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Mechanical and Microstructural Characterization of Aluminium Alloy, EN AC-Al Si12CuNiMg

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Abstract

Aluminium alloys have low density and good mechanical properties, making them suitable for the manufacture of mechanical structures where low weight is critical. However, when these alloys are subjected to elevated temperatures, their mechanical properties deteriorate significantly. The aim of this study is to investigate the effect of temperature on the mechanical properties of aluminium alloy, EN AC-Al Si12CuNiMg. For this purpose, an experimental investigation was performed at ambient and elevated temperatures on aluminium alloy samples prepared by casting. Tensile and hardness tests were carried out to characterize the mechanical properties of this material. Additionally, an optical microscope was used to examine the microstructures of this alloy. Finally, a scanning electron microscope was used to analyze the fracture modes of this material. The results show that the mechanical properties such as tensile strength, yield strength, and Young's modulus of this alloy dramatically decrease when the temperature exceeds 250°C. The microstructural investigation reveals several factors that are detrimental to the mechanical properties of this alloy. This includes coarse-grained structures, micro-pores, and several intermetallic compounds. Furthermore, fractography reveals a minor cleavage-like pattern and micro-cracks on the fracture surface of all failed samples under various temperatures, indicating semi-brittle fracture mode.

Keywords: Mechanical properties, Metallography, Microstructure, Fracture properties, Aluminium alloy

1. Introduction

A high strength-to-weight ratio and the ability to withstand high temperatures are typical requirements for the manufacture of various mechanical structures. Aluminium alloys possess a number of these distinctive properties that make them suitable for a wide range of applications, including the automotive, aerospace, and military industries [1-3]. For example, engine blocks, piston heads, steering boxes, inlet manifolds, rocker covers, deferential casings, brackets, and wheels are among the many components made from aluminium casting in the automotive industry [4]. Moreover, compared to other cast alloys, aluminium alloys offer excellent corrosion and oxidation resistance and favourable properties such as low density, wear resistance, high strength-to-weight ratio, and other good technological properties [5]. However, one of the main drawbacks of aluminium-silicon alloys is their propensity to produce coarse-grained structures, resulting in severe degradation of mechanical properties [6].

The most common alloying elements used in the production of aluminium alloys are Si, Mg, Cu, and Zn. Al-Si alloys have good casting properties and are widely used to manufacture automotive components that operate at ambient and moderately high temperatures [7, 8]. Alloying elements have an impact on both microstructural and mechanical properties [9]. Al-Mg, Al-Cu, and Al-Zn alloys have better mechanical properties than Al-Si alloys, but their casting properties are often poor. The silicon composition of standardized commercial cast aluminum alloys ranges from 5 to 23 by weight. Adding Si to aluminium alloys improves the fluidity and casting properties of the aluminium alloys, while Mg enhances corrosion resistance [10]. Typically, Cu is added to Al-Si alloys to improve machinability. Increasing the Cu and Mg content of an alloy enhances strength while decreasing ductility. Similarly, increasing the Fe content of an alloy decreases the ductility of the alloy [11]. On the other hand, Na in cast Al-Si alloys significantly improves mechanical properties, especially ductility [12, 13]. A small amount of Ni is added to aluminum-silicon alloys to improve hardness and strength at high temperatures [14].

On the other hand, the presence of Cu, Mg, Ni, and Fe in the Al-Si alloy causes the formation of various intermetallic compounds in the microstructure [15]. Al_2Cu, Mg_2Si, α-$Al_{12}(Fe, Mn)_3Si_2$, and β-Al_5FeSi are the typical intermetallic phases formed due to the presence of these elements [7]. On the other hand, the presence of the intermetallic phases influences the physical properties of the alloy such as ductility, thermal expansion, and hardness. In addition, the physical properties of individual constituents, such as the relative distribution of Al matrix and Si crystals, their volume percentage in the mixture, and morphological distribution, size, and shape, determine the mechanical properties of these alloys [16, 17].

Several studies have reported that various factors, such as: superheating of the melt, holding duration, and solidification rate, affect the microstructure of the cast aluminium-silicon alloy [18, 19]. Superheating Al-Si alloys produces a shift in the eutectic reaction toward higher levels of silicon, accompanying with the appearance of dendrites in the hypo eutectic and eutectic Al-Si alloys [20, 21]. The solidification rate determines the coarseness of the microstructure, the formation of dendrites and defects [22, 23]. The microstructural coarseness includes the percentage, size, shape, and distribution of intermetallic phases and the segregation profiles of solute in the α-Al phase.

