

## SERVICE PROBLEMS OF AN AXIAL COMPRESSORS OF A LAND BASED, HIGH POWER, REACTION GAS TURBINES

### PROBLEMY EKSPLOATACYJNE OSIOWYCH SPRĘŻAREK REAKCYJNYCH STACJONARNYCH SILNIKÓW TURBINOWYCH DUŻYCH MOCY

*A compressor blade failure was experienced at the 69 MW gas turbine of a combined cycle (C.C.) unit after four years operation since the last overhaul. Three unit failure events occurred at small periods, which caused forced outage. Visual examination carried out after the failure events indicated that the compressor vanes (diaphragms) had cracks in their airfoils initiating at blade tenons welded to the diaphragm outer shroud at some stages. Also, many stationary vanes and moving blades showed foreign object damage (FOD), rubbing and bending. A compressor failure evaluation was completed including cracked vane metallographic analysis, unit operation parameter analysis, history-of-events analysis, and crack initiation and propagation analysis. This paper provides an overview of the compressor failure investigation, which led to identification of the vane high cycle fatigue (HCF) failure mechanism generated by rotating stall during unit start-ups, highly accelerated by corrosion generated by the fogging system and influenced by high stationary vane and moving blade brittleness as the primary contribution to the observed failure. They are provided recommendations to avoid similar failure of the compressor blades in the future.*

**Keywords:** fogging, blades failure, high cycle fatigue, rotating stall, vibratory stresses, corrosion.

*W sprężarce turbiny gazowej o mocy 69 MW, pracującej w cyklu kombinowanym wystąpiły uszkodzenia łopatek po czterech latach eksploatacji od ostatniego remontu głównego. Zarejestrowano trzy przypadki uszkodzeń w krótkim odstępie czasu, które spowodowały potrzebę zatrzymania i remontu turbiny. Badania wzrokowe przeprowadzone po każdym stwierdzeniu uszkodzeń, ujawniły pęknięcia w łopatkach niektórych stopni palisad kierowniczych zlokalizowane w piórach łopatek. Pęknięcia zaczynały się w stopach łopatek spawanych do bandaża zewnętrznego palisad kierowniczych. Znaczna liczba łopatek kierowniczych i wirnikowych miała również uszkodzenia spowodowane przez obce ciała, przytarcia i były pognięte. Przeprowadzono badania i analizę uszkodzeń sprężarki włączając w to badania metalograficzne pękniętych łopatek, analizę parametrów operacyjnych turbiny, analizę historii zarejestrowanych przypadków uszkodzeń i analizę inicjacji i propagacji pęknięć. W niniejszym artykule opisuje się badania uszkodzeń palisad łopatkowych sprężarki, które doprowadziły do konkluzji końcowej, że pęknięcia łopatek palisad kierowniczych były rezultatem zmęczenia wysokocyklicznego materiału łopatek, spowodowanego przez oderwania wirów w czasie uruchomienia turbiny, przyspieszone przez korozję wywołaną chłodzeniem mieszkankowym. Uszkodzenia ułatwiła znaczna kruchość materiału łopatek sprężarki. Zostały sformułowane zalecenia, aby uniknąć podobnych uszkodzeń łopatek sprężarki w przyszłości.*

**Słowa kluczowe:** chłodzenie mieszkankowe, uszkodzenia łopatek sprężarki, zmęczenie wysokocykliczne, oderwanie wirujące, naprężenia spowodowane drganiami, korozja.

#### 1. Introduction

Inlet cooling systems are a popular choice worldwide to add power to gas turbines, especially during peak demand periods in summer time when high ambient temperatures reduce output [5]. Increased power output is achieved by injecting a water-droplet 'fog' into the turbine air inlet. Evaporation of water droplets within the inlet stream causes the air to be cooled, increasing mass flow through the turbine and turbine power output by up to ten per cent, depending on environmental conditions. As a rule of thumb, one per cent of injected water (relative to the intake airflow) boosts turbine power by 5-7 per cent [2, 5-6]. However, the main pre-requisite for proper fogging system performance is that the water droplets must be small enough to evaporate in their path through a compressor [5]. If the water droplets are larger than required, evaporation occurs within the compressor outlet, rather than at the early compressor stages. This reduces inter-cooling process efficiency and therefore the degree of power augmentation obtained

