SOLID PARTICLE EROSION IN SUPERALLOY INCONEL 600

Rogério Lago Mazur
Universidade Estadual Paulista - UNESP, Faculdade de Engenharia de Guaratinguetá, Departamento de Materiais e Tecnologia, Av. Dr. Ariberto Pereira da Cunha, 333 - CEP 12516-410 – Guaratinguetá, SP, Brasil.
e-mail: rogermaz@uol.com.br

Sérgio João Crnkovic
Universidade Estadual Paulista - UNESP, Faculdade de Engenharia de Guaratinguetá, Departamento de Materiais e Tecnologia, Av. Dr. Ariberto Pereira da Cunha, 333 - CEP 12516-410 – Guaratinguetá, SP, Brasil.
e-mail: crnkovic@feg.unesp.br

Abstract. *The Ni-base superalloys are applied in several and complexest engineering systems, however there are few data about the erosive behaviour of these superalloys regarding the impact of solid particles in a gaseous flow. The solid particle erosion is a complex phenomenon and it is characterized by the deformation and material removal during the impact of the particles generating high temperatures. The Ni-base superalloy 'Inconel 600', have excellent mechanical properties in high temperatures, by this reason, their characteristics in erosion at room temperature, will be measured and analyzed, in view of the losses of the mechanical properties of the steels in higher temperatures during the particles impact. The erosion tests have been performed in air-sand jet impingement device, where the erosive particles were introduced in a system with high pressure and accelerated along a nozzle before impact the surface of the material, simulating the main parameters of the erosion wear. The results showed small differences for all tested impact angles (15º, 30º, 60º e 90º), however the reliable intervals have been superimposed for almost all of them, in spite of the great differences among the mechanical properties of the superalloy 'Inconel 600' and steel PS 67.*

Keywords: *Wear, Erosion, Superalloy*

1. Introduction

As observed by Sundararajan (1995), the solid particle erosion is an important material degradation mechanism encountered in a number of engineering systems, such as thermal power plants, aircraft gas turbine, pneumatic bulk transport systems, coal liquefaction/gasification plants and ore or coal slurry pipe lines. As defined by Blau (1985), the erosion happens when a material surface is submitted to mechanical interactions with a fluid with one or more components, or for the successive impact of solid or liquid particles,

Initial studies on solid particle erosion in gaseous flow with Finnie (1960, 1995) and Kosel (1995), indicate a complex phenomenon and their main mechanisms are not still well understood. Erosion can be broadly separated into three types: impingement variables describing the particle flow, particle variable and material variable. The relative parameters of the impingement variables are: incidence angle (α), speed (ν) and flow (concentration of particles). The incidence angle is defined as the angle between the particles flow and the surface of the material. The relative parameters of the erosive particle are: shape, size, hardness and friableness and, in relation to the material the main mechanical properties as well as microstructure are included.

As observed by Finnie (1960, 1995) and Kosel (1995), materials are broadly classified as ductile or brittle, based on the dependence of their erosion rate on (α). Ductile materials, such as pure metals, have a maximum erosion rate, at low angles of incident (typically 15° to 30°), with its subsequent decrease until the angle of impact of 90°; while for brittle materials, such as ceramics, the maximum is at or near 90º. This behavior is related with the hardness, where ductile materials exhibit a larger erosion rate in low impact angles and a smaller erosion rate in high impact angles.

Analyzing the literature, we found a series of mechanisms that were proposed to explain the erosion in ductile materials, such as the cut mechanism and the one of the material plastic deformation. Finnie (1960), suggested for metals, a mechanism similar to the process of the cut of materials, where the impact of a hard angular particle acts as if it was a cut tool in contact with the surface of a material. This theory found good acceptance for low impact angles. However, for high angles there wasn't the same acceptance. Bitter (1963) trying to explain the cut mechanism better, decomposed the particle flow in two components, a horizontal one and a vertical one, and considered the simultaneous occurrence of two mechanisms which was denominated erosion for cut, that it prevails for low impact angles and erosion for deformation, that prevails for larger impact angles. Levy (1986) analyzing through MEV the surface of aluminum (AL 1100-THE), eroded for the impact of a single particle, observed extensive accumulated material at the end of some craters. This mechanism of erosion has been termed the "platelet" mechanism; this observation was also found by Hutchings and Levy (1989).