Aluminum-silicon alloys are composed of the aluminium phase (α -phase) and the silicon phase (β -phase). It should be noted that the aluminum phase has excellent ductility characteristics, while the silicon phase has brittle characteristics and mostly needle-like structure [24].

Despite the importance of the Al-Si alloy and its wide range of applications, the functionality of this alloy is limited to low and moderate temperatures because its strength decreases significantly when exposed to high temperatures. The ability of an aluminum alloy to retain its desirable properties at elevated temperatures is critical in several applications where it is widely used. Therefore, to ensure structural stability and determine the temperature range in which components made of this alloy can operate, mechanical characterization of Al-Si alloys at various temperatures is essential.

This article focuses on the mechanical characterization of EN AC-Al Si12CuNiMg alloy subjected to high loads at various temperatures. Furthermore, the study intends to investigate the microstructural characterization of as-cast EN AC-Al Si12CuNiMg alloy. Hence, tensile and hardness tests were carried out to describe the mechanical properties of the materials at both normal temperature and elevated temperatures. Besides, an optical microscope and a scanning electron microscope were used to characterize the microstructure and the fracture properties of this alloy, respectively.

2. Materials and Methods

The investigated alloy was a commercial Al-Si alloy produced by Nicromet company. An ingot of 2.5 kg was cut and melted in the resistance furnace at the temperature of 720°C. After melting, the charge was kept at the same temperature for 15 minutes for homogenization. During the heating process, argon was used to blow the furnace chamber at a rate of 0.5 l_N/min. Before casting, the oxide layer was removed with a trowel. The castings were prepared with the use of the MetalHelth system, which provided a stable mold heating temperature up to 400 °C. The mold feeding system was based on the KALPUR-POURING SLEEVES system with Foseco's SVX 0R X 22/10 filter.

The chemical composition of the investigated alloy, which is presented in Table 1, was measured by optical emission spectroscopy (OES). A total of 27 tensile specimens with a length of 60 mm and a diameter of 10 mm were prepared. In accordance with ISO 6892-1, tensile tests were performed on these specimens in their as-cast condition on the Zwick/Roel Z100 universal testing machine. At each temperature, the tensile tests were repeated five times. A clip-on extensometer was used to record load elongation data in the elastic zone. For the high-temperature tensile test, the heating furnace installed on the Z100 universal testing machine was used to heat the specimens up to 350℃. The strain rate of 0.0067 1/sec was employed in all tests. The specimens were loaded under the uniaxial tensile load until a fracture occurred. The Zwick testXpert software was used to record the load elongation data during the test. Figures 1 a) and b) show the tensile test setup for room and elevated temperatures, respectively. From the load extension data, the tensile properties of the EN AC-Al Si12CuNiMg alloy were determined.

The samples approximately 20 mm x 20 mm x 30 mm in size were prepared for hardness measurement. The samples were then heated to a different temperature and held for approximately 2 hours. The Brinell hardness test was performed by applying 2450 N of load for a period of 15 seconds according to the standard test method ISO 6506-1. Three measurements were taken, and their average was presented as a result.

Metallographic samples were prepared using standard metallographic preparation processes such as grinding, polishing, and etching. Etching was performed by dipping the ground surface of the samples in a hydrofluoric acid (HF) solution to reveal the material structure. After the metallographic samples were prepared, the microstructures were examined using a light microscope. A scanning electron microscope (Hitachi S-3400N) was employed to examine the tensile fracture surface of the test specimens. High magnifications were used for the profound observation.

Table 1.
The chemical composition of EN AC-Al Si12CuNiMg (weight percentage)