[6]. The presence of large particles can also increase the risk of compressor blade erosion and corrosion [1]. Fogging presents additional technological challenges such as the proper adjustment and modification of gas turbine air-cooling, combustion, control and protection systems [2]. Caution must also be taken to maintain compressor stability and blade mechanical integrity. Of prime importance are droplet size and water droplet distribution and concentration within the fog, as this defines how rapidly the droplets evaporate in the compressor system [2]. Inlet fogging is very common for combustion turbines in all cycle configurations. For all classes of turbines there are two types, one which applies just enough fog to evaporate all the water prior to any moisture coming in contact with rotating turbine parts and another that actually allows the first several stages of compression to run wetted. For complete evaporation from typical high pressure fog nozzles, a residence time of around 3s is required [1, 4]. No fog nozzle produces homogeneous droplet size, but rather droplets are produced over a range of

sizes. Larger droplets are unlikely to evaporate in time and will impinge on IGV's and compressor blades, causing erosion and corrosion [2]. A significant amount of water will also impinge on duct surfaces, silencers etc, requiring an extremely effective drain system and a lined duct since demineralized water is quite aggressive. If the drain system is ineffective and/or fails, a slug of water could be ingested into the compressor causing catastrophic failure [2]. In some cases water injection into the compressor (overspray) will cause mismatching of successive stages as flow coefficients will increase and design temperature rises will not be met. This will cause points on the compressor map to move towards the surge line and increase stage loading, possibly pushing the later stages nearer to stall [2]. Excessive water injection, along with off-design operating conditions, non-standard fuels, combustion dilution and compressor blade degradation can lead to aerodynamic instabilities and subsequent high-cycle fatigue failures [1, 4]. This paper provides an overview of the compressor stationary vane (diaphragm) failure investigation, which led to an identification of the HCF failure mechanism generated by rotating stall during unit start-ups, highly accelerated by corrosion generated due to the fogging system.

2. Compressor blades failure analysis

2.1. Background

The gas turbine under evaluation is a 69-MW Combined Cycle (C.C.) unit operated at 3600 rpm, which consists of 19 compressor stages and 4 gas turbine stages and had accumulated approximately 200,000 operation hours [3]. During the last main overhaul in 2005, all compressor moving and stationary blades were replaced. In 2006, the unit was equipped with a fogging system at the compressor air inlet duct to increment unit power output during high ambient temperature days (hot days) as is shown in fig. 1

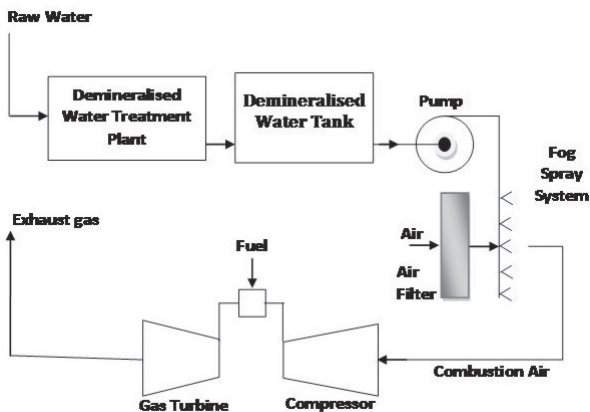


Fig. 1. Outline of the fog inlet air cooling system

Fog water nozzles were installed upstream of the compressor inlet air filter without any water filter/catcher before the water spray nozzles. Since the last overhaul up to the date of the first failure event in December 2008, the unit had accumulated 27,000 operation hours and 97 start-ups in total, and 740 hours operation and 4 start-ups with a fogging system [3]. Three failure events of the unit occurred at small periods. The first failure occurred in December 2008, a second event in March 2009 and

a third event in May 2009. The compressor damage distribution during the three failure events is shown in fig. 2.

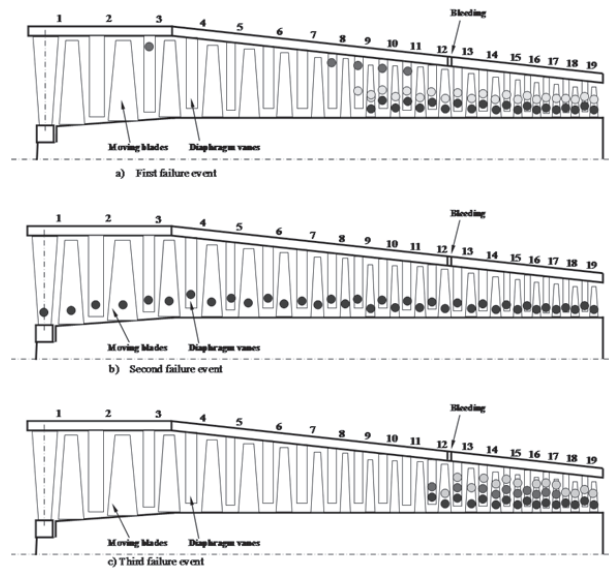


Fig. 2. Compressor damage distribution during the three failure events

- Legend: 1-19 – Compressor stages  
 ● - FOD of moving blades and vanes  
 ○ - Rubbing of moving blades and vanes  
 ⊙ - Fracture of moving blades and vanes

During the first failure event in December 2008, there was FOD and rubbing of compressor moving blades (see fig. 3) and FOD, rubbing, bending and fracture of compressor stationary vanes (diaphragms) as shown in fig. 4. There were also vane fractures at the vane union diaphragm shrouds, stages 8 to 10 as shown in fig. 5.



