

Assessment of the chemical composition homogeneity of turbine blades from a jet engine turbine

ARTICLE INFO

The variability of primary emission signals from high-pressure turbine blades originating from the same stage of an SO-3 turbojet engine was evaluated using Laser Ablation coupled with Microwave-Induced Plasma Optical Emission Spectrometry (LA-MIP OES). Forty turbine blades were investigated, with one analytical measurement performed for each blade. Direct solid sampling enabled multi-element analysis without chemical sample preparation. The primary emission signal intensities of nickel, molybdenum, chromium, cobalt, and aluminum were statistically evaluated using mean values, standard deviations, coefficients of variation, interquartile ranges, confidence intervals, and boxplot analysis. The coefficients of variation ranged from 3.44% to 11.60%, indicating relatively low variability of the measured emission signals among the investigated blades. The lowest variability was observed for cobalt, nickel, and molybdenum, whereas chromium exhibited the highest dispersion. The results demonstrate a high degree of uniformity of the measured emission signals and indicate the potential of LA-MIP OES for comparative assessment of turbine blade materials.

Received: 17 July 2026

Revised: 29 September 2026

Accepted: 2 October 2026

Available online: 8 October 2026

Key words: turbojet engine, turbine blades, LA-MIP OES, emission signal uniformity, nickel-based superalloys

This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>)

1. Introduction

The continuous development of aircraft propulsion systems has led to increasingly stringent requirements regarding engine efficiency, reliability, and operational safety. Among all engine components, turbine blades are subjected to the most severe service conditions, including extremely high temperatures, centrifugal forces, cyclic mechanical loading, and aggressive combustion environments. Consequently, the integrity of these components is essential for ensuring the performance and durability of gas turbine engines [10, 20, 24, 28].

The service life of turbine blades is largely determined by the properties of the nickel-based superalloys from which they are manufactured. Their exceptional high-temperature performance results from a carefully designed chemical composition and microstructure, providing excellent resistance to creep, oxidation, thermal fatigue, and high-temperature corrosion [9, 21, 22]. During long-term operation, however, degradation processes such as oxidation, diffusion of alloying elements, erosion, and thermo-mechanical fatigue may alter the local chemical composition and consequently reduce the mechanical performance of the material [2, 26, 32].

Numerous studies have investigated the degradation mechanisms, microstructure, and mechanical properties of turbine blade superalloys. However, relatively limited attention has been devoted to assessing the chemical composition uniformity among blades originating from the same turbine stage after service. Such an assessment is important because differences in elemental composition may indicate manufacturing variability, non-uniform degradation processes, or localized material deterioration. Moreover, determining the degree of chemical homogeneity within an entire turbine stage can provide valuable information for condition assessment, maintenance planning, and life prediction of turbine components [16, 27, 29].

Laser Ablation coupled with Microwave-Induced Plasma Optical Emission Spectrometry (LA-MIP OES) enables direct multi-element analysis of solid materials by combining localized laser sampling with optical emission detection in a microwave-induced plasma. Previous studies have demonstrated the applicability of this approach to the analysis of solid samples and simultaneous determination of multiple elements, including analyses of metallic materials [7, 15, 31]. The method allows direct sampling of the investigated material and can therefore be applied to the comparative analysis of individual components without extensive chemical sample preparation [7, 31].

The objective of this study was to evaluate the uniformity of primary emission signal intensities recorded for turbine blades originating from the same stage of a jet engine turbine. Multi-element analyses were performed using Laser Ablation coupled with Microwave-Induced Plasma Optical Emission Spectrometry (LA-MIP OES). The obtained results were statistically analysed to assess the variability of the measured emission signals among the investigated turbine blades.

2. Jet engine turbine

2.1. Design

Turbines in jet engines are key components that convert exhaust gas energy into mechanical work, which is necessary to drive the compressor and other engine components. In jet engines, such as turbojet and turbofan engines, turbines recover energy from the hot, expanding exhaust gases generated in the combustion chamber. This energy is used to drive the compressor, which compresses the air drawn into the engine, which is necessary to maintain a continuous combustion process and generate thrust [20]. Turbines in jet engines are essential components that enable energy recovery from exhaust gases and drive the compressor, which is the basis of engine operation. Their design and materials

must withstand extreme operating conditions, and their efficiency directly impacts the engine's performance and economy [8, 28]. Turbine components include:

- turbine blades – made of high-strength metal alloys or ceramic materials resistant to high temperatures. They are arranged on the rotor and have a special aerodynamic profile that allows for effective capture of the kinetic energy of gases [10]
- turbine rotor – the rotating part of the turbine to which the blades are attached. The rotor is connected to the compressor by a shaft
- turbine housing – holds the blades and rotor in place and directs the gas flow [9].