Fe	Si	Cu	Mg	Zn	Mn	Ti	Ni
0.4	11.4	1.27	1.24	0.18	0.18	0.04	1.48

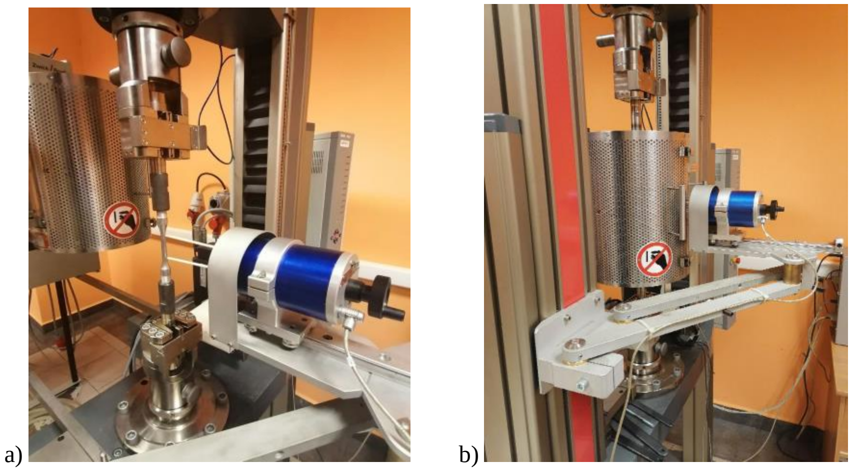
a) b)

Fig. 1. Specimen clamped in a testing machine: a) normal temperature b) elevated temperature

3. Results and Discussion

3.1. Microstructural surface Analysis

The microstructures of the investigated alloy were observed, and their micrographs are presented in Figures 2. The micrographs reveal that the α-Al matrix, eutectic Si particles, and other intermetallic particles. Gray silicon plates and other intermetallic particles are embedded in a large white α-Al matrix. In all samples, microstructural observation reveals dendrites of α-Al as the main constituent and with an elongated needle-like structure (flakes) of silicon. The aluminium dendrite arms are visible in the framework, indicating that the cast samples have not solidified under equilibrium conditions. In Figure 2, the aluminum dendrite arms are clearly visible. Non-equilibrium solidification of the cast produces non-homogeneity in the microstructural of the the alloy. This non-homogeneity includes micro and macro-segregation of eutectic Si solute in the α-Al phase. The dark semi-circular shape shown in the microstructure is a shrinkage pore. The formation of shrinkage porosity is related to the parameters used in the crystallization and casting processes. In general, the shrinkage porosity and segregation of the solute components resulting from non-equilibrium solidification are detrimental to the mechanical properties of the alloy. For example, the segregation of Si solute atoms in the composition of that alloys affects the mechanical properties of these alloys by reducing the ductility [23].

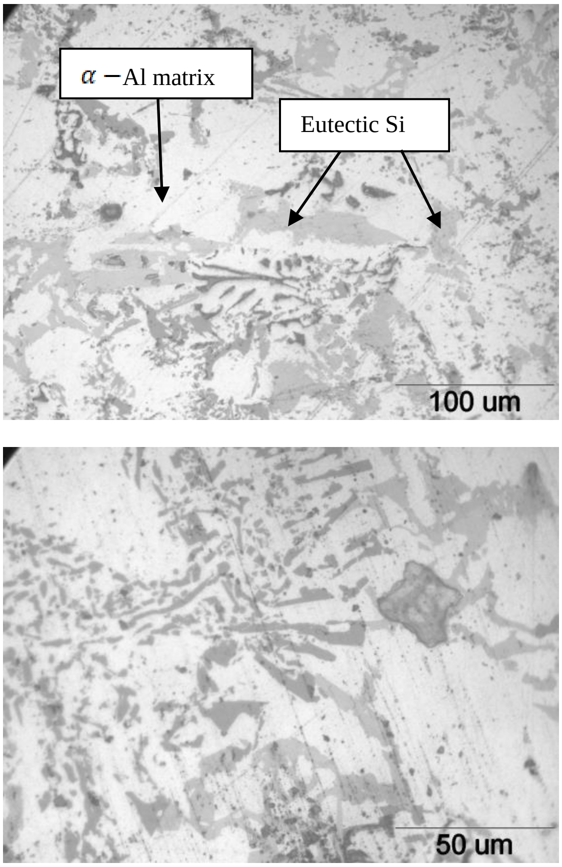

Fig.2. Microstructure of as-cast EN AC-Al Si12CuNiMg alloy

3.2. Fracture surface analysis

Fractographic analysis of all the samples reveals that they have a similar appearance. A transcrystalline fracture was observed in all samples. In addition, the dimpled fracture surface of the specimens, despite the absence of typical ductile cup cone fracture, suggests ductile fracture of cast aluminum alloys when subjected to high-temperature tensile loads. Figures 3 show the fracture morphology of EN AC-Al Si12CuNiMg alloys samples after normal temperature tensile test. On the fracture surface of this sample, intergranular-like fractures, as well as tiny cleavage-like brittle cracks, can be seen. Additionally, a few fracture planes and a few dimples can be seen on the morphology of these fracture surfaces. However, the dimples' size is tiny, exhibiting a semi-brittle behavior.