Fig. 3. Compressor moving blade damage



Fig. 4. Compressor stationary vane (diaphragms) damage stage 11

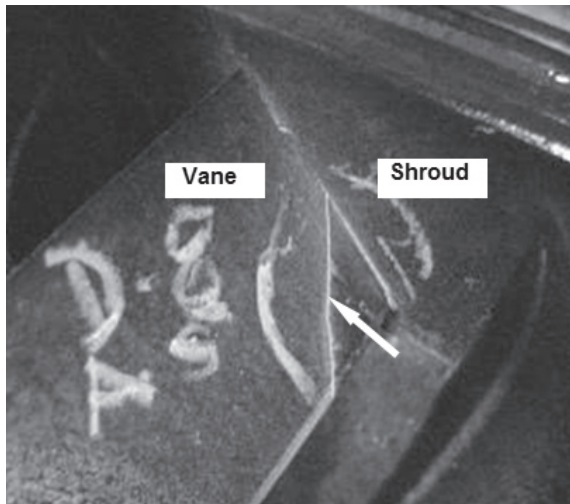


Fig. 5. Vane fractures at the union of vanes with diaphragm shrouds stages 8 to 10.

During the second failure event in March 2009, there occurred FOD of compressor moving blades and stationary vanes (diaphragms) stages 1 to 19 as shown in figs. 6 and 7. The failure was attributed to the fogging system water spray nozzle, which broke and was separated from the nozzle support structure and then introduced in the compressor flow path channel at high velocity causing FOD in the compressor. During the third failure event in May 2009, there occurred FOD of compressor moving blades and stationary vanes (diaphragms) stages 12 to 19 as shown in figs. 8 and 9.

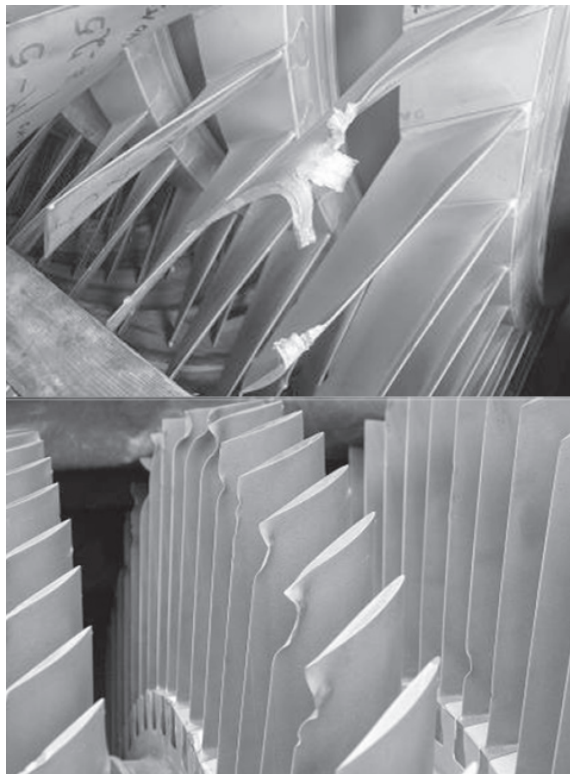


Fig. 6. FOD damage of compressor moving blades

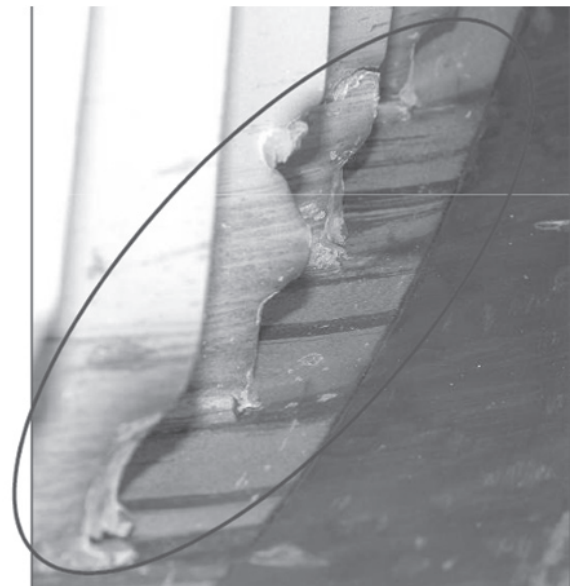


Fig. 7. FOD damage of compressor vanes (diaphragms)