The high-pressure turbine (HPT) is located directly behind the combustion chamber and drives the high-pressure compressor. High-pressure turbines can spin at speeds of 13,000 to 15,000 revolutions per minute (rpm) at full power, which occurs during takeoff or climb. The low-pressure turbine (LPT) drives the low-pressure compressor or fan in turbofan engines. During cruising, the turbine's rotational speed typically drops to around 8,000 to 10,000 rpm.

Jet engine fans typically operate at lower speeds, around 3200 rpm [22]. The resulting high-temperature, high-pressure exhaust gases exit the combustion chamber and enter the turbine blades. As they flow through the blades, the gas expands, losing pressure and temperature while simultaneously transferring mechanical energy to the turbine rotor. The rotating rotor drives a shaft, which in turn turns a compressor, enabling continuous air intake and compression [21].

2.2. Significance and design challenges

The design and operation of jet engine turbines involve meeting a number of stringent engineering requirements. Turbine components operate under extreme thermal, mechanical, and aerodynamic loads, where even minor design deficiencies may significantly reduce engine efficiency, reliability, and service life. Therefore, turbine design requires a careful balance between mechanical strength, aerodynamic performance, thermal resistance, and structural integrity while maintaining stable operation at very high rotational speeds [26].

One of the primary design challenges is ensuring resistance to elevated temperatures. Modern turbine blades are exposed to gas temperatures exceeding 1000°C, which necessitates the use of advanced high-temperature materials, internal cooling systems, and thermal barrier coatings to maintain acceptable operating temperatures and extend component life [19, 32]. Another critical requirement is achieving high energy conversion efficiency by maximizing energy extraction from the expanding combustion gases while minimizing aerodynamic losses [2]. In addition, the turbine rotor must be precisely balanced and exhibit high structural durability to prevent excessive vibrations, mechanical damage, and premature failure during operation at rotational speeds reaching several thousand revolutions per minute [29].

The overall efficiency of a turbojet engine depends on numerous parameters, including the compressor pressure ratio, turbine inlet temperature, flight speed, and operating conditions [18]. Under practical operating conditions, the

thermal efficiency of conventional turbojet engines is typically in the range of 20–30%, although higher values can be achieved through improvements in engine design and operating parameters. Owing to their relatively simple construction, turbojet engines are particularly effective at high and supersonic flight speeds, where their propulsion characteristics provide significant performance advantages [16].

2.3. Properties of gas turbine blades

Gas turbine blades are among the most highly loaded components of modern aircraft engines. During operation, they are subjected to extreme thermal gradients, high centrifugal forces resulting from elevated rotational speeds, and continuous exposure to aggressive combustion gases. These severe service conditions require the blades to simultaneously satisfy a range of demanding and often conflicting material and structural requirements. As a result, the design and material selection of turbine blades remain one of the greatest challenges in aerospace engineering, directly influencing engine efficiency, operational reliability, and service life [27].

To ensure reliable performance under such conditions, turbine blades must exhibit a unique combination of mechanical, thermal, and chemical properties. These include high mechanical strength at elevated temperatures, allowing the material to retain its load-bearing capability at temperatures exceeding 1000°C; excellent creep resistance to withstand prolonged exposure to high temperatures and stresses; high fatigue resistance against cyclic thermal and mechanical loading; and superior oxidation and corrosion resistance to protect the material from degradation in aggressive high-temperature environments. In addition, controlled thermal conductivity is required to minimize thermal stresses, while maintaining a low density and a high strength-to-weight ratio contributes to improved turbine efficiency and reduced centrifugal loading [25, 27].

Achieving these performance requirements necessitates the application of advanced materials engineering and manufacturing technologies. Modern turbine blades are typically produced from nickel-based superalloys and incorporate sophisticated design solutions, including internal cooling channels, thermal barrier coatings (TBCs), and carefully controlled microstructures. In practice, turbine blade design involves optimizing the balance between mechanical strength, thermal resistance, oxidation resistance, and component weight, as improving one property often compromises another. Furthermore, long-term degradation mechanisms, such as creep, oxidation, diffusion of alloying elements, and thermal fatigue, must be considered because they gradually reduce the mechanical performance and service life of turbine blades during operation [6].

