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Procedia Structural Integrity 66 (2024) 518–524

Structural Integrity

Procedia

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8th International Conference on Crack Paths

Fatigue crack path of an Al-Zn alloy reinforced with dispersed zirconium dioxide nanoparticles

C. Bellini[a], D. Scorza[b], S. Vantadori[b], F. Iacoviello[a], V. Di Cocco[a]*

[a]*University of Cassino, Via G. Di Biasio, 43 – 03043 Cassino (FR), Italy*
[b]*University of Parma, Parco Area delle Scienze 181/A – 43124 Parma, Italy*

Abstract

Aluminum-zinc (Al-Zn) alloys are widely used in various industries due to their low weight, good mechanical properties, and excellent corrosion resistance. However, their susceptibility to fatigue failure under cyclic loading conditions limits their application in components subjected to dynamic stresses. To improve the fatigue behavior, additions of zirconium dioxide have been used as dispersed particles in the alloy matrix. Zirconium oxide (ZrO_2) nanoparticles are characterized by high strength, hardness, and thermal stability. Under stress, ZrO_2 nanoparticles change their crystal structure from a tetragonal to a monoclinic. This study investigates the fatigue crack growth behavior of an Al-Zn alloy reinforced with dispersed zirconium oxide (ZrO_2) nanoparticles. The influence of ZrO_2 nanoparticles on crack initiation, propagation, and the resulting fracture surfaces was examined. The results revealed that the addition of ZrO_2 nanoparticles significantly altered the fatigue crack path, leading to improved fatigue resistance compared to the unreinforced alloy.

Keywords: Nanoparticles; Aluminum Alloy; Fatigue

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1. Introduction

Aluminum alloys are widely used in various industries due to their low weight, good mechanical properties, and excellent corrosion resistance. The 7075 aluminum alloys are a type of aluminum alloy that is known for its high

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* Corresponding author. Tel.: +39 07762994334; fax: +390776299733.
E-mail address: v.dicocco@unicas.it

10.1016/j.prostr.2024.11.105

strength-to-weight ratio. They are commonly used in aerospace and other applications where weight is a critical factor. ZrO_2 (zirconia) nanoparticles are very hard and strong ceramic particles. Djebbar et al. (2020) found that when added to Ergal alloys, nanoparticles can significantly improve the material's mechanical properties. Ergal is renowned for its exceptional strength-to-weight ratio. Here is a breakdown of its chemical composition:

- Aluminum (Al): this forms the base of the alloy, typically making up around 90% or more of its composition.
- Zinc (Zn): this is the primary alloying element in ergal, contributing significantly to its strength. It typically ranges from 5.1% to 6.1%.
- Magnesium (Mg): magnesium, usually present between 2.1% and 2.9%, further enhances the strength and hardness.
- Copper (Cu): copper improves both strength and machinability, generally found in the range of 1.2% to 2.0%.
- Chromium (Cr): chromium increases resistance to stress corrosion cracking, usually present around 0.18% to 0.28%.
- Trace elements: these include smaller amounts of elements like iron, silicon, manganese, and titanium, each playing a role in the alloy overall properties.

The 7000 series aluminum alloys, like the commercial Ergal alloys we discussed, are heat-treatable, meaning their properties can be significantly enhanced through controlled heating and cooling processes. The most commonly used heat treatment for these alloys:

- Solution heat treatment: the alloy is heated to a high temperature (typically around 475-500°C) and held there for a specific duration. This allows the alloying elements (like zinc, magnesium, and copper) to dissolve completely into the aluminum matrix, forming a single-phase solid solution. This step essentially "resets" the alloy's microstructure, creating a homogenous structure with a supersaturated solid solution of alloying elements.
- Quenching: the alloy is rapidly cooled from the solution treatment temperature, usually by immersing it in cold water or a polymer solution. This rapid cooling "traps" the alloying elements in the supersaturated solid solution, preventing them from forming large, undesirable precipitates. This creates a metastable structure with increased strength and hardness.
- Aging: the quenched alloy is then reheated to a lower temperature (typically around 120-190°C) and held for a specific period. This is often referred to as "artificial aging" or "precipitation hardening". This controlled aging allows fine precipitates to form within the aluminum matrix. These precipitates act as obstacles to dislocation movement, thereby strengthening and hardening the alloy.

