Defence Science Journal, Vol. 75, No. 4, July 2025, pp. 444-450, DOI : 10.14429/dsj.19931

Qualification and Certification of Nickel based C1023 Super Alloys for Aero-Engine Applications

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ABSTRACT

The Nickel-based super alloys are favoured for manufacturing turbine blades and vanes because these alloys can withstand high temperatures with high-stress levels. The microstructure of C1023 in as-cast condition exhibits a dendritic structure and few secondary particles. In this study, the room temperature tensile (1063±7 MPa) and high temperature (800 °C and 850 °C) stress rupture is carried out the life obtained is 92 hrs and 74 hrs respectively of cast alloy C1023 super alloy. The main objective of certification societies like CEMILAC is to qualify and certify metal parts through the development of guidelines, standards, and specifications that address technical and operational challenges in the manufacturing process. In tandem with the advancement of technology and the transformation of the industry, the qualification and certification methodology will evolve.

Keywords: Ni-based super alloys; Cast alloy C1023; Certification; Investment casting

NOMENCLATURE

γ : Gamma
γ' : Gamma prime

1. INTRODUCTION

The superior mechanical behaviour of nickel-based superalloys is attractive to engineers considering their application in the manufacture of hot section components on aero engines. It is generally accepted that single crystals are used for blades and vanes because they have high corrosion resistance, superior creep strength, and oxidation resistance due to their lack of grain boundaries as well as high creep strength[1-5]. Nickel-based superalloys, such as the C1023 superalloy, are essential for aero-engine applications due to their outstanding high-temperature performance and resistance to oxidation and corrosion[6]. The C1023 superalloy primarily consists of nickel, with additional elements like chromium, cobalt, and molybdenum to enhance its mechanical properties and thermal stability. This composition provides the alloy with exceptional strength and creep resistance, crucial for withstanding the extreme conditions in aeroengines. In aero-engine environments, where temperatures can exceed 1,000 °C, the C1023 superalloy maintains its mechanical integrity, offering durability and longevity[7-8]. Its resistance to oxidation and corrosion is critical for withstanding aggressive combustion gases and high-pressure conditions[9]. To ensure its reliability, the C1023 superalloy undergoes rigorous testing and certification processes. This includes assessing mechanical properties, thermal stability, and resistance to creep and fatigue under simulated operational conditions. It must comply with industry standards set by ASTM and AMS, and the manufacturing process is closely monitored to maintain consistency and performance. Overall, the C1023 superalloy's advanced composition and thorough qualification ensure its effectiveness in the demanding environment of aeroengines, supporting advancements in aerospace technology.

The grain structure of turbine blades manufactured by the conventional (precision) casting route is coarse and not homogeneous. There is a problem with such a material since it does not satisfy criteria relating to mechanical properties, which is essential for aeronautical materials[10-11]. Investment casting is the most common method for producing super alloy cast parts that are based on Ni. A few of the reasons for this could be higher temperatures causing brittle-ductile transitions, a narrow solidification range, the reactivity of the solidifying melt with mold material as well as time and cost-intensive machining procedures[12-13]. According to Flowchart 1, the main steps of the process for qualifying the process to produce C1023 components are shown in the steps that are described for the qualifying process. It is imperative to incorporate controlled grain morphology into the design process to obtain the mechanical properties. By controlling process parameters, such as the casting temperature and the mold preheating temperature, it is possible to achieve precise grain size control in the casting operation[10]. Chemical methods of refinement of the cast structure are also employed to achieve this grain size control. During the casting process, grain refinement is achieved, chemically, by adding inoculants (modifiers). These are added to the inside surface of the investment mold to refine the grains of super alloys[14-16].

Center for Military Airworthiness and Certification (CEMILAC), is a regulatory body under DRDO, vested with

Received : 26 February 2025, Revised : 05 March 2025
Accepted : 09 April 2025, Online published : 26 June 2025

the responsibility of Airworthiness certification of military Aircraft, Helicopter, Unmanned Aerial Systems (UAS), Aero-engines, Air launched weapons, and other Airborne stores[16-17]. Part of the Design, Development and Production of Military Air Systems and Airborne Stores (DDPMAS) is a document facilitating private industry participation and Make-in-India policy presenting it in a clear structured coherent and hierarchal manner comprising of framework and procedure, requirements and manual, thereby making it process dependent. It consists of guidelines and a framework for approving and certifying air systems and airborne stores[18-19].