2.4. Blade construction and structure

The turbine blade is a crucial component of every gas turbine section, playing a key role in harnessing the energy from the high-temperature, high-pressure gas generated by the combustion chamber [1]. Under operating conditions, it operates in an extreme environment characterized by very high temperatures, high rotational speeds, and severe mechanical and chemical loads, necessitating the use of advanced materials and design technologies. Blades should

have a single-crystal or directionally crystallized structure, which reduces grain boundaries and improves creep and fatigue resistance. Eliminating grain boundaries reduces crack initiation and slows material degradation at high temperatures, directly impacting component durability. Cooling air flows through the blades, extending their service life. Their aerodynamic shape should be optimized for efficient energy conversion from hot gases. The blade profile geometry is the result of advanced flow analyses and aims to minimize aerodynamic losses and ensure maximum energy recovery from the gas flow. Turbine blades should be as light as possible while maintaining high structural strength. Achieving this compromise is crucial due to the very high centrifugal forces acting on the blades during engine operation, which increase with the increase in turbine rotational speed [4].

2.5. Composition of turbine blades and their properties

Gas turbine blades, particularly those used in aircraft and industrial turbines, are made of advanced materials resistant to very high temperatures and heavy mechanical loads. Superalloys (in gas turbines) are advanced metallic materials that enable turbine components to operate at extremely high temperatures and in aggressive environmental conditions. Their unique mechanical and chemical properties are crucial for the efficiency, durability, and safety of gas turbine operation [23]. The most commonly used materials for building blades are:

- heat-resistant superalloys (superalloys): mainly nickel- or cobalt-based or, less frequently, iron-based in less extreme conditions
- main elements in superalloys: nickel (Ni): the leading superalloy is based on it, it provides high strength at high temperatures, is valued for its exceptional strength and extraordinary resistance to high temperatures; cobalt (Co): improves strength and corrosion resistance; chromium (Cr): protects against oxidation; molybdenum (Mo) and tungsten (W): increase creep resistance and mechanical strength; aluminum (Al) and titanium (Ti): create protective layers and strengthen the alloy structure; rhenium (Re) – improves the stability of the structure at high temperatures; other alloying elements, e.g. iron (Fe) and carbon (C)
- ceramic coatings – TBC (thermal barrier coatings): applied to the blades to reduce heat transfer and protect the alloy against thermal degradation [30].

Efforts are underway to develop materials for blades with the highest possible strength, suitable for use in the high-temperature turbine section. The addition of nanoparticles is a promising strategy that allows for simultaneous improvements in hardness, strength, corrosion resistance, and creep resistance [11].

2.6. Wear processes in the elemental composition of jet engine turbine blades

Turbine blades in jet engines are exposed to extreme operating conditions that cause various wear processes affecting their elemental composition and material properties [34]. The processes that influence the elemental composition are primarily:

- high-temperature oxidation and corrosion – high temperatures and the presence of oxygen cause the formation of oxides on the surface of the blades, mainly chromium oxides (Cr_2O_3) [14]. This process can lead to the loss of alloying elements from the surface, weakening the protective layer and accelerating degradation. Oxidation can cause element migration, for example, enriching the surface with chromium oxides at the expense of other components [13].
- erosion and cavitation – solid particles, dust, and liquid droplets striking the blade surface cause mechanical abrasion. This can lead to the removal of the surface layer and changes in the local elemental composition. During aircraft engine operation, large amounts of particulate contaminants, such as sand and dust, are drawn into the engine interior by external airflow, seriously affecting safety and economy. The main components of these particles are CaO , MgO , Al_2O_3 and SiO_2 , collectively known as CMAS (calcium-magnesium-aluminosilicate). Some CMAS particles may be deposited on the surfaces of turbine blades [5, 17]
- thermomechanical fatigue – cyclic changes in temperature and stress cause microcracks and delamination. Local changes in elemental composition, e.g., element segregation, may occur at the crack sites [12]
- elemental diffusion – at high temperatures, diffusion of elements occurs between different alloy phases, which can lead to changes in the microstructure and mechanical properties. An example is the migration of aluminum and titanium, which form hard reinforcing phases [3, 33].

3. Materials and methods

3.1. Object of the study

The material investigated consisted of high-pressure turbine blades from the same turbine stage of an SO-3 turbojet engine. The SO-3 is a single-spool turbojet engine used in military aircraft. The turbine blades operate under severe service conditions, including elevated temperatures, high mechanical stresses, and significant centrifugal forces, making them among the most highly loaded components of the engine.