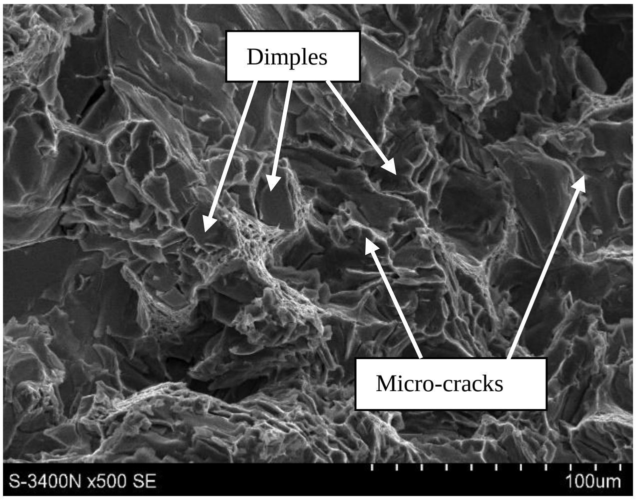

Fig. 3. The fracture surface of the specimen under normal temperature tensile load

Figure 4 shows the fracture surfaces of the EN AC-Al Si12CuNiMg alloys after a tensile test at 350°C temperatures. Like the sample tested at normal temperature, the cleavage-like brittleness is observed but very low. In addition, the observation demonstrates the presence of a large and more extensive dimple size, suggesting ductile fracture [25]. The larger the dimple size and depth, the greater the fracture strain. In general, particle dislocation due to high temperature, high stresses at specific locations, or plastic deformation around inhomogeneous inclusions or other defects are factors that contribute to the formation of micro-cracks.

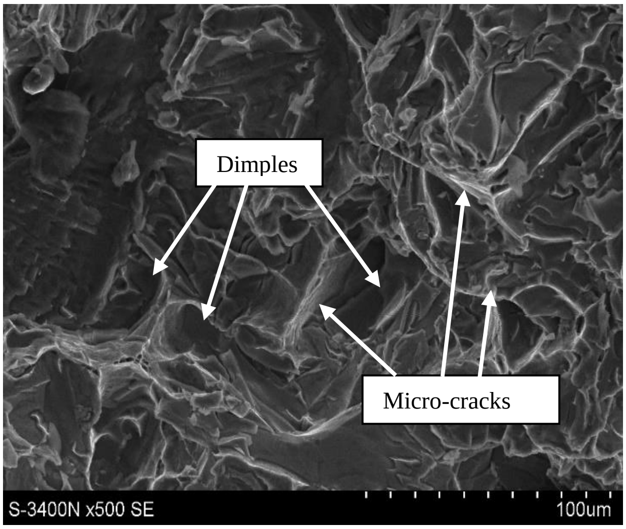

Fig. 4. The fracture surface of the specimen under 350°C of temperature tensile load

3.3. Mechanical characterization

The stress-strain curve is essential for describing the tensile properties of materials, such as yield strength, tensile strength, Young's modulus, and fracture strain. Figure 5 shows the engineering stress-strain curve of the investigated alloys at different temperatures. As the temperature increases, the percentage of elongation increases. At normal temperature, the materials tend to exhibit brittle failure behavior. However, it tends towards ductile fracture behavior at elevated temperatures, despite the absence of cup shape and cone at the fracture site. Therefore, the fracture behavior of this material changes in response to temperature changes.