Some 7000 series alloys can also undergo natural aging at room temperature; although this process is much slower than artificial aging, there are many treatments. The T6 temper is a common temper for 7000 series alloys, achieved through solution heat treatment, quenching, and artificial aging. It provides a good balance of strength and toughness. Another most used treatment is the T7. This temper involves an overaging treatment after artificial aging, which slightly reduces strength but improves stress corrosion cracking resistance.

Heat treatment is essential for optimizing the mechanical properties of 7000 series aluminum alloys (Zhang et al. (2024)). By carefully controlling the heating, cooling, and aging processes, manufacturers can achieve the desired balance of strength, toughness, and corrosion resistance for specific applications (Brotzu et al. (2017)).

The heat treatments are expensive compared to the additions of chemical alloying elements, as stated by Abd-Elaziem et al. (2024). In recent years, the addition of nanoparticles has been one of the most used and cheaper techniques to improve mechanical behavior, as determined by Prakash et al. (2024). For example, Vinod Kumar et al. (2009) found that adding nanoparticles to 7075 aluminum alloys can bring about several benefits, primarily due to their ability to refine the microstructure and improve the mechanical properties. Sabati et al. (2024) enhanced the fatigue behavior of an aluminum alloy by adding titanium oxide particles. Azar et al. (2022) and Parast and Azadi (2022) improved the fretting fatigue behavior of an aluminum alloy by heat treatment and nano reinforcing.

ZrO_2 nanoparticles act as nucleation sites during solidification, promoting the formation of finer and more uniformly distributed grains. The finer grain size achieved through the addition of ZrO_2 nanoparticles contributes to an increase in both yield strength and ultimate tensile strength of the 7075 alloy. This makes the material more resistant to deformation and fracture under load. While increasing strength often comes at the expense of ductility, the addition of ZrO_2 nanoparticles can actually improve ductility in 7075 alloys. This is because the finer grain size allows for more uniform deformation and reduces the tendency for crack initiation and propagation (Alqahtani et al. (2024)).

To improve the fatigue behavior, additions of zirconium dioxide have been used as dispersed particles in the alloy matrix. ZrO_2 nanoparticles are characterized by high strength, hardness, and thermal stability. Under stress, ZrO_2 nanoparticles change their crystal structure from a tetragonal to a monoclinic. This transformation is characterized by a volume expansion, which can induce compressive stresses in the surrounding matrix. These compressive stresses can help to close cracks and inhibit their growth. Finally, the strong interfacial bonding between ZrO_2 nanoparticles and the Al-Zn matrix allows for efficient load transfer and stress redistribution. This can reduce stress concentrations at crack tips, further impeding crack propagation.

Overall, adding ZrO_2 nanoparticles offers a promising route to enhance the mechanical properties and performance of 7075 aluminum alloys, making them suitable for a wider range of demanding applications in aerospace, automotive, and other industries.

However, their susceptibility to fatigue failure under cyclic loading conditions limits their application in components subjected to dynamic stresses.

In this work, a 7075 aluminum alloy reinforced employing nanoparticles of ZrO_2 has been investigated. The fatigue crack growth micromechanisms have been observed through surface crack observation using the SEM (Scanning Electron Microscope).

2. Material and methods

The chemical composition of the investigated aluminum alloy is shown in Table 1. This is a typical chemical composition of a 7075 alloy, characterized by a total contents of Zr and Ti equal to 0.25%. The presence of Zr is due to the presence of zirconium dioxide (ZrO_2) nanoparticles dispersed in the matrix.

Table 1. Chemical composition of investigated aluminum alloy.

Cu	Fe	Mn	Mg	Si	Zn	Cr	Ti	Zr
1.22	0.50	0.30	2.4	0.40	5.5	0.20	0.1	0.15

The mechanical properties of the alloy are like those of medium carbon alloys, as shown in Table 2.

Table 2. Tensile mechanical properties of the investigated aluminum alloy.

Rm [MPa]	Ry 0.2% [MPa]	Hardness HB	Z %
560	495	145	7

In this work, the fatigue crack growth behaviour has been investigated by tests performed according to the ASTM E647. All the tests have been performed using sinusoidal loads at 30 Hz, with constant amplitude R=Pmin/Pmax=0.1.