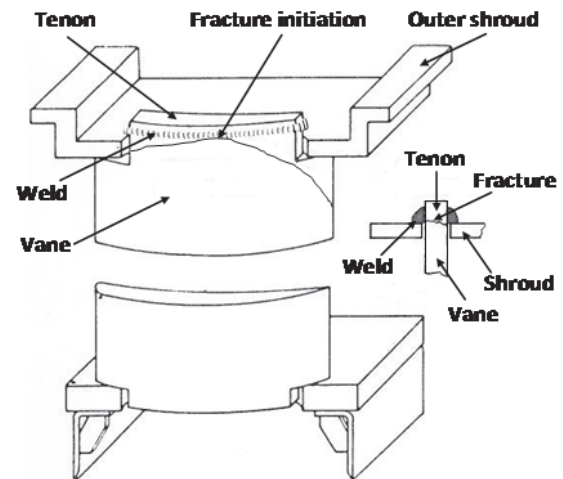


Fig. 8. General view of compressor damage in the bleeding zone between stages 12 y 13

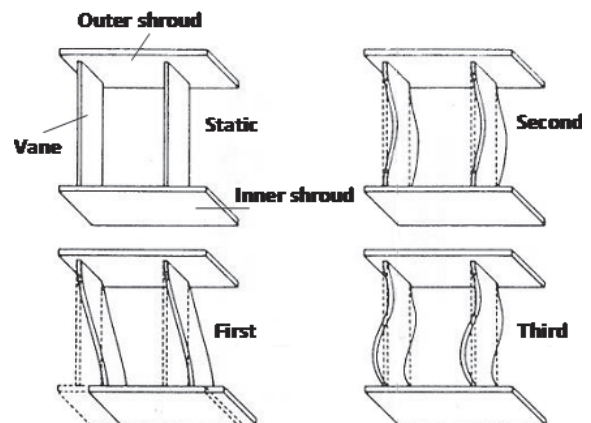


Fig. 9. Damage of stationary vanes of stage 13

Many blades/vanes were heavily impacted and deformed; some moving blades and stationary vanes were fractured. An apparently fatigued type fracture surface was found in the union of vane tenons with diaphragm outer shrouds, stage 13, as shown in fig. 10. It can be seen from fig. 10 that fracture was initiated at the vane tenon weld heat affected zone and the presence of fatigue beach marks can be observed. Also, there were corrosion deposits on the compressor vanes and casing as shown in fig. 9. Among the three compressor failure events presented, the third one is the root cause analysis in this paper.



Fig. 10. Fracture surface of compressor diaphragm vane tenons, stage 13 with appearance of HCF

**2.2. Analysis of the compressor vane cracking mechanism**

Vane cracks were developed in the vane tenons at the outer shroud of the diaphragm (fig. 11). As mentioned before, these cracks were of the high cycle fatigue type (fig. 10) and initiated in the heat affected zone adjacent to the tenon weld. They were caused by vibratory stresses which occurred during start-up acceleration as a result of diaphragm resonance in one of its first three natural frequencies [7] with local air flow disruptions associated with the presence of rotating stall cells, as explained before, and upstream rotating blade wakes. The first three diaphragms vibratory mode shapes corresponding to mentioned previously diaphragms natural frequencies are shown in fig. 12 [7]. The manufacturer reported that the stress concentration factor due to the weld heat affected zone of diaphragm tenons is 3.5 approximately [7]. Due to this fact and the presence of corrosion pits on the vane/tenon, local stresses rise significantly in this zone, leading to fatigue failure initiation and propagation.

