composites (MMC) fabricated through suction casting. The microstructure and chemical composition of strengthening phases were investigated by light microscopy, scanning electron microscopy and energy-dispersive X-ray spectroscopy. The results showed that fabricated MMC composites are characterized by a dendritic microstructure with irregular distribution of the strengthening precipitates. Based on chemical composition analysis, the strong enrichment in Nb and Ti was revealed.

Introduction

Over the years, metal matrix composites (MMCs) have been developed for use in the automotive, power, and aerospace industries. Two main manufacturing methods are used based on the temperature processing of the metallic matrix: liquid-state and solid-state processes. The aim of preparing MMCs is to combine the properties of both the matrix and particles to create a unique blend of properties. These composites combine the strength and rigidity of non-metallic reinforcing particles with the ductility of a metal matrix. Ni-based alloys are preferred as a matrix for refractory composites in high-temperature applications because they have high strength during service, as well as good hot corrosion and oxidation resistance. Ceramic particles are chosen based on criteria such as their reactivity with the matrix, wetting ability, coefficient of thermal expansion, and density. These particles possess much higher Young's moduli compared to the matrix, allowing the composite to withstand maximum stress without developing cracks. Fractured particles not only exhibit reduced effectiveness in stress accommodation but, depending on their morphology, can also contribute to the formation of defects, which adversely affect Young's modulus and strength. The selected particles should have a minimal variance in thermal expansion coefficient relative to the matrix, thus facilitating the generation of compressive or tensile stresses during service. The stresses exerted on the interfaces can enhance the density of dislocation networks, serving as an additional strengthening mechanism, which is particularly advantageous in systems featuring finer particles. An excessive difference in the coefficients used to reinforce the metal matrix can cause microcracks to form [1-5]. Particles used to strengthen the matrix include oxides, carbides, intermetallics, nitrides, borides, and silicides. These particles come in different shapes, such as nearly spherical particles, irregular blocks, whiskers, and fibres [4]. Arsenault [5] indicated that particles with an aspect ratio exceeding 1, such as platelets and whiskers, contribute more to increasing dislocation density during deformation than equiaxed particles. However, the existence of sharp edges can encourage the early formation of cracks, leading to a significant reduction in the service life. The volume fraction of particles ranges from a few to several dozen, depending on the desired mechanical properties.

However, increasing the volume fraction of particles can have consequences [6]. Beyond a certain threshold, not only does flexibility decrease quickly, but mechanical strength can also decrease, particularly at high temperatures [7]. To overcome this limitation, a metal matrix must have exceptional heat resistance and also have high compatibility with the reinforcement [8]. Assuming the metal matrix of the composite is a precipitation-hardening alloy, microstructural changes may occur during production, involving chemical reactions between the particles and the matrix, resulting in precipitate formation [9]. The interfaces between the matrix and particles, along with their surroundings, are of particular significance. The strength of bonds at these interfaces profoundly influences the final properties. It is widely acknowledged that relatively weak bonds at the interface increase susceptibility to cracking [10]. Additionally, the partial dissolution of particles can lead to the enrichment of the matrix in alloying elements, precipitating the formation of secondary phases. TiC is a promising phase for reinforcing the FCC matrix. It has a cubic structure ($Fm\bar{3}m$) with a melting point of 3065°C, low density (4.93 g/cm^3), and high Young's modulus at intermediate temperatures (350 GPa at 700°C) [11]. Titanium carbide is also renowned as one of the hardest refractory metal carbides with a Vickers hardness range of 19.6–31.4 GPa. It is expected to enhance the abrasion resistance of various metal matrix [12]. Although Alloy 625-carbide MMCs possess a high potential for improvement in products manufactured from those materials, they are still in the early stages of development.

Materials and Methodology

The composites were produced using Alloy 625 and TiC powders (Table 1). Their morphology is presented in Figure 1. The homogenised mixtures were submitted to the suction casting to fabricate the MMC rods.

Table 1. Chemical composition of Alloy 625, wt%.

Cr	Mo	Nb	Fe	Mn	Si	C	Ni
21.5	9.3	3.8	1.1	0.29	0.18	0.028	Bal.