The DDPMAS revised version was published in 2021, which provides an international quality management framework to ensure consistent quality in air systems and airborne stores. Manufacturers, sub-suppliers, and end users of aircraft materials can benefit from this standard. Under Subpart C3.1, test schedule, Airworthiness Certification Plan (ACP), Quality Assurance Plan (QAP), Design and development, Clearance for Pre-production, and issue of LoTA[20-21]. It is generally agreed that physical inspections and testing are the most powerful means of validating certifications, and they are performed by standards, rules, and regulations incorporated by certification societies, as well as international and national standards.

This study takes into consideration these aspects and investigates the microstructure and mechanical behaviors of cast alloy C1023 in the context of the present study. Additionally, the work aims to determine whether the alloy qualifies as a candidate material suitable for designing components in aero-engine applications as well as determining its feasibility. An in-depth microstructural analysis of the as-cast specimens and the mechanical behaviour (tensile and stress rupture) was subsequently carried out to confirm the results.

2. METHODOLOGY

The current investigation involves the preparation of specimens in the nickel base super alloy C1023, which contains a typical composition of (wt, %) 0.18 C, 16.5 Cr, 10.50 Co, 9 Mo, 4.40 Al, 3.8 Ti, and the remaining nickel. To manufacture precision components, a super alloy ingot was melted in a vacuum induction furnace.

The as-received material was melted and investment cast under the following conditions: melt pouring temperature Tm = 1550 ±10 °C. An explanation of the details is given in section 3.2 of this study. Ring flare casings for aero gas turbines are often made from nickel-based super alloy C1023, especially for low-pressure turbines as shown in Fig 1. Furthermore, the chemical composition of the alloy is shown in Table 1, which is the standard composition of nickel-based super alloy C1023. An X-ray-radiography test was carried out on the parts per ASTM E1742/E1742M. Acceptance standard as per AMS 2175. A liquid (fluorescence) penetrant test was also conducted on the parts by ASTM E1417.

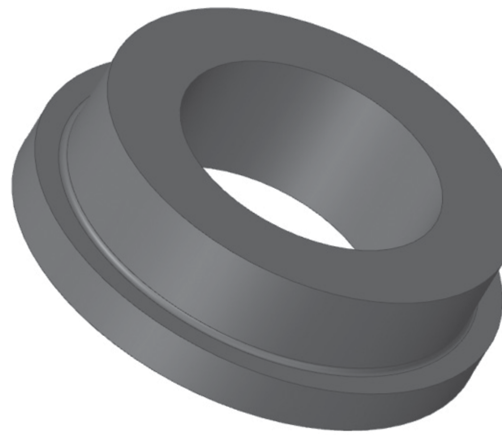

Figure 1. CAD model of ring flare casing.

The specimens are polished and etched metal samples by mechanically polishing and using a solution of 100 ml alcohol + 5 g $CuCl_2$ + 100 ml HCl (Waterless Kalling's reagent) according to ASTM E3 for optical image. After that, tensile tests were performed at room temperature on the C1023 super alloy as cast by ASTM E8. A stress rupture test was conducted under 800 °C and under 850 °C as per the ASTM E139 standard.

3. RESULTS AND DISCUSSION

3.1 Process Qualification of Ring Flare Casing

In addition to the fact that Ni-based super-alloy is a very demanding material, it requires special processing technologies to become useful. A ring flare casing is manufactured through investment casting. The overview of investment casting is shown in Fig. 2.