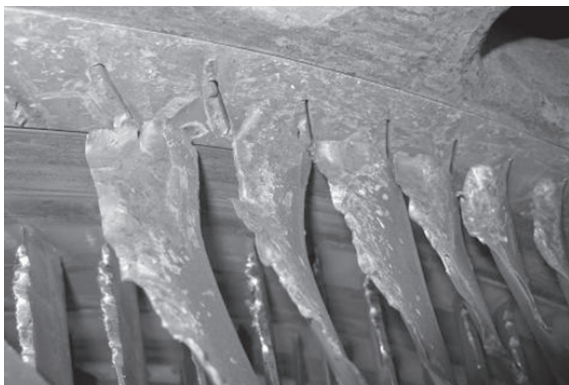


Fig. 11. Fracture localization at compressor vanes of diaphragms

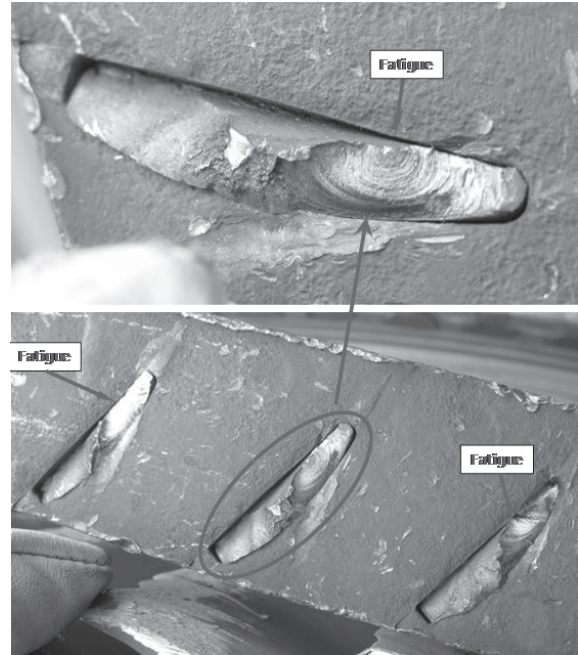


Fig. 12. Diaphragm first three vibratory mode shapes

**2.3. Analysis of compressor “Rotating Stall”**

The rotating stall phenomenon is generic to all axial flow compressors and can be explained as follows. The throat area and vane and blade angles at each compressor stage are designed to operate with maximum efficiency at full speed. In the low speed range, the air is not sufficiently compressed in the front stages to allow it to flow readily through the smaller throat areas in the rear stages. This choking in the rear stages reduces incoming air flow and, hence, velocity. This reduction in velocity in turn causes an increase in the incidence angle of air impinging on blades in the front stages. When this incidence angle exceeds a given amount, the blade in question stalls; i.e., the air flow separates from the suction side of the blade causing turbulence and low velocity flow (fig. 13).

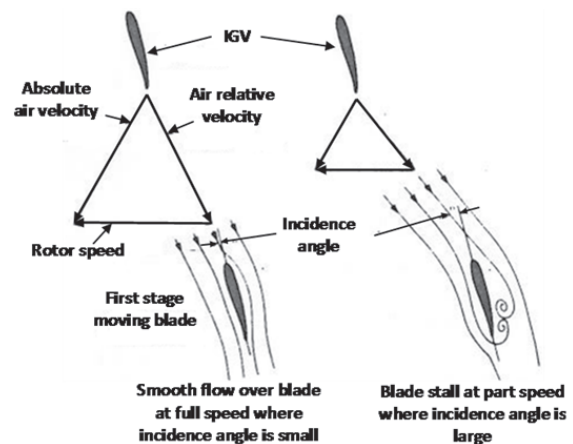


Fig. 13. Stall diagram in compressor blades when the incidence angle exceeds a boundary angle

This stalling does not occur simultaneously over all the blades in the stage but instead occurs as one or more pockets, called stall cells, distributed around the stage circumference (fig. 14). By a somewhat involved mechanism these cells rotate, hence, the term “rotating stall”. The speed range over which rotating stall can occur in the analyzed unit identified by the O.E.M. referring to the same frame is between 1500 rpm and 2600 rpm [7]. The manufacturer reported some similar cases of diaphragm failures in other units of the same frame caused by rotating stall [7].

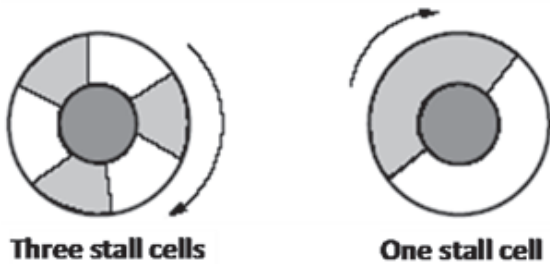


Fig. 14. Typical stall cell patterns.

There may be one to four cells present, with the number of cells decreasing with increasing speed, and they rotate at 50 % to 65 % of rotor speed [7]. Each time a stall cell passes over a rotating blade or stationary vane, the aerodynamic load on that component is sharply reduced as a result of low velocity flow in the cell. Hence, the effect of rotating stall cells is to induce vibratory stresses on vanes and blades. These stresses reach their maximum when the rotating stall excitation frequency or one of its harmonics is coincident with the blade natural frequency. The stall excitation frequency is relatively low even when compared to the blade first mode resonance frequency; thus only the higher harmonics will cause resonance and only to the first blade mode. However, due to the number of cells which can occur and their irregular shape and spacing, many harmonics of the fundamental stall excitation frequency can be present. Although rotating stall during start-up cannot be eliminated, its effects are minimized by modulating the inlet guide vanes (IGV) and increasing inter-stage bleeding. Normally the vibratory stresses generated at blades/vanes are low, but the presence of corrosion pits on blade/vane surfaces can dramatically reduce material fatigue strength, causing small surface cracks which propagate due to stress concentration at the crack front. Since rotating stall only exists in the low speed range, cracking is related to the number of startups rather than operating hours at full speed.