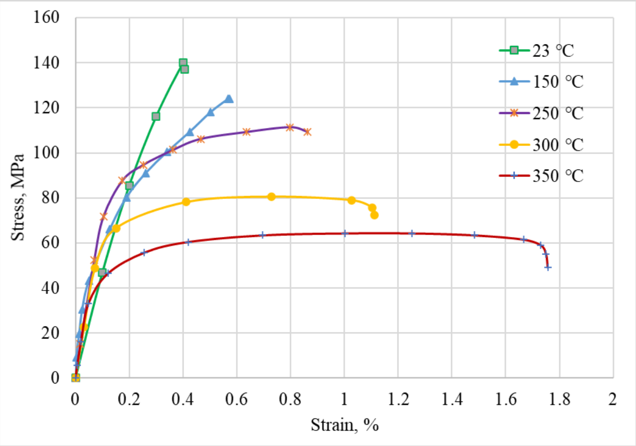

Fig. 5. Stress-strain curve of EN AC-Al Si12CuNiMg at different temperature

The tensile strength is the maximum stress value on the stress-strain curve. Figure 6 shows the tensile strength of EN AC-Al Si12CuNiMg alloys as a function of temperatures. The values shown are the average of five test results compared with the result obtained by Siemińska [26]. The figure clearly shows the decrease in tensile strength with increasing temperature. For example, at normal temperature, the tensile strength of this alloy is 140 MPa, but at 150°C and 250°C, the tensile strength is 125 MPa and 112 MPa, respectively. Therefore, the tensile strength decreases by 5% to 15% from normal temperature to 150°C and 250°C, respectively. On the other hand, temperatures between 250°C and 350°C lead to a 40-50% reduction in the tensile strength of the alloy. This indicates that the decrease in tensile strength is very small at low and moderate temperatures; but, when the temperature exceeds 250°C, the tensile strength dramatically degrades.

The low tensile strength of this investigated alloy results from various casting conditions and the nature of microstructures compared to those in the literature [26]. The coarse-grained microstructures of these alloys have a detrimental effect on their mechanical properties at low and high temperatures.

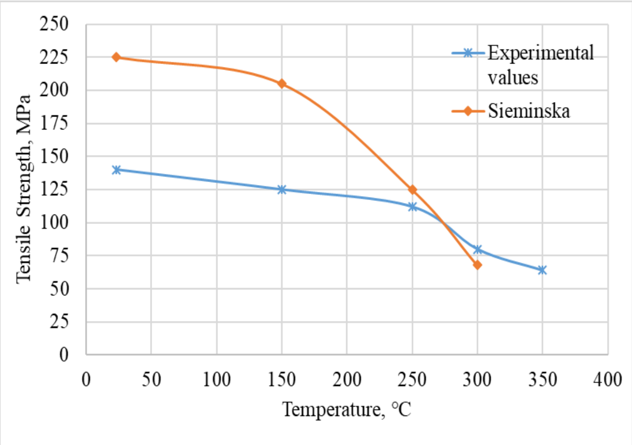

Fig. 6. Tensile strength as a function of the temperature of the EN AC-Al Si12CuNiMg alloy compared to Sieminska [26]

Figure 7 shows the yield strength and fracture strain of the alloy plot against temperature. The average values of the five test results are presented in this graph. Unlike the 10% drop of the yield strength observed in the temperature range from normal temperature to 250°C, a rapid decline of the yield strength is observed at temperatures above 250°C. In other ways, the fracture strain of the sample at low testing temperature is extremely low compared to the fracture strain at high temperature. Therefore, the relationship between fracture strain and test temperature is contrary to yield strength. For temperatures above 250°C, the deformation of the fracture increases significantly with increasing temperature. The fracture strain determines the ductility of the materials. Therefore, the ductility of the alloy increases with increasing temperature.

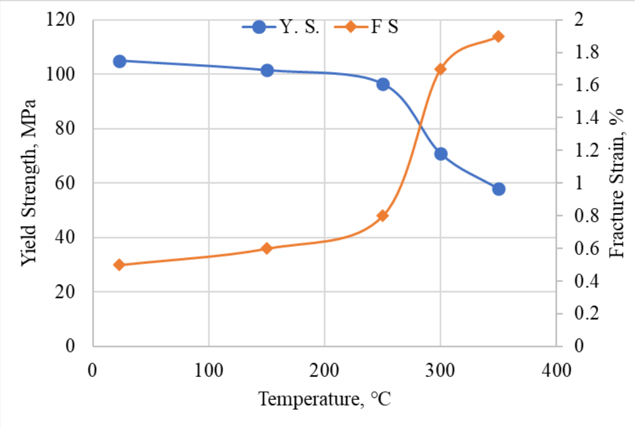

Fig. 7. Yield strength and fracture strain of EN AC-Al Si12CuNiMg alloy at different temperature

Young's modulus measures the resistance of a material to axial deformation. Its value is obtained by measuring the slope of the axial stress-strain curve in the elastic region. The temperature of the test affects Young's modulus of materials. Figure 8 shows the effect of temperature on Young's modulus of this alloy. The average Young's modulus of the five test results was plotted against temperature. The test result reveals that Young's modulus of EN AC-Al Si12CuNiMg alloys increases in the low temperature up to about 200°C and decreases with the increase of temperature.