The crack length measurements were performed using the compliance method, using a double cantilever mouth gage, and the process was controlled using an optical microscope (x40).

3. Results and discussion

The fatigue test behavior obtained using R=0.10 is shown in Fig. 1. Three different stages can be observed, as usual in metallic alloys, but the second stage is characterized by a slope greater than the first stage.

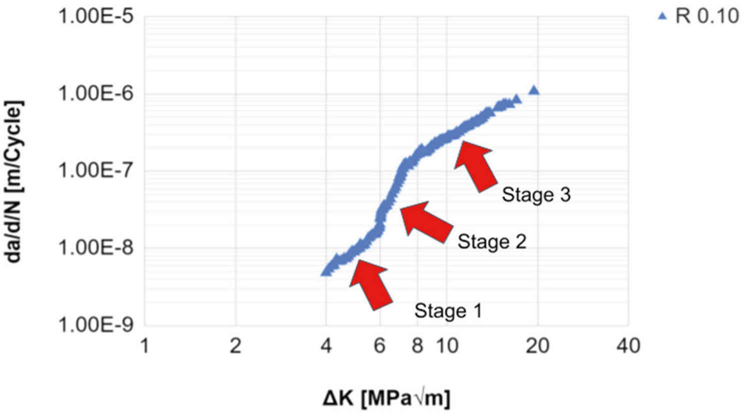

Fig. 1. Fatigue crack growth behavior at R=0.10: three stages with different slopes.

The stages can be observed directly on the fracture surfaces of the specimens (see Figure 2), where the different morphology of the fractures can also be observed at the macroscopic scale.

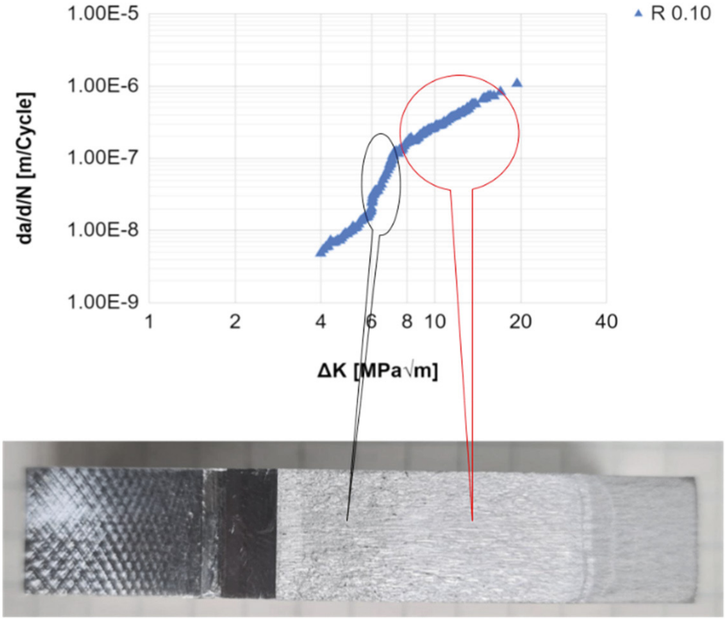

Fig. 2. Macromorphology of the fracture surface.

In the first stage, the main fracture micromechanism is of ductile type, probably due to the effect of nanoparticles interacting with the crack advancement, whose rate is very low. As can be seen from Fig. 3, the crack advancement is mainly governed by the grains that are arranged in the longitudinal direction, for example along the main crack advancement direction.