**2.4. Metallurgical investigation**

A metallurgical investigation of the failed vanes was carried out, including metallography, SEM (scanning electronic microscopy), fractography and chemical analysis. The vane airfoil zone microstructure is shown in fig. 15. The microstructure consists of tempered homogenous martensite typical for forged stainless steel according to specification AISI 410. Chemical composition and hardness tests of the failed vanes confirmed concordance of the blade material used to the design specification. The average blade material hardness was 24 HRC, which falls within design limits. Also, a hardness test was performed on the fracture surface of vane/tenon stage 13. The hardness

falls within the range 40–56 HRC. This value is very high (brittle material) and means that, after vane-to-shroud welding, no stress relieving process of the diaphragms was executed. Fractography evaluation was achieved on the exposed vane/tenon crack surface using scanning electronic microscopy (SEM) to determine the origin of the fracture. Fig. 16 shows a general view of the vane/tenon fracture surface. Two different zones were found: a dark zone with appearance of sudden fracture and a shiny zone with beach marks typical of a HCF failure mechanism.

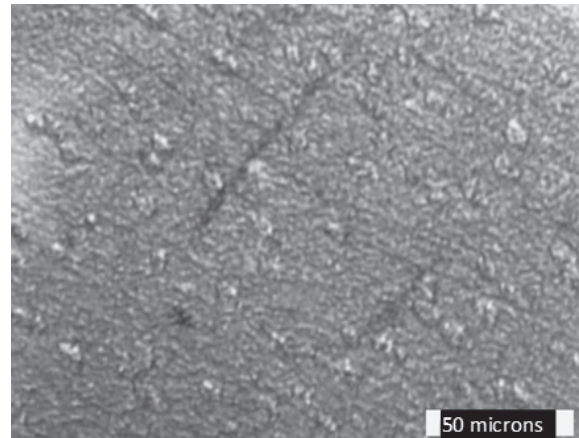


Fig. 15. Microstructure of AISI 410 alloy obtained by SEM

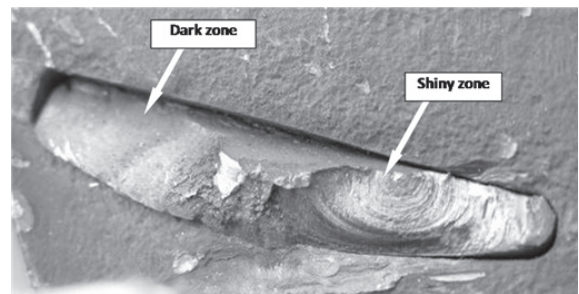


Fig. 16. General view of the vane/tenon fracture surface, stage 13

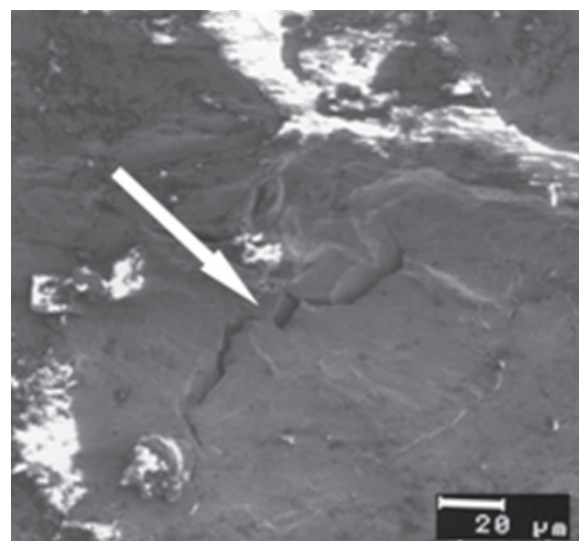


Fig. 17. Detail of the vane/tenon fracture initiation zone, stage 13

Fig. 17 shows a detail of the fracture initiation zone of the vane/tenon stage 13. It can be appreciated that fracture initiation was trans-granular which is typical for an HCF mechanism and the presence of micro cracks on the fracture surface close to the fracture initiation zone. Blade fracture initiated in corrosion pits (Fig. 18 b). The presence of beach marks on the fracture surface is noticeable (fig. 18a) as well as a high quantity and density of corrosion pits, which indicates severe corrosion attack (fig. 18b). Twelve (12) beach marks were counted on the fracture surface, and no visible striation lines were detected. The shiny appearance of this fracture surface zone suggests that it is a recent fracture. Fig. 19 shows an Energy Dispersion Spectrum (EDS) of deposits found on the vane fracture surface in two zones: the dark zone and the shiny zone shown in fig. 16. It may be concluded from fig. 19, that the dark zone/surface has more oxygen concentration than the shiny one has, which means it was exposed more time to a corrosive ambient than the latter. Deposits of Na, Al, S and Zn were also found on the fracture surface, among which Na and S are principal corrosive agents in reaction with water.