The investigated blades were manufactured from a cast nickel-based superalloy designed for high-temperature applications. Nickel-based superalloys exhibit excellent mechanical strength, creep resistance, oxidation resistance, high-temperature corrosion resistance, and thermal fatigue resistance owing to their carefully controlled chemical composition and microstructure.

All blades examined in this study originated from the same high-pressure turbine stage and had been operated under comparable service conditions. This enabled the assessment of chemical composition homogeneity while minimizing the influence of manufacturing variability and differences in operating conditions.

3.2. Experimental setup

Emission measurements were performed using a PlasmaQuant 100 microwave-induced plasma optical emission spectrometer (MIP-OES) (Analytik Jena, Germany),

equipped with an Echelle optical system and a rectangular microwave cavity operating in the TE₁₀₁ mode. The spectrometer was coupled to a LA J200 laser ablation system (Applied Spectra Inc., Fremont, CA, USA), enabling direct solid sampling without sample dissolution.

The laser ablation system employed a 266 nm Nd:YAG laser. The generated aerosol was transported from the ablation chamber to the plasma using helium as the carrier gas, while argon served as the plasma support gas. Both instruments were connected by a 1 m Teflon transfer tube (3 mm i.d.) to minimize aerosol losses during transport.

3.3. Sample preparation

Prior to analysis, the turbine blade surfaces were cleaned with distilled water, followed by high-purity methanol to remove surface contaminants. No additional mechanical or chemical treatment was applied. The investigated turbine blades, with approximate dimensions of 28×64 mm, were mounted directly in the laser ablation chamber using a dedicated sample holder. A motorized x–y–z translation stage enabled precise positioning of the blades and accurate focusing of the laser beam at the selected analytical locations. To ensure measurement consistency, all analyses were carried out at the central region of each turbine blade, with the laser beam focused at the same predefined location on every specimen.

3.4. LA-MIP OES analysis

Before each analytical sequence, the microwave-induced plasma was ignited by briefly inserting an insulated high-purity tantalum wire into the discharge tube. After ignition, the plasma was allowed to stabilize for approximately 10 min. Throughout the experiments, the microwave forward power was maintained at 170 W.

Laser ablation was performed under a continuous helium flow, while argon was supplied as the plasma support gas. The laser operating conditions were optimized in preliminary experiments to ensure efficient material removal while minimizing thermal effects on the surrounding material. The optimized operating parameters are presented in Table 1.

The aerosol generated during laser ablation was transported directly into the microwave-induced plasma, where atomization and excitation of the sample constituents occurred. The emitted radiation was dispersed by the Echelle optical system and recorded for elemental analysis.

Because the manufacturer-provided software could not record transient emission signals, a dedicated in-house-developed multichannel data acquisition system was employed. Twelve analog outputs from the polychromator photomultiplier circuits, along with the monochromator

output, were recorded simultaneously. Custom-developed software enabled time-resolved acquisition and processing of transient emission signals, allowing successful coupling of the laser ablation system with the MIP-OES spectrometer.

Table 1. Operating parameters for the LA system

Parameter	Value/setting
Instrument	LA J200, Applied Spectra Inc., Fremont, CA)
Wavelength/nm	266
Laser output energy/mJ	25
Laser repetition rate/Hz	10
Ablation mode	Pointed
Laser scan speed/mm s ⁻¹	0.1–10
Ablation time/s	1.5
Spot size/μm	200
Number of investigated blades	40
Number of measurements per sample	1
Carrier gas mL/min	0.5 Helium (N-50 purity)
Supporting gas mL/min	0.5 Argon (N-50 purity)

3.5. Statistical analysis

A total of 40 turbine blades originating from the same high-pressure turbine stage were investigated. One analytical measurement was performed for each blade, resulting in 40 independent observations. No repeated measurements were performed for individual blades. The statistical analysis was based directly on the primary emission signal intensities recorded by the LA-MIP OES system. No calibration procedure was applied, and the measured emission signals were not converted into elemental concentrations. For each investigated element, mean value, median, standard deviation (SD), coefficient of variation (CV), minimum and maximum values, interquartile range (IQR), and 95% confidence interval (CI) were calculated from the 40 independent measurements. The distributions of the measured emission signal intensities were additionally evaluated using boxplots.

4. Results

The variability of the primary emission signal intensities recorded for the investigated SO-3 turbine blades was evaluated for nickel (Ni), molybdenum (Mo), chromium (Cr), cobalt (Co), and aluminum (Al). The statistical characteristics of the obtained results are summarized in Table 2, while the distribution of the measured values for each element is presented in Fig. 1–5.