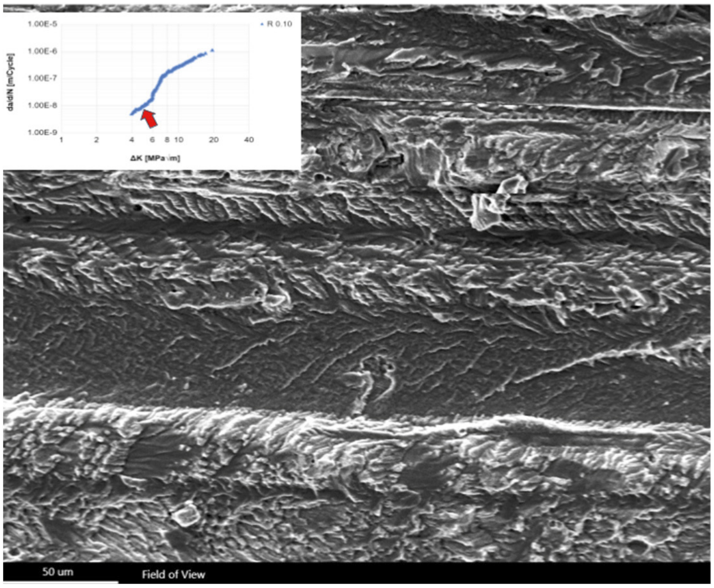

Fig. 3. Fatigue fracture micromechanisms corresponding the stage 1.

In the second stage, the one characterized by the increase in the slope of the da/dN-ΔK curve, the fracture micromechanisms become less and less ductile and the propagation, although markedly transgranular, in some areas crosses the grain boundaries, giving rise to “stepped” morphologies (Fig. 4). At this stage, the presence of nanoparticles no longer constitutes an efficient obstacle to crack propagation, which is governed by traditional intergranular/transgranular micromechanisms with a strong increase in the slope of the da/dN-ΔK curve.

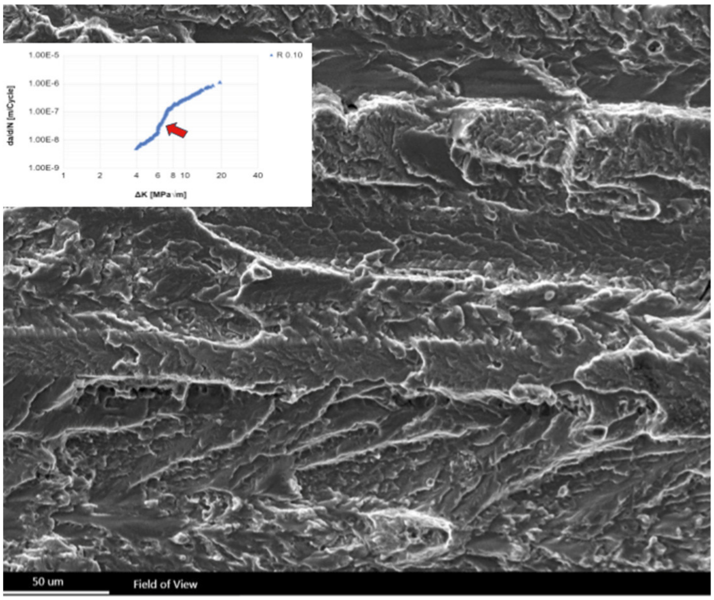

Fig. 4. Fatigue fracture micromechanisms corresponding to stage 2.

This is even more evident in the last stage, where it is possible to observe the fatigue striations present especially at the transgranular level, as reported in Fig. 5. Under these conditions, there is no evidence of the influence of nanoparticles on the fatigue behavior, probably because the fatigue crack advancement rate is too high compared to the size of the nanoparticles which are completely bypassed by the dislocations under the effect of the high ΔK values.

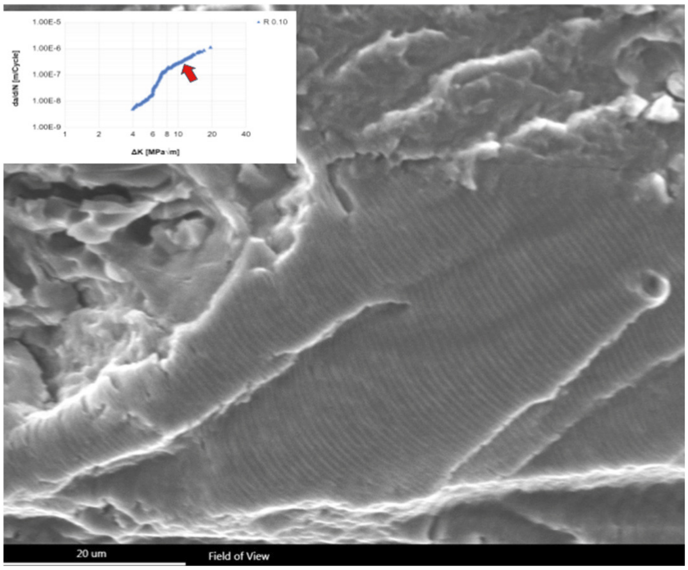

Fig. 5. Fatigue fracture micromechanisms corresponding the stage 3.