3.1.1 Wax Injection

During processing, shrinkage should be considered, and a CAD drawing is modified as necessary to compensate for shrinkage, as well as machined surfaces and interfaces for joining parts with the gating system (Fig. 1). Injection dies are manufactured based on CAD, with special attention being given to surface quality as well as dimensional accuracy. For aerospace applications, steel dies are preferred to prevent wear or distortion of die surfaces. The FDIINV-5473- injection tools shall be used for the injection of individual wax patterns. The wax was injected inside the die cavity at a pressure of 400±5 psi, duration of 22±3 s, and holding time of 30±4 s. Dress the parting lines of the wax pattern smoothly. Apply repair wax on any minor dents and nicks, neatly repair, and blend smoothly merging with surrounding surfaces.

3.1.2 Gating Assembly

An assembly process is followed wax injection dies have been constructed for the gating channels and the clusters have been manually assembled. To track and document, each cluster

Table1. Chemical composition of C1023 (As per)

Elements	C	Cr	Co	Mo	Ti	Al	Mg	B	Ni
Requirement	0.12-0.18	14.5-16.5	9-10.5	7.6-9	3.4-3.8	3.9-4.4	0.005	0.008	Rem.

is assigned a production number after being inspected for quality.

The gating system design is chosen for manufacturing the part based on the following behaviour during the simulation trials. Bottom gating helps in filling the casting which raises slowly and avoids free fall. Conical ingate avoids shrinkage in bosses and the center of the casting. Solidification starts from the casting and ends in spure. This creates shrinkage in the spure and not in casting, which is desirable.

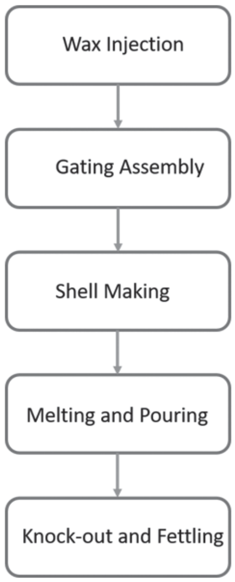

Figure 2. Investment casting process steps.

3.1.3 Shell Making

One of the key difficulties in investment casting C1023 alloy was mold shell integrity. Early attempts revealed issues with the shell cracking during the dewaxing process or surface imperfections due to an insufficiently strong shell or poor mold material properties.

Table 2. Coat the cluster with a thin layer of investment material

Coat number	Materials		No. of Coats	Drying time
1	Slurry	Prime slurry	01	2-4 (Hrs.)
	Stucco	Zircon sand (-80 +120 grade)		
2	Slurry	Backup slurry	01	3 (Min.)
	Stucco	Fused silica sand (-50 +100 grade)		
3-5	Slurry	Backup slurry	03	4 (Min.)
	Stucco	Fused silica sand (-30 +50 grade)		
6	Slurry	Backup slurry	01	8 (Min.)

In Table 2, a succession of stages of coating and stuccoing until a specified thickness is obtained. Wax trees shall be cleaned by dipping in Iso-propyl alcohol/ Denaturised spirit. Dry the wax trees in the stands for 15 mins. Dip the wax trees in the slurry first and then apply stucco. Dry the shells. Once, the shells are dried, the shell shall be loaded in an inverted position, inside the de-waxing autoclave. The de-waxing steam pressure shall be 125±15 psi. Hold the pressure for 15±5 min. and release slowly. Load the de-waxed shells in the shell-firing furnace at room temperature. Shell firing shall be carried out at 700±25 °C for 2 hrs to 4 hrs. and cool the shells in the furnace to below 150°C. Shells shall be checked for leaking by filling water. Shells may be repaired if required.

3.1.4 Melting and Pouring

Wrap the shells with glass wool on ingate, sprue, and casting. Casting is to be covered up to the flange near the spare. Load the shells vertically in the preheating furnace, shell mold preheat temperature, Ts = 1100±20 °C, soaking time 4 hr, and vacuum level 10^{-3} Mbar.

3.1.5 Knockout and Fettling

Allow the poured casting to cool for 4 hrs and cut the castings using abrasive cut-off wheel/belt grinding at necessary locations and grind the cut surfaces for a smooth finish using an abrasive grinding machine.

It is necessary to develop and implement a quality assurance plan to qualify the process regarding part quality and reproducibility. Because C1023 Ni-based super alloy is still a relatively new material for series production, this presents quite a challenge. As part of this development, dimensions accuracy specifications, visual inspection criteria, internal defects, crack detection criteria, and roughness specifications were checked.