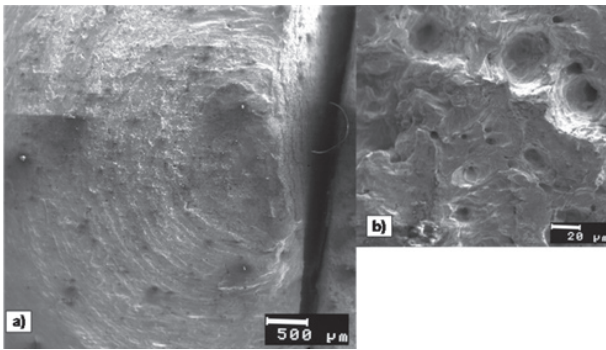


Fig. 18. Details of the fracture surface shiny zone from figure 16. Beach marks a) and corrosion pits b) on the fracture surface of vane/tenon stage 13

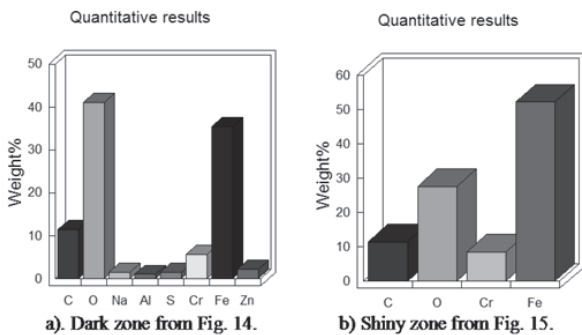


Fig. 19. Deposits found on the vane/tenon fracture surface, diaphragm stage 13: a) Dark zone from fig. 16, b) Shiny zone from figure 16

### 2.5. Compressor vane failure analysis

Analyzing details of the features recorded in compressor vanes/diaphragms (stage 13) and the failure mechanism presented above, it may be concluded that failure origin/initiation and propagation can be attributed to high cycle fatigue (HCF) generated by the rotating stall phenomenon during unit start-ups with very important corrosion contribution. Metallurgical investigation

results revealed that fracture initiation points were localized in corrosion pits that raise local stresses compared to the original unaltered surface. Corrosion products (deposits) were also found in the same zone. The fog water nozzles had been installed upstream of the compressor inlet air filter without any water filter/catcher before the water spray nozzles. Because of this, many compressor stages operated with humid air which, in contact with corrosive agents, developed a corrosion process. These findings lead to the conclusion that blade high cycle fatigue failure initiation and propagation were highly influenced by corrosion processes. From fig. 20 it can be appreciated that the existence of assembly clearances between the vane and outer diaphragm shroud is an open way for corrosive agents to deposit on the vane/tenon heat affected zone (weakest zone), causing corrosion pits that lead to accelerated fatigue initiation of the vane/tenon.

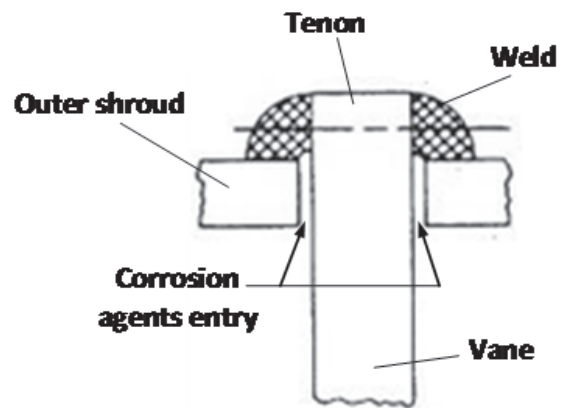


Fig. 20. Scheme of the union of diaphragm vanes with the outer shroud

Severe FOD impacts on the vanes close to the diaphragm outer shroud during the first failure event (December 2008) could generate sudden partial fractures of the vanes/tenons due to their high hardness and related brittleness, as appears in the dark zone in fig. 16. Diaphragm stages 13 and 14 in which vanes/tenons fatigue fractures occurred during the third failure event (fig. 10, May 2009) operated continuously since the overhaul in 2005 and were present during all unit failure events. These vanes were probably fractured partially during the first failure event by FOD and not detected by non destructive examination. As can be seen in fig. 11, if tenon fracture is localized within the diaphragm outer shroud width (not propagated to the vane airfoil), this fracture is covered by the weld and outer diaphragm shroud, making it impossible to detect by the magnetic particle examination commonly used for diaphragm non-destructive testing. It supports the conclusion mentioned above that tenon partial fractures (dark zone in fig. 16) were developed during the first failure event. This conclusion is supported also by the chemical analysis of the vane/tenon fracture surface presented in fig. 19, which indicates that the fracture dark zone (fig. 16, sudden fracture) is more oxidized than the shiny zone (fatigue fracture), meaning that sudden fracture was developed some time before fatigue fracture. A pre-existence of initial sudden fractures at the vanes/tenons before the unit third failure event is also supported by the fact that vane fatigue failure soon developed during the third failure event after only two unit start-up attempts. Diaphragm vanes are joined to the shrouds by one