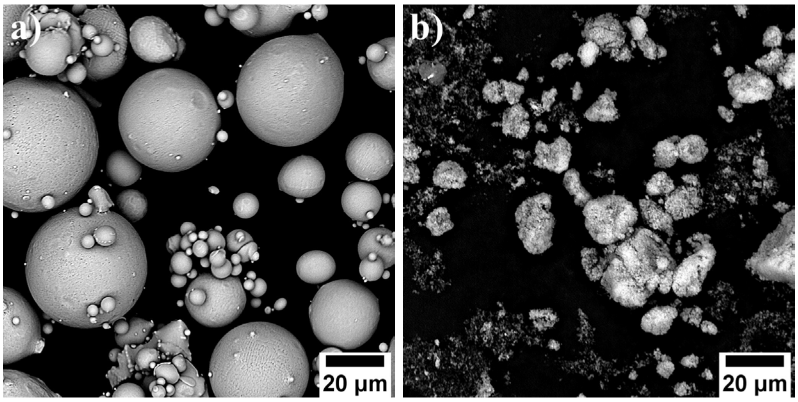


Fig. 1. Morphology of the raw powder: a) Alloy 625; b) TiC, SEM-BSE.

The samples for microstructure analysis were taken and hot-embedded in Struers Polyfast conductive resin. Then, the grinding process was carried out on sandpaper of increasing grit levels, starting from #100 to #4000. After grinding, a three-stage polishing was conducted. Firstly, on Struers DiaDuo diamond suspension with a 3 μm particle size, followed by Struers DiaDuo diamond suspension with a 1 μm particle size, and finally using Struers OP-S reagent with a silica particle size of 0.06 μm. The unetched samples were then observed using a Leica DM/LM light microscope for preliminary observations. Subsequently, observations were carried out using a BSE (back-scattered electrons) detector to identify microstructural constituents and characterize the precipitates morphology. Point semi-quantitative analysis of the chemical composition of selected elements and distribution maps of selected alloying elements was performed using the EDX detector. The accelerating voltage for imaging and analyses was set at 20 kV.

Results and Discussion

The microstructure of the Alloy 625-nTiC composites is presented in Figs 2-3. The images of the unetched microstructure confirm the lack of hot cracks and unacceptable defects. Only a local microporosity has been observed. Locally, precipitates with orange-like contrast and a size of approximately several micrometers are revealed. In Ni-based alloys, this type of precipitate is usually TiN nitrides, and their presence originates from the manufacturing process of composites.

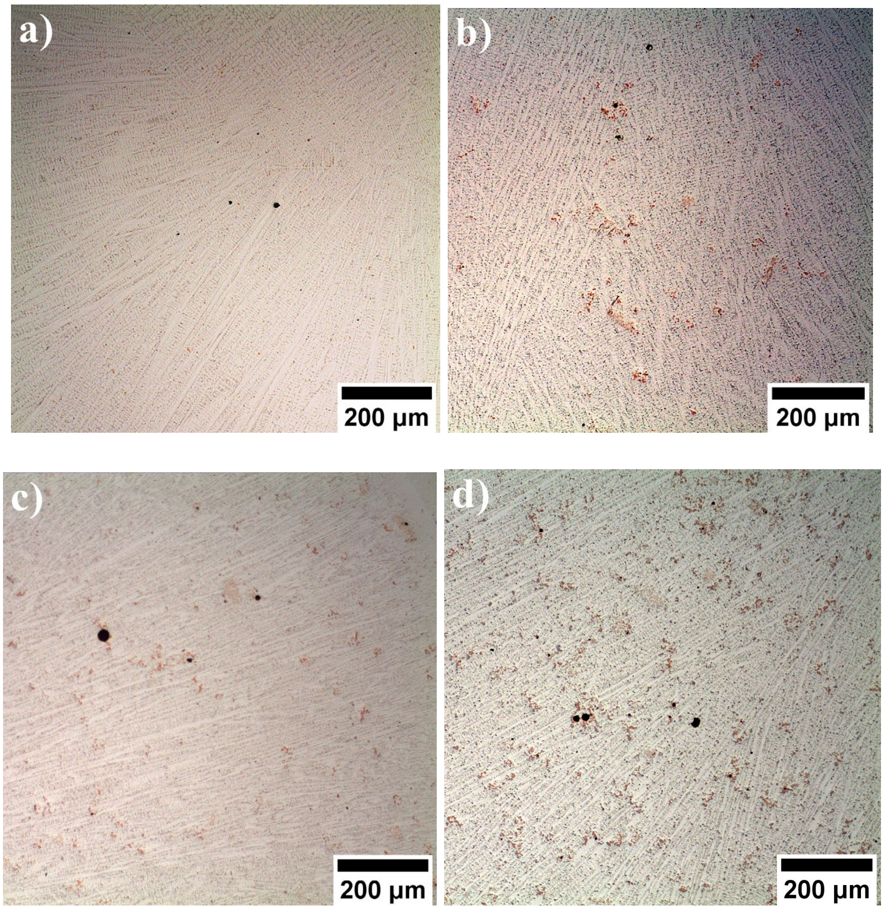
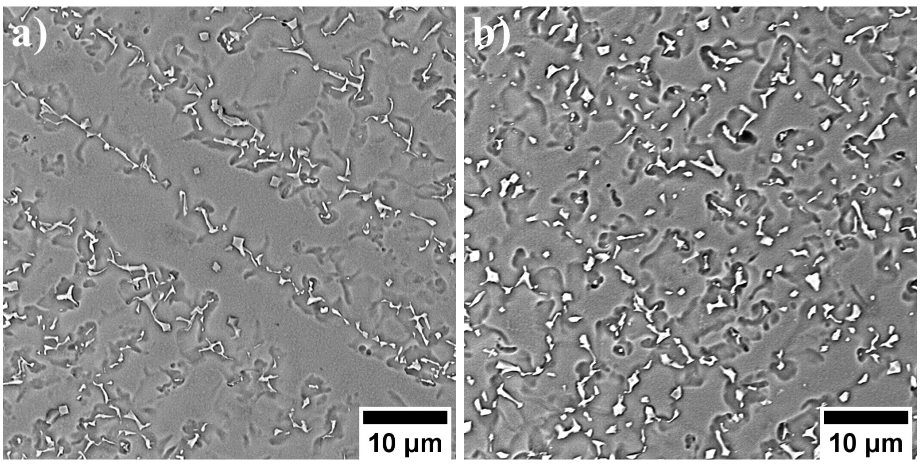