Table 2. Statistical characteristics of the emission signal intensities of the analyzed alloying elements

Element	Mean	Median	SD	CV [%]	Minimum	Maximum	IQR	95% CI Lower	95% CI Upper
Ni221	5727	5680	202	3.57	5376	6432	208	5661	5793
Mo281	8746	8816	328	3.69	8000	9312	544	8639	8853
Cr359	22176	22520	2486	11.60	17392	26240	3904	21364	22988
Co237	11887	11928	399	3.44	11088	12832	576	11756	12017
Al308	25609	25464	1584	9.54	22000	29088	1952	25092	26126

The statistical analysis presented in Table 2 indicates relatively low variability in the primary emission signal intensities of the investigated alloying elements. The lowest coefficients of variation were obtained for cobalt (3.44%), nickel (3.57%), and molybdenum (3.69%), indicating a high degree of uniformity of the measured emission signals among the investigated turbine blades. Higher variability was observed for aluminum (9.54%) and chromium (11.60%), with chromium showing the highest dispersion among the investigated elements.

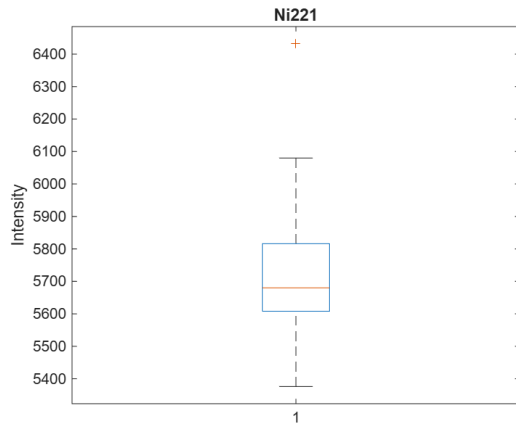


Fig. 1. Distribution of nickel (Ni) emission signal intensities measured for the investigated SO-3 turbine blades

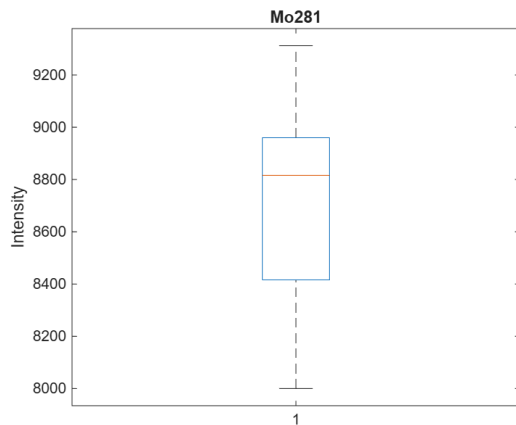


Fig. 2. Distribution of molybdenum (Mo) emission signal intensities measured for the investigated SO-3 turbine blades

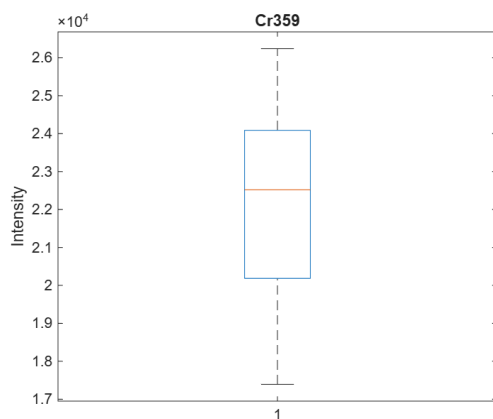


Fig. 3. Distribution of chromium (Cr) emission signal intensities measured for the investigated SO-3 turbine blades

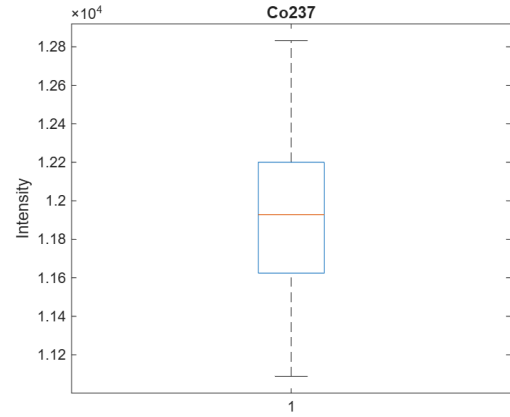


Fig. 4. Distribution of cobalt (Co) emission signal intensities measured for the investigated SO-3 turbine blades