4. Conclusions

In this work, the fatigue behavior of an aluminum alloy characterized by the presence of nanoparticles of zirconium dioxide has been investigated at load ratio R=0.1. The crack growth behavior seems to be different compared to the traditional ones. This is due to the presence of nanoparticles in the matrix that influences the mechanical behavior at the first stage.

Considering the experimental results and the results of the analyses on the fracture surfaces, the following conclusions can be summarized:

- The phases respond in different ways to the fatigue loads.
- The crack path follows the orientation of the laminated phases.
- Macromorphologies of the crack propagation show a fading of the grey at the first and second stages, and a sharp changing grayscale between the second and third stages.

For high values of ΔK, the nanoparticle dimension does not allow an “arrest” action of the dislocations and the fracture micromechanisms observed are similar to the traditional aluminum alloys.

References

Abd-Elaziem, W., Khedr, M., Elsheikh, A.H., Liu, J., Zeng, Y., Sebae, T.A., Abd El-Baky, M.A., Darwish, M.A., Daoush, W.M., Li, X., 2024 Influence of nanoparticles addition on the fatigue failure behavior of metal matrix composites: Comprehensive review. Engineering Failure Analysis 155, art. no. 107751.

Alqahtani, I., Niyaz Ahmed, B., Ashoka, E., Rajesh, A. M., Bharath, P. B., Saleemsab, D., 2024. Indentation Fracture Toughness of Aluminium-Graphite Composites: Influence of Nanoparticles. Frattura ed Integrità Strutturale 19(71), 11–21.

Azar, R.G., Parast, M.S.A., Azadi, M., 2022. Heat-treating and nano-reinforcing improvements on fretting fatigue properties and fracture behaviors of cylinder head aluminum alloys Journal of Materials Research and Technology 20, 1927–1939.

Brotzu, A., Felli, F., Pilone, D., 2017. Investigation on some factors affecting crack formation in high resistance aluminum alloys. Frattura ed Integrità Strutturale 11(42), 272–279.

Djebbar, N., Hadj Boulenouar, R., Boutabout, B., 2020. Three-dimensional Numerical Analysis of a Joint Bonded Reinforced with Silica Nanoparticles (SiO2). Frattura ed Integrità Strutturale 14(52), 128–136.

Parast, M.S.A., Azadi M., 2022. Effect of Nano-Clay Particles and Heat Treating on Pure and Fretting Fatigue Properties of Piston Aluminum Alloy under Stress-Controlled Cyclic Bending Loading Journal of Materials Engineering and Performance 31 (7), 5927–5942.

Prakash, T. B., Gangadharappa, M., Somashekar, S., Ravikumar, M., 2024. The Impact of nanoparticles (B4C-Al2O3) on mechanical, wear, fracture behavior and machining properties of formwork grade Al7075 composites. Frattura ed Integrità Strutturale, 18(69), 210–226.

Sabari, K., Sekhar, K.Ch., Thirunavukkarasu, M., Prasad, D.V.S.S.S.V., Rathinasabapathi, G., Medikondu, N.R., 2024. Investigating the Fatigue Behaviour of TiO2 Nanoparticle Reinforced AA7071 Aluminium Alloy. Journal of Environmental Nanotechnology 13 (2), 127–134.

Vinod Kumar, G.S., Murty, B.S., Chakraborty, M., 2009. Grain refinement response of LM25 alloy towards Al–Ti–C and Al–Ti–B grain refiners. Journal of Alloys and Compounds 472, 112–120.

Zhang, B., Zhang, Y., Zheng, K., Chi, Y., 2024. Research on the microstructure, mechanical and fatigue performance of 7075/6061 dissimilar aluminum alloy fusion welding joint treated by nanoparticle and post-weld heat treatment. Engineering Fracture Mechanics 311, art. no. 110550.