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# **A comparative study of the fatigue resistance of aluminide coatings on P91 steel substrate under cyclic impact loading**

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*ABSTRACT: Aluminide coatings have been used for the protection of gas turbine blades in power plants during the last years due to their very good resistance against steam corrosion. However, very limited information exists on their mechanical properties and especially on their fatigue resistance. In this paper we present the experimental results of the impact testing examination of the above coatings. This experimental method is capable to assess the fatigue and the impact wear resistance of coatings working under cyclic impact loading conditions. From the experimental results it was concluded that the HVOF Al, Ni coatings deposited on P91 steel substrate show a higher fatigue strength under cyclic loading compared to Slurry Al, Fe, Cr, Si coatings deposited on the same substrate.*

*KEY WORDS: aluminide coatings, impact testing, fatigue resistance.*

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## **1. Introduction**

The modern power generation steam turbines are being designed to have higher efficiencies and to meet the stringent environmental regulations, ensuring plant reliability, availability and maintainability, without increased costs. High efficiencies can be achieved by increasing the operating temperature of the whole process. At temperatures above 550°C coatings are implemented to protect turbine materials against corrosion, oxidation and degradation due to fatigue wear.

Aluminide coatings, especially those with Fe, Cr or Ni, do meet the above requirements of the power plant industry. These coatings are being explored already for use in the power plants steam turbines that operate at superficial temperatures, but they have not been applied in production still.

In this paper we assess the wear fatigue resistance of aluminide coatings working under cyclic loading conditions by means of the impact testing method. The impact testing method already has been introduced as a convenient experimental technique to evaluate the fatigue strength of coatings being exposed in successive impact loads during the last years (Voevodin *et. al.* 1995), (Bantle *et. al.* 1995), (Heinke *et. al.* 1995), (Ziegele *et. al.* 1997). According to this method the coated specimen is cyclically loading by a cemented carbide ball that repetitively impacts on the specimen surface at a frequency of 50 Hz. The superficially developed Hertzian pressure induces a complex stress field within the coating, as well as, in the interfacial zone between the coating layer and the substrate. Both these stress states are responsible for distinct failure modes, such as cohesive and/or adhesive one. The exposure of the layered compound against impulsive stresses creates the real conditions for the appearance of coating fatigue phenomena based upon structural transformation, cracking generation and cracking growth, which are responsible for the gradual microchipping and the coating degradation.

## 2. Experimental procedure

The examined coatings were characterized regarding their fatigue strength using the impact testing system that is shown in Figure 1. The system comprises three units:

- The main testing device (depicted in the center of the photo)
- The power supply unit (left side of the photo)
- The evaluation and controlling unit (right side of the photo)

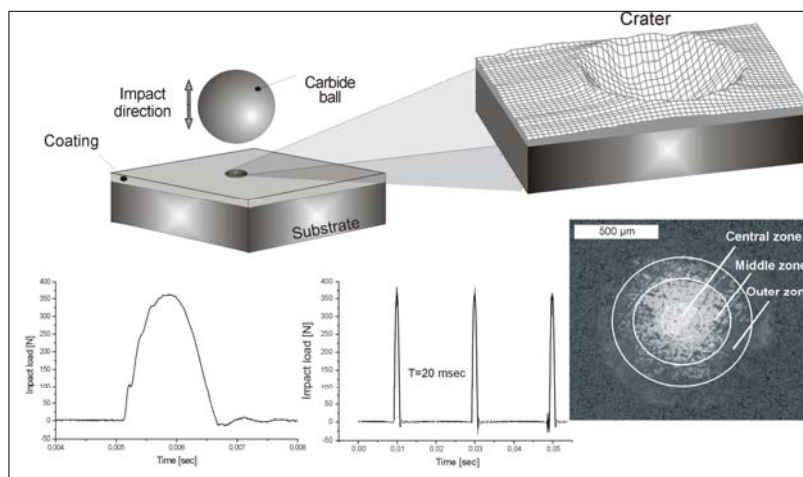
The working principle of the impact testing is represented in Figure 2 and it is based on the alternate Laplace magnetic forces that are produced by an electromagnetic field, which is induced by a coil located in the mechanical unit. In order to enhance the impact testing efficiency the mechanical unit with the coil were analyzed by finite elements method to achieve the optimum magnetic flux density resulting in higher electromagnetic force and correspondingly in an increased impact load. The stress strain state related to the impact test is attributed to the Hertzian contact, which is developed between the spherical indenter (cemented carbide ball) and the examined layered space resulting in an impact crater. Gradual intrinsic coherence release and coating microchipping or abrupt coating adhesive fracture and consequent exposure of the substrate material designate the coating failure. These two kinds of coating failure usually appear in three distinct zones inside and outside of the impact crater. A central zone in the mid of the impact cavity, where the