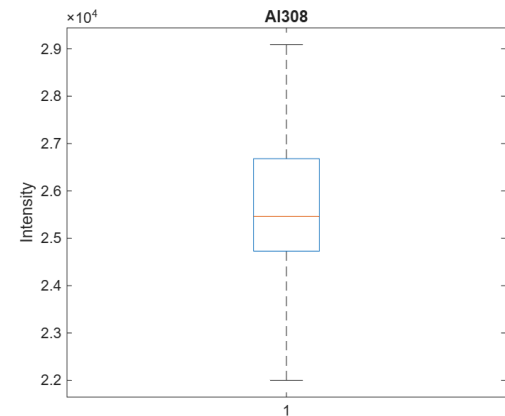


Fig. 5. Distribution of aluminum (Al) emission signal intensities measured for the investigated SO-3 turbine blades

The distribution of the primary emission signal intensities presented in Fig. 1–5 indicates a high degree of uniformity of the measured signals among the investigated SO-3 turbine blades. For all analyzed elements, the median is located near the center of the distribution, while most observations fall within the interquartile range, indicating relatively low variability in the measured emission signal intensities among the analyzed blades. The lowest dispersion was observed for nickel, molybdenum, and cobalt, which is consistent with the low coefficients of variation (CV below 4%). Higher variability was observed for aluminum and chromium, with chromium exhibiting the highest CV (11.60%).

Individual outlying observations are visible in several boxplots; however, their occurrence is limited and does not affect the overall assessment of the variability of the measured emission signals. These observations may be associated with local microstructural heterogeneity, non-uniform distribution of strengthening phases, or natural variability related to the service history of the investigated material. The graphical analysis is consistent with the statistical parameters presented in Table 2 and indicates a relatively high uniformity of the measured emission signals among the investigated turbine blades.

5. Discussion

The results obtained for the investigated turbine blades indicate a relatively uniform distribution of the primary

emission signal intensities recorded for the analyzed alloying elements. The differences observed between individual blades may be associated with local variations in the material structure and the distribution of alloying phases. Such variations are particularly relevant in nickel-based superalloys, in which the local microstructure can influence the analytical response obtained during laser ablation.

The differences in signal variability observed between the investigated elements may also reflect differences in their distribution within the alloy matrix and in the response of the LA-MIP OES measurement system. The higher variability observed for chromium and aluminum compared with nickel, molybdenum, and cobalt suggests that these elements may exhibit greater local heterogeneity in the analyzed material. However, the present results should be interpreted as a comparative assessment of the recorded emission signals rather than as a direct determination of elemental concentrations.

An important feature of the applied LA-MIP OES approach is the possibility of direct analysis of solid turbine blade material. The method allows individual components to be compared using the same analytical procedure while avoiding extensive chemical sample preparation. This is particularly useful for investigations involving a relatively large number of turbine components originating from the same turbine stage.

The obtained results also demonstrate the importance of considering the local characteristics of the analyzed surface and material when interpreting laser ablation measurements. The measurements were performed in a predefined

central region of each blade; therefore, the present study characterizes the variability between individual blades rather than the spatial variability within a single blade.

6. Conclusions

Based on the experimental results and the statistical evaluation of the primary emission signal intensities recorded for the investigated SO-3 turbine blades, the following conclusions can be drawn:

1. The LA-MIP OES methodology enabled rapid and direct multi-element analysis of SO-3 turbine blades without chemical sample preparation. The obtained primary emission signals provided a basis for comparative assessment of the variability of the investigated alloying elements.
2. The statistical analysis of 40 independent measurements demonstrated relatively low variability of the measured emission signal intensities. The coefficients of variation ranged from 3.44% to 11.60% for the investigated elements.
3. The lowest variability was observed for cobalt, nickel, and molybdenum, while chromium exhibited the highest variability. Aluminum also showed higher dispersion than Ni, Mo, and Co.
4. The proposed approach can be used for comparative assessment of the uniformity of emission signals among turbine blades originating from the same turbine stage and may provide a basis for further investigations of material variability and degradation processes in aircraft gas turbine components.