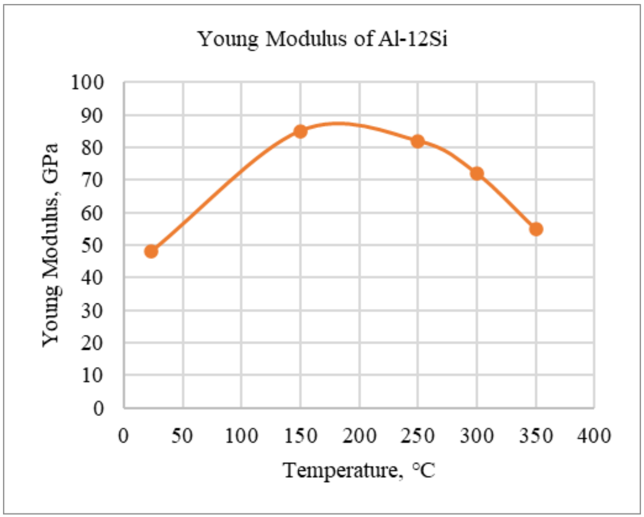

Fig. 8. Young’s modulus vs. Temperature of EN AC-Al Si12CuNiMg alloys

The tensile and hardness test result of the EN AC-Al Si12CuNiMg alloy for different temperatures are shown in Figure 9. As the temperature was increased over 150°C, both tensile strength and the Brinell hardness of the alloy declined considerably.

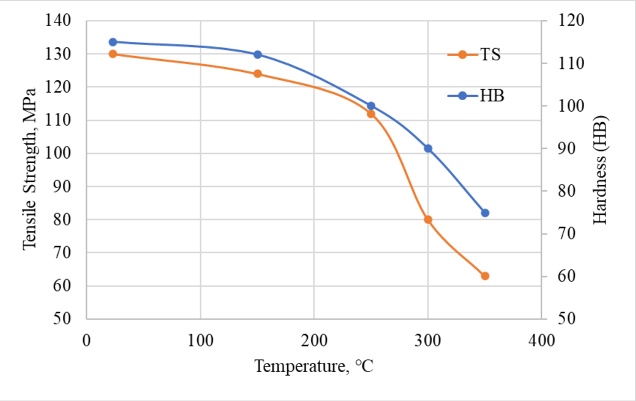

Fig. 9. Brinell hardness measurement and tensile strength vs. temperature

4. Conclusions

In this paper, the mechanical properties of EN AC-Al Si12CuNiMg alloy were investigated at various temperatures. In addition, the microstructure of the as-cast EN AC-Al Si12CuNiMg alloy was also analyzed. The microstructure contains the α-Al matrix, eutectic Si particles, and other intermetallic particles. The aluminum dendrite arms are visible in the microstructure, indicating that the cast samples were not solidified under equilibrium conditions. In addition, a small number of dispersed pores, probably because of liquid shrinkage during solidification, were observed with the light microscope. The grain size of some intermetallic compounds is coarse and not uniformly distributed in the microstructure.

In addition, a tensile test was performed to investigate the effect of temperature on the basic tensile properties of the EN AC-Al Si12CuNiMg alloy. The study showed that from normal to 150°C temperature, the tensile strength decreases by 5%. The strength of the alloy decreases by 15% between 150°C and 250°C. Temperatures between 250°C and 350°C reduce the tensile strength of the alloy by 40-50%. This shows that the tensile strength decreases slowly at low and moderate temperatures but rapidly above 250°C. Unlike the tensile strength, Young's modulus of this alloy increases with temperature up to about 200°C; then, it also decreases with the continued increase of temperature.

The photographic study of the fractured surfaces of the alloy reveals intergranular type fractures, brittle cleavage type cracks, and shallow dimples at low temperatures. However, the result shows the large depth of the dimple and minor cleavage-type structures and microcracks at high temperatures. These indicate the semi-brittle fracture modes of the alloy.

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