3.2 Metallurgical Qualification of Ring Flare Casing

3.2.1 Chemical Analysis

The composition of the chemical inoculants plays a critical role in controlling the microstructure and defect formation. During early trials, we observed that the initial levels of ferrosilicon, ferromanganese, and aluminum resulted in either excessive oxidation or incomplete filling of complex mold geometries.

The experimented with varying the levels of inoculants, especially ferrosilicon, to balance the fluidity of the molten metal while preventing the formation of unwanted oxides. By fine-tuning the addition of 0.7-1.0 % ferrosilicon and 0.5 % aluminum, we achieved improved fluidity and reduced oxidation, leading to better mold filling and fewer internal voids. This adjustment was key to achieving a more uniform and defect-free casting. As shown in Table 3, the chemical

Table 3. Chemical analysis report of C1023

Elements	C	Cr	Co	Mo	Ti	Al	Mg	B	Ni
Requirement	0.12-0.18	14.5-16.5	9-10.5	7.6-9	3.4-3.8	3.9-4.4	0.005	0.008	Rem.
Obtained	0.15	14.71	9.05	7.99	3.74	4.36	0.001	0.004	Rem.

composition of Ni alloy is carried during the melting (Vacuum Induction Melting), by atomic absorption spectroscopy Noticeably from these results, the alloy's chemical composition is within allowable limits, which is comparable to the equivalent International Material Specification/Grades for this type of alloy. This indicates that the alloy is of high quality and suitable for use in Ring Flare Casing.

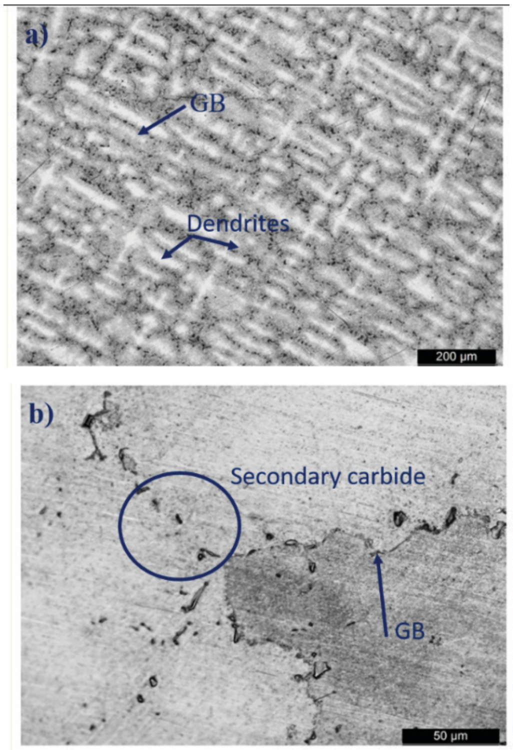

Figure 3. Optical micrograph of C1023.

3.2.2 Microstructure of C1023

The metallurgical microstructure (Fig. 3) of super-alloys can be used to determine the morphological difference between carbides. Certain carbides in the super alloy tend to extend their dendritic arms along grain boundaries (GBs). Under as-cast conditions, the morphology of enormous primary carbides and tiny black flecks surrounding large primary carbides were observed. Moreover, inclusions in blocky carbides show that carbide nuclei play an important role during the solidification process of the carbide. In addition, the super alloy can also be observed to possess many gamma prime (γ') and carbides occurring in the matrix, which strengthens it to withstand higher temperatures.

There is a fine distribution of precipitates γ' that are formed directly after the melting process of this alloy which is the primary reason for its high strength[22]. At the same time, the precipitation of Ni and Al forms the salient strengthening particle of super alloy as cast (Ni_3Al), which means that the particles are irregular in shape[23-25]. Ni_3(Al, Ti) precipitate in fine distribution strengthens C1023 super alloy. This material tends to produce precipitates of the size of a few microns, but it can also produce precipitates of submicron size[26]. A variety of carbides, such as MC, $M_{23}C_6$, and MC_6, can be formed during solidification, with M being typically Mo or Ti-based. The solidification of the casting can be too slow in certain cases, causing detrimental μ phase to form at temperatures of 800 and 900 ^{o}C [27].