weld in the case of stages 12 to 19 (fig. 21a) and by two welds in the case of stages 1 to 11 (fig. 21b). It may be seen from fig. 21 that the joint with two welds (fig. 21b) provides a better distribution of flexural moments ( $M$ ) because each weld is loaded by half of the moment ( $M/2$ ). In the case of joints with only one weld (fig. 21a) the load is twice as high, and the probable failure of this joint is much greater. During the first and third failure events, vane fatigue fracture is related to rotating stall initiated at vanes of the front stages, before air bleeding, see fig. 2a) and fig. 2c) which is consistent with the rotating stall mechanism described in previous sections. Fatigue fracture of the rear stage vanes, after air bleeding during the third failure event (fig. 2c) is related to upstream rotating blade wakes associated with rotating stall. Also, the weaker vane-to-shroud weld joint design of the rear stages (fig. 21a) accelerated the fatigue fracture of these vanes. Other possible causes of vane failure were verified including IGV angles and IGV schedule control logic, excessive water injection by fogging (water overspray), possible off-design operating conditions and compressor blades/vanes degradation, but no related irregularities were found.

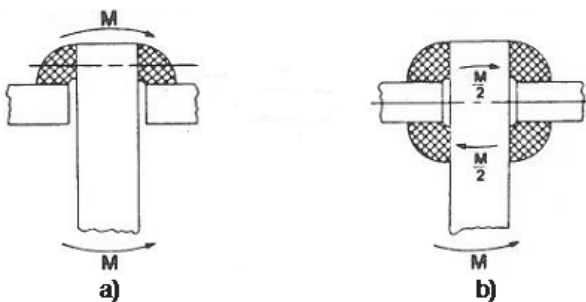


Fig. 21. Design of the diaphragm vane-to-shroud weld joint: a) Stages 12-19; b) Stages 1-11.

#### 4. References

1. Bhargava R. K., Meher-Homji C. B., Chaker M. A., Bianchi M., Melino F., Peretto A., Ingistov S. Gas turbine Fogging Technology: A state-of-the-art review, Part III: Practical considerations and operational experience. *Journal of Engineering of Gas Turbines and Power*, 2007; 129: 461-472.
2. Fogging state of the art, 2009, [www.meeefog.com](http://www.meeefog.com).
3. Mazur Z., Hernandez-Rossette A., Porcayo-Calderón J., Mariño-López C. 2009 Diagnóstico de la causa raíz de la falla de la U2 de la central de Ciclo Combinado Tula (In Spanish), Report IIE/43/I/2827/002/2009, Instituto de Investigaciones Electricas, Cuernavaca, 2009.
4. Mercer M. Hot Times For Turbine Cooling”, *Diesel & Gas Turbine Worldwide*, 2002; 62: 5-13.
5. Savic S., Kippax P. Fogging dynamics solved. (*Advanced Gas Turbines*). *Power Engineering International*, 2003; 11: 264-272.
6. Savic S., Mitsis G., Härtel C., Khaidarov S., Pfeiffer P. (2002) Spray Interaction and Droplet Coalescence In Turbulent Air-Flow, an Experimental Study With Application To Gas Turbine High Fogging, *Proceedings of Institute for Liquid Atomisation and Spray Systems-Europe*, Zaragoza, Spain, 2002; 221-226.
7. Westinghouse: *Proceedings of Gas Turbine User Association Conference*, Pittsburgh, USA, 1978; 68-76.

It may be concluded that compressor diaphragm failure origin/initiation and propagation can be attributed to high cycle fatigue (HCF) generated by a rotating stall phenomenon during unit start-ups. Vanes/tenon HCF during the third failure event was very high, accelerated by the pre-existence of sudden vane fractures and corrosion pits caused by the humid ambient generated by the fogging system. Also, vane fatigue failure was accelerated by the high brittleness of vane tenons (heat affected zone) generated by the welding process without any stress relieving process. The stress concentration factor for the weld heat affected zone in the analyzed case was 3.5 [7].

#### 3. Conclusions

Based on an analysis of the results from compressor vane metallographic examination, unit operational parameters, rotating stall phenomenon, fogging system, compressor vane cracking mechanism, and chemical analysis of deposits, it may be concluded that compressor diaphragm failure initiation and propagation was driven by a high cycle fatigue mechanism accelerated to a high degree by corrosion processes in the vane tenon heat affected zone. The rotating stall phenomenon is generic to all axial flow compressors during startup and was identified by the O.E.M. referring to the same frame. The vibratory stresses generated at blades/vanes are low, but the presence of corrosion pits on the blade/vane surface dramatically reduced material fatigue strength, causing small surface cracks which propagated due to stress concentration at the crack front. Conditions for the corrosion process were generated by fogging (humid air), assembly union geometry between vanes and diaphragm outer shrouds and the presence of corrosive agents in the compressor flow. Vane fatigue failure was accelerated by the high brittleness of vane tenons (heat affected zone) generated by the welding process without any stress relieving process and weak design of vane-to-shroud weld joints in some stages.

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