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coating is strained with compressive stresses and a gradual cohesive degradation takes always place. The intermediate zone inside the piled up rim formed around the impact cavity, where tensile and shear stresses are building up and both cohesive and adhesive delamination arises. Finally, the peripheral zone of the impact cavity, where macrocracks might propagate and adhesive coating failure occurs, depending on the brittleness of the coating. Both the coating failure initiation and the failure extent were assessed by SEM observations and EDX analysis. The impact load, at which the coating does not fail, after  $10^6$  impacts, is assigned as coating fatigue endurance limit.



**Figure 1.** *Impact testing system*



**Figure 2.** *Impact testing working principle*

The impact loads that are leading to coating fatigue fracture are recorded in coating life diagrams (coating fatigue curves). For each impact test at a distinct impact load and a concrete number of impacts a mark on the diagram is resulted. This represents the impact load versus the number of impacts taking into account the criterion of coating failure appearance as it is discussed above. In this way a coating fatigue curve was resulted for all examined coatings, as it is illustrating in figure 3.

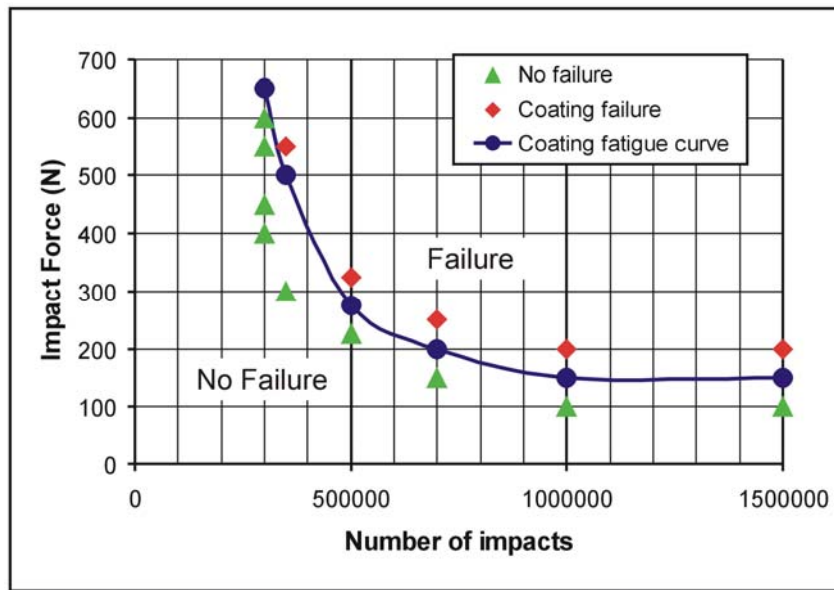
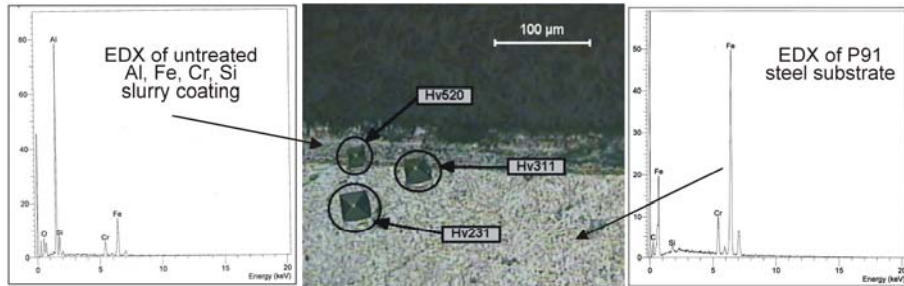