3.3 Non-Destructive and Destructive Qualification of Ring Flare Casing

As part of quality inspection procedures, it is necessary to be able to detect defects non-destructively in Ni-based

Table 4. X-ray radiography acceptance standards and results for ring flare casing

Type of indication	Acceptance standards						Results						
	XC			XD			Zones	Nature of defect observed	Level of imperfection		Verdict		
									Observed	Allowable	Re-work	Rej.	Acc.
Crack, hot tear, cold Shut, misrun and cross indications	None			None									
	ASTM E1320 (inch)												
	1/8	3/8	3/4	1/8	3/8	3/4							
Gas holes	3	2	4	4	3	4							
Shrinkage cavity	-	-	0	-	-	1	A (Thin), A1 (Thick)	No Defects	Nil	Nil	-	-	Y
Shrinkage sponge	1	2	1	5	3	2							
Shrinkage dendritic	3	2	2	3	3	3							
Shrinkage filamentary	-	-	0	-	-	1							
Less dense indication	2	2	3	3	2	3							
More dense indication	None			None									

superalloys. The non-destructive detection of subsurface cracks-like defects in casting materials plays a crucial role in the quality inspection process and the safe usage of parts in manufacturing and other industries. Two techniques can be used to detect crack-like defects in Casting C1023, which are digital X-ray radiography and liquid penetration. Even though dye penetrant inspection and conventional X-ray are efficient in detecting defects, each technique has its limitations. The size of the defect, along with its orientation, can also be a significant determinant of the inspection results; therefore, quality inspections must consider these factors at the time of the inspection. The defects can be evaluated throughout the part using X-ray radiography in any solid material. In general, the defects can be evaluated both on the surface and the subsurface (test process described in Table 4).

For better results, the intensity of the X-ray source needs to be higher as the thickness increases A is thin and A1 is a thick section. In the cast parts, there are no visible defects or porosities, and it is non-contaminating. This means that it can detect cracks or other surface defects that are not visible to the naked eye. There are no defects like surface porosity, leaks in new products, and hairline cracks. According to the results, the X-ray images and dye penetrant inspection measurements are in good agreement with each other. This can help ensure that the product meets the performance and safety standards expected of it and can avoid costly delays or failures in production.

Table 5. Tensile properties of C1023 Ni-based super alloys

	0.2 % Proof stress (MPa)	Ultimate tensile strength (MPa)	% Elongation
Experimental value	855	1017	5.97
	869	1039	5.19

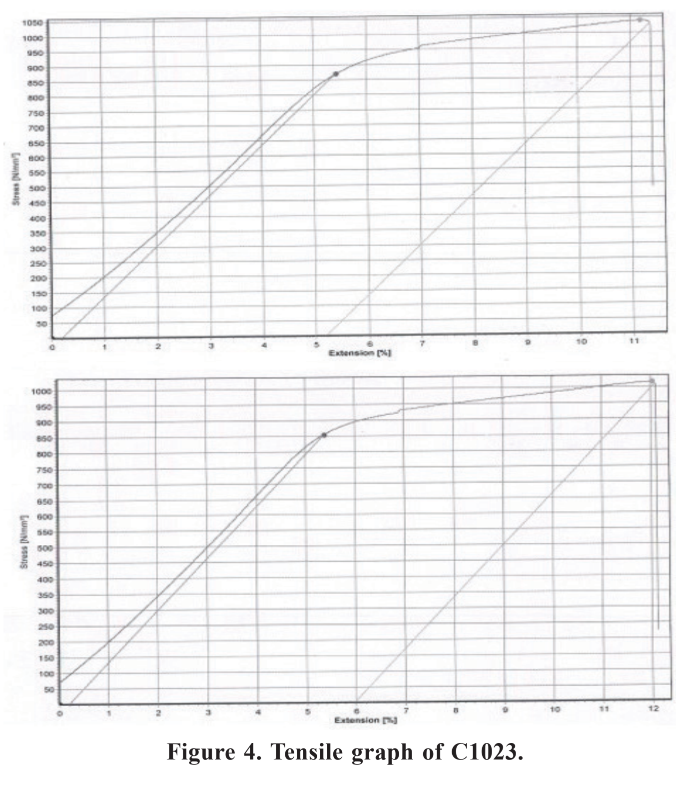

Figure 4. Tensile graph of C1023.