Nomenclature

Al	aluminum	LPT	low-pressure turbine
CI	confidence interval	MIP-OES	microwave-induced plasma optical emission spectrometry
CV	coefficient of variation	Mo	molybdenum
Co	cobalt	Ni	nickel
Cr	chromium	SD	standard deviation
HPT	high-pressure turbine	SO-3	SO-3 turbojet engine
IQR	interquartile range	TBC	thermal barrier coating
LA	laser ablation	TE ₁₀₁	transverse electric mode (TE ₁₀₁)
LA-MIP OES	laser ablation microwave-induced plasma optical emission spectrometry		

Bibliography

- [1] Badyda K. Perspektywy rozwoju technologii turbin gazowych oraz bloków gazowo-parowych. Rynek Energii. 2014;9-15.
- [2] Badyda K, Miller A. Energetyczne turbiny gazowe oraz układy z ich wykorzystaniem. Kaprint. Lublin 2014.
- [3] Bin G, Yang P, Li J, Li C, Zhang W, Miao H et al. Review of particle deposition on aeroengine turbine blades and its mitigation. Int J Heat Fluid Flow. 2026;117:110023. <https://doi.org/10.1016/j.ijheatfluidflow.2025.110023>
- [4] Boyce MP. Gas turbine engineering handbook. 4th ed. Butterworth-Heinemann. Oxford 2011.
- [5] Bravo LG, Jain N, Khare P, Murugan M, Ghoshal A, Flatau A. Physical aspects of CMAS particle dynamics and deposition in turboshaft engines. J Mater Res. 2020;35:2249-2259. <https://doi.org/10.1557/jmr.2020.234>
- [6] Callister WD, Rethwisch DG. Materials science and engineering: an introduction. 10th ed. Hoboken. John Wiley & Sons. NJ 2018.
- [7] Ciocan A, Uebbing J, Niemax K. Analytical application of the microwave induced plasma used with laser ablation of solid samples. Spectrochim Acta B At Spectrosc. 1992;47:611-617. [https://doi.org/10.1016/0584-8547\(92\)80056-M](https://doi.org/10.1016/0584-8547(92)80056-M)
- [8] Czarniecki ML. Micro gas turbine evolution, a quarter-century review. Combustion Engines. 2025;2(201):83-90. <https://doi.org/10.19206/CE-203003>
- [9] Dixon SL, Hall CA. Fluid mechanics and thermodynamics of turbomachinery. 7th ed. Butterworth-Heinemann. Oxford 2014.
- [10] El-Sayed A. Aircraft propulsion and gas turbine engines. Boca CRC Press. Raton 2008.