Figure 3. Typical coating fatigue strength curve determined by impact testing

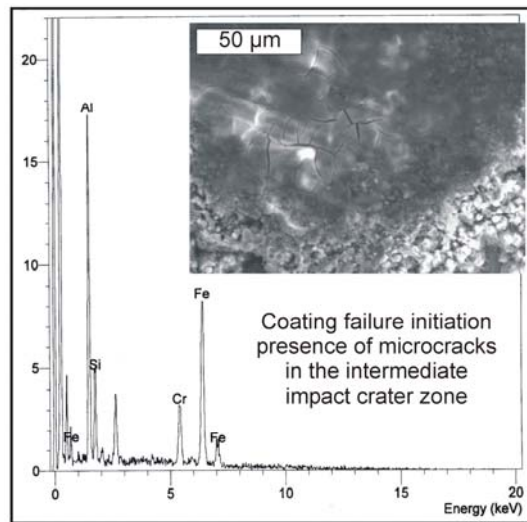
### 3. Results and discussion

In Figure 4 the typical morphology of the aluminide Al, Fe, Cr, Si coatings deposited on P91 steel substrate is shown. The above coatings that are used for the purposes of the current investigation have been produced by slurry deposition method. This kind of coatings is characterized for their dense structure in comparison to the aluminide coatings produced by HVOF method [6]. In the same figure the Vickers microhardness measurements of the coating; the interfacial zone and the substrate are also presented. The coating has an average thickness of 35  $\mu\text{m}$  and microhardness values about 500-600HV. According to the EDX analysis of the untreated coating before the impact testing process the identified elements of the coating are the expected ones (Al, Fe, Cr, Si). From the EDX analysis of the P91 steel substrate we can see that the main substrate elements are Fe at higher consistency than in the coating and Cr.



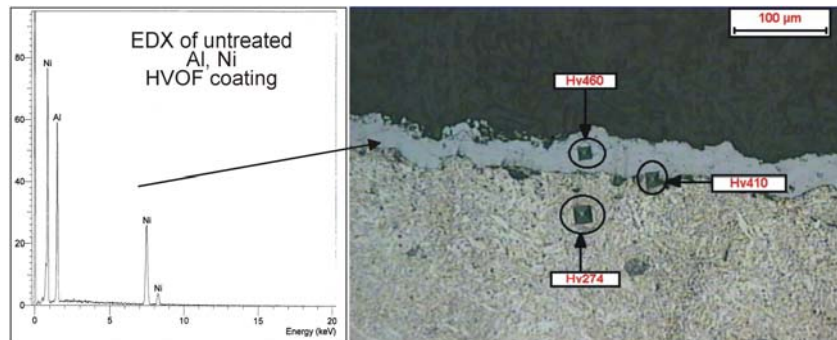
**Figure 4.** Microhardness and EDX analysis of Al, Fe, Cr, Si coating deposited on P91 steel substrate

From the impact testing examination of the Slurry Al, Fe, Cr, Si coatings it was found out that the endurance limit regarding their fatigue strength amounts to 100 N approximately. The main failure of the examined coating-substrate compound occurred in the intermediate zone e.g. in the inside vicinity of the impact crater periphery. The high tensile stresses of the layered space in this region due to plastic deformation of the substrate and the relatively brittle behaviour of this coating caused the development of a large number of coating microcracks (Fig.5) indicating its failure.



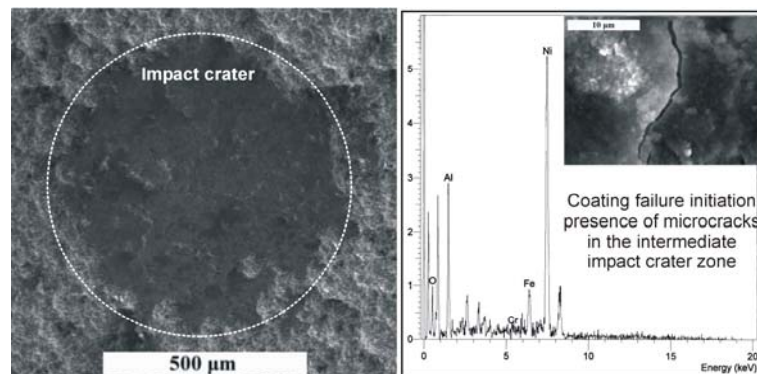
**Figure 5.** SEM photo and EDX analysis of Al, Fe, Cr, Si coating deposited on P91 steel substrate after  $10^6$  impacts by an impact force of 100 N. Coating fatigue failure initiation due to the presence of microcracks