Table 6. Stress rupture of C1023 Ni-based super-alloys

Temperature (°C)	Stress (MPa)	Life (hrs.)	
		Obtained	Acceptance Std.
800	325	92	39 min
850	228	74	

The results of destructive tests are evaluated to assess the material's mechanical properties and suitability for a particular application. Table 5 gives the mechanical properties of C1023. The tensile strength at room temperature including the proof stress (967±5 MPa) and ultimate tensile strength (1063±7 MPa) increases obviously in as-cast conditions. This is because the as-cast microstructure of the C1023 alloy contains a primary gamma solid solution and a second phase with γ' particles. Furthermore, the existence of these γ' particles act as a barrier to dislocation movement and thus makes the material harder and more resistant to deformation[27-28]. Additionally, the difference in thermal expansion coefficient between the matrix and the precipitates can lead to residual stresses in the interface region and further induce crack propagation. This is especially true for the interdendritic zones, which demonstrate a higher degree of segregation and a more brittle phase. The lamellar structure of MC carbide makes it more brittle than metals with a single-phase structure, which leads to it cracking directly under stress without significant plastic deformation. The ceramic nature of MC carbide also contributes to its brittleness.

A stress rupture test was performed at elevated temperature to be able to see the life and elongation of the stress rupture with different long-term thermal exposure times (Table 6). As the exposure time increases, the degree of embrittlement increases, resulting in a decrease in the alloy's strength. When the exposure time reaches 39 hrs., the alloy is at its most embrittled state. Furthermore, an increase in the service temperature to 850 °C further increases the degree of embrittlement, resulting in decreased life (74 hrs) of the alloy.

In the as-cast condition it has, a complex dendritic structure because of the different cooling rates of the alloy during the casting process. The primary dendrite arm is the fastest to cool and thus has the largest grain size. As cooling continues, the secondary arms form, with smaller grain sizes. Generally, the segregation of Mo and Cr elements during alloy solidification occurs due to the low solubility of these elements in the γ matrix. As a result, they tend to accumulate in the areas of the alloy with the lowest solidification rate, i.e. the inter-dendritic regions. This increases the concentration of these elements in the inter-dendritic regions, leading to the formation of Cr-rich $M_{23}C_6$ and Mo-rich M_6C carbides[28-29]. According to the results, the carbide has a low affinity for the matrix, meaning there is not a strong bond between them. As a result, when subjected to stress, the weaker bond between the carbide and the matrix will be broken, and the interface will become the cracking source. As the C1023 Ni-based super-alloy is exposed to high temperatures and other environmental factors, the microstructural changes lead to the redistribution of alloying elements, which changes the microstructure and properties of the material. This can result in a decrease in mechanical properties, leading to a decrease in the service life of the super-alloy. In accordance with the test schedule, above tests are conducted, and test compliance reports are validated. A pre-production clearance is granted for component level testing. CEMILAC (Indian military airworthiness certification body) recently certified the ring flare casing after passing all above tests[30-32].

4. CONCLUSION

The qualification and certification approach for the ring flare casing starts with a detailed design analysis to ensure that the part is structurally sound and can withstand the stresses.

The results indicated that the tensile properties of the material were within the requirements of the standard, indicating that the material was able to withstand the applied stresses without failing. The fracture was caused by the presence of carbides in the material which caused the material to be weaker and more prone to cracking. The ductile fracture was caused by the stress being applied transgranularly, meaning across the grain boundaries of the material, causing the material to break in a ductile manner.

The performance of the material manufactured has been found to comply with aerospace quality requirements as specified by the relevant standards. The material has been subjected to a series of tests and trials to establish its airworthiness and compliance with the relevant specifications. The indigenization program has helped in significant cost savings and enabled the country to be self-reliant in terms of producing the materials required for its defence programs.

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