Fig. 2. Microporosity in the fabricated 625-nTiC composites:
a) n=1.25%; b) n=2.5%; c) n=3.75%; d) n=5.0%, LM.

On the etched samples, a dendritic structure typical of castings is revealed (Fig. 3). A relatively homogeneous microstructure characterizes the dendritic regions. In contrast, in the interdendritic spaces, the primary strengthening precipitates have been revealed. Its amount tends to increase with the initial nTiC particles in the mixture. These precipitates are characterized by various morphology, from blocks to more complex shapes like elongated parallelograms.



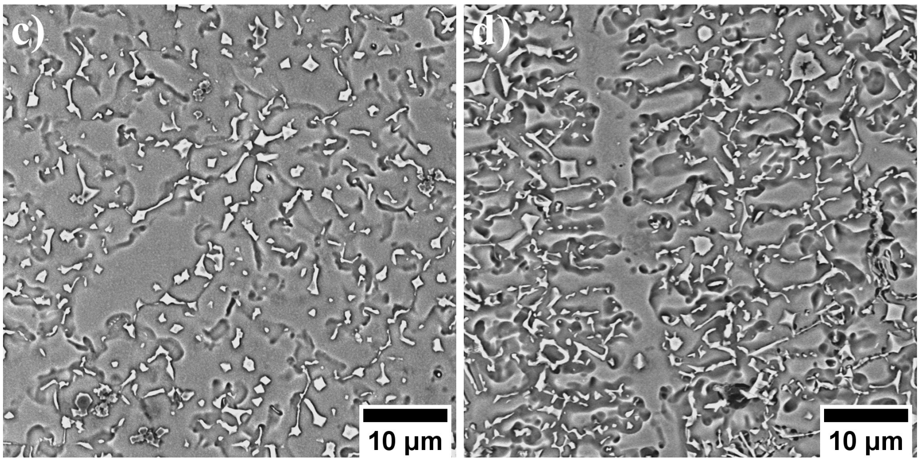


Fig. 3. As-cast microstructure of 625-nTiC composites: a) n=1.25%; b) n=2.5%; c) n=3.75%; d) n=5.0%, SEM-BSE.

The chemical composition of formed precipitates has been analyzed in selected regions. The location of points is presented in Figure 4, and the results of semi-quantitative analysis are in Table 2. In composites, precipitates with the dominating concentration of Ti and Nb are observed, which can suggest the presence of (Ti, Nb)C carbides (points 1, 9, 11). Similar precipitates were also observed in castings and overlays made of the Alloy 625 Ni-based superalloy. Other precipitates with a bright phase contrast are characterized by increased Ni and Nb concentrations. The concentration relationship between is in the range of 1.5-2.0.