In Figure 6 the typical morphology of the Al, Ni coatings produced by HVOF method on P91 steel substrate is shown. These coatings had an average thickness of 40  $\mu\text{m}$  and Vickers microhardness of 450-500HV.

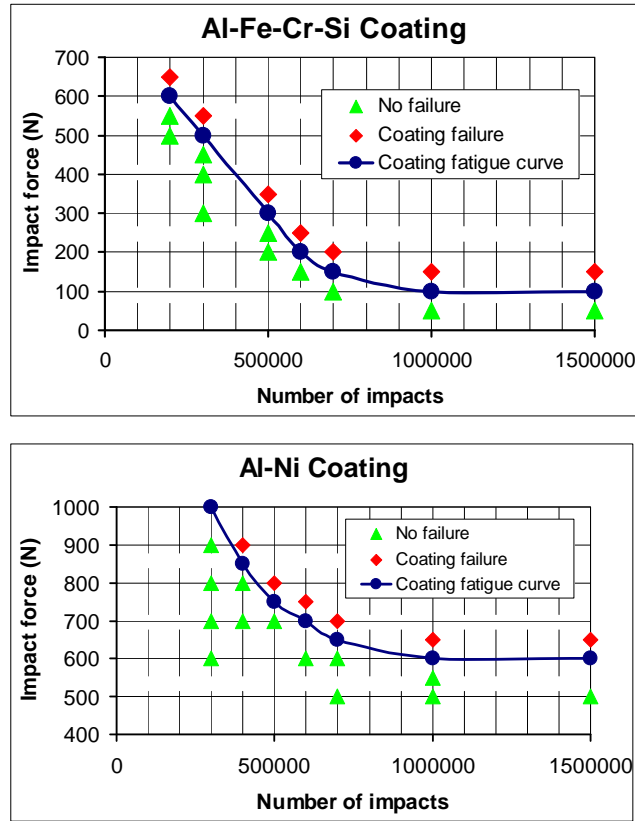


**Figure 6.** Microhardness and EDX analysis of Al, Ni coating deposited on P91 steel

From the impact testing examination of the HVOF Al, Ni coating it was ascertained that its fatigue endurance limit amounts to 600 N. This coating proved to be ductile enough to accommodate the stresses induced by the ball indenter and to follow the flexure and deformation of the substrate [5]. Due to this fact only at very high impact forces namely above 600 N, localized microcracks could arise on the coating surface indicating its failure initiation (Fig.7). Mainly the coating was gradually degraded and did not removed.



**Figure 7.** SEM photo and EDX analysis of the Al, Ni coating deposited on P91 steel substrate after  $10^6$  impacts by an impact force of 600 N. Failure initiation – microcracks



**Figure 8.** The *fatigue strength curves of the examined aluminide coatings determined by impact testing*

In Figure 8 the experimental resulted fatigue strength curves for the examined aluminide coatings is opposing inserted. Apparently, the HVOF Al-Ni coatings revealed considerably higher fatigue strength against cyclic impact in comparison to the relevant one produced by Slurry deposition method.

#### 4. Conclusions

The current research work presents a step forward in understanding the failure mechanisms of aluminide coatings and provides a feedback approach for the design optimization of surface engineered components that serve under impact wear operating conditions. More specifically the paper reports the results of a novel experimental approach adopted to investigate the fatigue strength of coating systems working under cyclic loading conditions with refer to their mechanical properties

and to deliver a semi-empirical design approach. The current impact testing investigation revealed the very good fatigue strength of HVOF nickel-aluminide coatings due to their excellent ductility in comparison to Fe-Cr-Si-aluminide coatings produced by Slurry method.

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