- [11] Faizal WM, Mazlan NM, Khor CY, Hazwan MHM, Misbah MN, Haidiezul AHM. Fluid-structure interaction in turbine blade under different sustainable aviation fuel: a featured study of mechanical behavior. *Fuel*. 2026;406:137027. <https://doi.org/10.1016/j.fuel.2025.137027>
- [12] Fathyunes L, Mohtadi-Bonab MA. A review on the corrosion and fatigue failure of gas turbines. *Metals*. 2023;13(4):701. <https://doi.org/10.3390/met13040701>
- [13] Gong N, Meng TL, Teo SL, Cao J, Lee CJJ, Tan CKI et al. High-temperature oxidation and hot corrosion of Ni-based single crystal superalloy in the incubation stage. *Corros Sci*. 2023;214:111026. <https://doi.org/10.1016/j.corsci.2023.111026>
- [14] Guo HY, Tan ZH, Li YM, Zou MK, Tao Y, Wang XG et al. Diffusion of alloying elements during high temperature oxidation in a low-cost third generation Ni-based single crystal superalloy. *Mater Charact*. 2024;211:113913. <https://doi.org/10.1016/j.matchar.2024.113913>
- [15] Hiddemann L, Uebbing J, Ciocan A, Dessenne O, Niemax K. Simultaneous multi-element analysis of solid samples by laser ablation–microwave-induced plasma optical emission spectrometry. *Anal Chim Acta*. 1993;283:152-159. [https://doi.org/10.1016/0003-2670\(93\)85217-8](https://doi.org/10.1016/0003-2670(93)85217-8)
- [16] Jakubowski R, Orkisz M. Sprawność turbinowego silnika odrzutowego dla różnych warunków pracy dyszy wylotowej. *Journal of KONES*. 2000;7:207-216.
- [17] Kurzawska-Pietrowicz P. Comprehensive analysis of particle emissions from miniature turbojet engine. *Combustion Engines*. 2025;1(200):12-18. <https://doi.org/10.19206/CE-192421>
- [18] Kurzawska-Pietrowicz P, Szrama S, Jasiński R, Siedlecki M. Evaluation of jet engine performance parameters fueled with sustainable aviation fuel. *Combustion Engines*. 2026;1(204):35-42. <https://doi.org/10.19206/CE-208774>
- [19] Laguna-Camacho JR, Villagrán-Villegas LY, Martínez-García H, Juárez-Morales G, Cruz-Orduña MI, Vite-Torres M et al. A study of the wear damage on gas turbine blades. *Eng Fail Anal*. 2016;61:88-99. <https://doi.org/10.1016/j.engfailanal.2015.10.002>
- [20] Langston LS. Turbines, gas. In: Reference module in earth systems and environmental sciences. Elsevier 2013. <https://doi.org/10.1016/B978-0-12-409548-9.09044-8>
- [21] Léonard O, Thomas JP, Borguet S. Ten years of experience with a small jet engine as a support for education. *J Eng Gas Turbines Power*. 2009;131(1):012303. <https://doi.org/10.1115/1.2967487>
- [22] Mattingly JD. Elements of gas turbine propulsion. McGraw-Hill. New York 1996.
- [23] Padture NP, Gell M, Jordan EH. Thermal barrier coatings for gas-turbine engine applications. *Science*. 2002;296(5566):280-284. <https://doi.org/10.1126/science.1068609>
- [24] Palkus K. Numerical analysis of the front deflector at the outer air seal of low-pressure turbine. *Combustion Engines*. 2026;3(206):121-129. <https://doi.org/10.19206/CE-217829>
- [25] Reed RC, Tao T, Warnken N. Alloys-by-design: application to nickel-based single crystal superalloys. *Acta Mater*. 2009;57(19):5898-5913. <https://doi.org/10.1016/j.actamat.2009.08.018>
- [26] Saravanamuttoo HIH, Rogers GFC, Cohen H, Straznicki PV, Nix AC. Gas turbine theory. 7th ed. Pearson. Harlow 2017.
- [27] Sims CT, Stoloff NS, Hagel WC, eds. Superalloys II: high-temperature materials for aerospace and industrial power. 2nd ed. Wiley-Interscience. New York 1987.
- [28] Şöhret Y, Ekici S, Altuntaş Ö, Hepbaşlı A, Karakoç TH. Exergy as a useful tool for the performance assessment of aircraft gas turbine engines: a key review. *Prog Aerosp Sci*. 2016;83:57-69. <https://doi.org/10.1016/j.paerosci.2016.03.001>
- [29] Świerżawski T. Sprawność napędu odrzutowego. *Zeszyty Naukowe Politechniki Śląskiej. Energetyka*. 1957;2.
- [30] Tetsui T. Identifying low-cost, machinable, impact-resistant TiAl alloys suitable for last-stage turbine blades of jet engines. *Intermetallics*. 2024;168:108263. <https://doi.org/10.1016/j.intermet.2024.108263>
- [31] Uebbing J, Ciocan A, Niemax K. Optical emission spectrometry of a microwave induced plasma used with laser ablation of solid samples. *Spectrochim Acta B At Spectrosc*. 1992;47:601-610. [https://doi.org/10.1016/0584-8547\(92\)80055-L](https://doi.org/10.1016/0584-8547(92)80055-L)
- [32] Walsh PP, Fletcher P. Gas turbine performance. 2nd ed. Blackwell Publishing. Oxford 2004. <https://doi.org/10.1002/9780470774533>
- [33] Xie J, Ma Q, Li YC, Pu H, Li RD. Study of particle deposition characteristics on turbine blade surfaces based on a dual-parameter model. *Int J Heat Mass Transf*. 2026;265:128812. <https://doi.org/10.1016/j.ijheatmasstransfer.2026.128812>
- [34] Zhao X, Zhang D, Li ZY, Yang HY, Zhong XM, Chen JB. Microstructure and high-temperature creep behavior of nano-strengthened superalloys. *J Mater Res Technol*. 2026;41:2000-2021. <https://doi.org/10.1016/j.jmrt.2026.01.123>

Prof. Grzegorz M. Szymański, DSc., DEng. – Institute of Transport, Poznan University of Technology, Poland.
e-mail: grzegorz.m.szymanski@put.poznan.pl



Alicja Szymańska, Eng. – Institute of Technical Chemistry and Electrochemistry, Poznan University of Technology, Poland.
e-mail: alicja.szymanska.1@student.put.poznan.pl



Prof. Mariusz Ślachciński, DSc., DEng. – Institute of Technical Chemistry and Electrochemistry, Poznan University of Technology, Poland.
e-mail: mariusz.slachcinski@put.poznan.pl



Prof. Bogdan Wyrwas, DSc., DEng. – Institute of Technical Chemistry and Electrochemistry, Poznan University of Technology, Poland.
e-mail: bogdan.wyrwas@put.poznan.pl