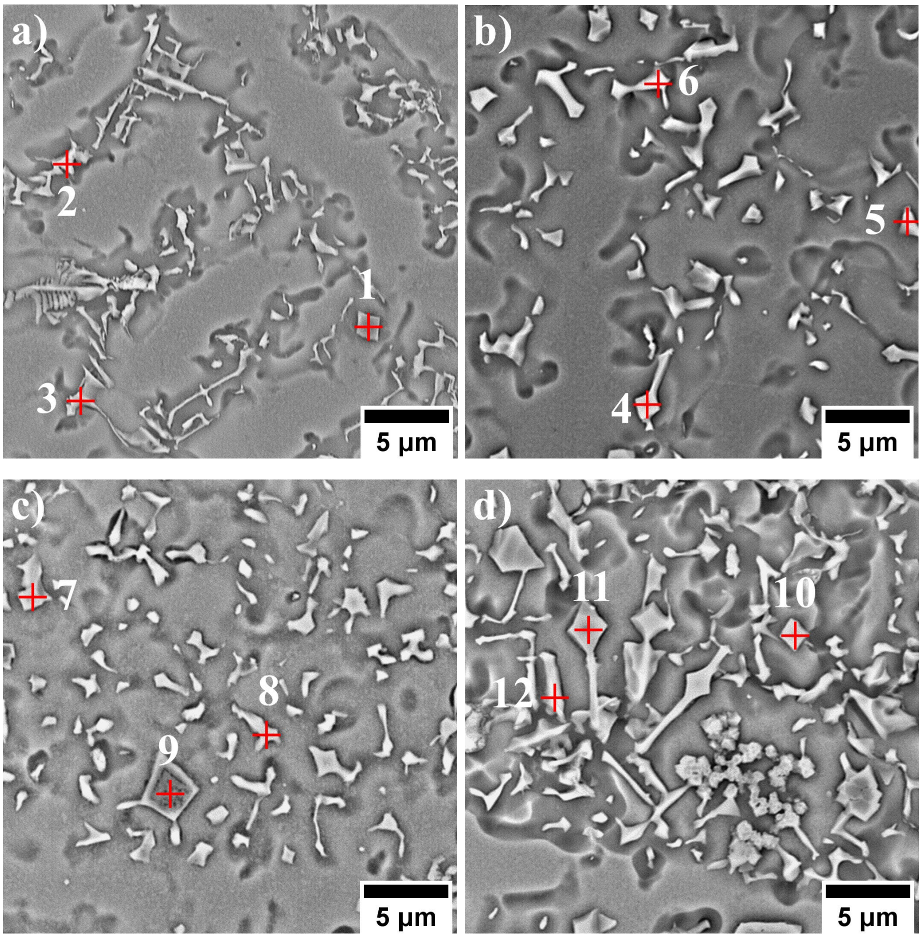


Fig. 4. Morphology of the precipitates in the interdendritic spaces of 625-nTiC composites: a) n=1.25%; b) n=2.5%; c) n=3.75%; d) n=5.0%, SEM-BSE.

Table 2. Results of the semi-quantitative SEM-EDX analysis in the precipitates, at%.

Element Point	Ni	Fe	Cr	Si	Nb	Ti	Mo
1	19.5	1.5	11.3	2.1	16.5	Bal.	0.6
2	Bal.	2.5	21.3	4.8	11.4	0.9	23.5
3	Bal.	3.1	19.9	3.0	22.1	3.8	6.4
4	12.6	1.0	8.6	3.8	Bal.	25.8	4.0
5	Bal.	2.3	15.5	3.0	30.8	11.4	5.5
6	23.3	1.5	14.4	3.6	Bal.	12.9	8.6
7	22.8	1.6	11.8	3.7	32.5	20.1	7.6
8	17.4	1.4	11.3	2.8	Bal.	25.6	7.1
9	14.3	0.9	7.8	1.8	21.5	Bal.	1.8
10	12.5	1.0	8.9	4.7	Bal.	32.2	8.3
11	4.3	0.2	5.0	4.4	31.8	48.2	6.2
12	Bal.	2.6	16.9	3.5	18.9	13.9	10.0

Summary

The Alloy 625-nTiC series composite rods were successfully fabricated via the suction casting method. Their as-cast microstructure properties and properties were systematically analyzed and discussed. Some important conclusions were obtained:

The suction casting method allows the production of Alloy 625-nTiC composites with a porosity of less than 0.05%.

Alloy 625-nTiC composites possess a typical dendritic microstructure with irregular distribution of strengthening phases.

Precipitates in the interdendritic spaces are strongly enriched in Nb and Ti or Ni and Nb, which can suggest the presence of MC carbides and Laves phase precipitates.

Acknowledgements

The author gratefully acknowledge the funding by National Centre for Research and Development (Poland) under grant "Development of the manufacturing and deposition technology of metal ceramic nanocomposite coatings for the structural reconstruction of heat-resistant nickel-based superalloys" (Project no. 0036/L-13/2022).

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The publication of this article was funded by the AGH University of Krakow 10.13039/501100007751