Studying the characteristics of several materials, Sundararajan (1995) found some contradictory relationships. In the system nickel Ni, Ni-Cr, Ma754 and 17-4PH SS system, the material with the highest 'n' (n= work hardening) value exhibit the best erosion resistance. In the stainless steel and copper systems, the material with the highest 'n' value does not exhibit the best erosion resistance. In the system copper, Cu, Cu-Zn, and Cu-Al (alumina fiber) and in some melted iron, the material with the highest ductility exhibits the best erosion resistance. In the systems hardened by precipitation (Al-Li and 17 PH SS), Ti alloys and stainless steel, the material with low or intermediate ductility exhibits the best erosion resistance. In the pure metals, stainless steel (304, 316 and 410 SS) and in melted iron there is a good correlation between erosion resistance and material strength, that is an increase in erosion resistance with increasing strength. However, in the system CU, CU-Zn, Cu-Al, 17-4 PhSS (low resistance) and Al-Li, Ni, Ni-Cr, Ma754, Ti, (intermediate resistance), exhibited the best erosion resistance.

There is an industrial demand for appropriate materials that efficiently resist to the erosion for solid particle in a gaseous flow and the alloys base-nickel (Inconel 600) are important options due to its combination of high mechanical properties at high temperatures (650°C) and its resistance to the hot corrosion and erosion. The superalloys derive their strength from solid–solution hardeners and precipitation phases. As noted by Donachie (1995), physical, chemical and mechanical properties of Ni-base superalloys are satisfactorily documented; however, there are few data about the erosive behavior.

For the accomplishment of the experiment, the erosion tests have been performed in air-sand jet impingement device, where the erosive particles were introduced in a system with high pressure and accelerated along a nozzle before impact the surface of the material, simulating the main parameters of the erosion wear (ASTM G76-95). This work determine the behavior of the erosion rate of the Ni-base superalloy (Inconel 600), in function of the angles of impact of solid particles flow, as well as, to determine the influence of the mechanical properties in the erosion resistance.

2. Experimental details

The chemical composition in weight and the mechanical properties of the superalloy Inconel 600 is respectively illustrated by tab. 1 and 2. The superalloy Inconel 600, base of the system nickel-chrome, it is annealed and have considerable amounts of nickel, chrome and iron. The steel PS 67 was used with the purpose of serving as reference material.

Table 1 - Chemical Composition in weight of the superalloy Inconel 600 and the steel PS 67.

Chemical Composition in Weight	
Inconel 600	0,02%C – 0,0003%S – 8,7%Fe – 0,21%Si – 15,35%Cr 0,26%Mn – 0,004%Cu – 0,02%Co – 0,26%Al – 0,16%Ti - 74,18%Ni
Steel PS 67	0,43%C – 0,026%S – 96,51%Fe – 0,22%Si – 0,89%Cr 0,92%Mn – 0,14%Ni – 0,020%P – 0,64%Mo

Table 2 - Mechanical properties of the superalloy Inconel 600 and the steel PS67.

Mechanical Properties					
	Yield tensile strength (σ_e) [MPa]	*Ultimate tensile stenght (σ_l) [MPa]*	*Elongation [%]*	*Hardness [Hv]*	*Work hardening [n]*
Inconel 600	418	700	34	273	0,24
Steel PS 67	744	997	8	325	0,1

The erosion tests for solid particle in gaseous flow were accomplished with the following parameters:

- Particle velocity (ν): 50m/s.
- Angle of incidence (α): 15°, 30°, 60° and 90°.
- Flux: 2,8 g/min
- Particle size: 150 to 300 μm.
- Particle shape: angular.
- Distance between the surface and nozzle: 10mm.
- Particle dose: 100g.
- Temperature: ambient.

Figure1 illustrates the schematic drawing of the test device that consists of the following components: feeding of compressed air (a), injector (b), funnel (c), feeder of particles and vibrator (d), nozzle (e) and sample (f). The gaseous flow coming from a compressor (a), it feeds the injector (b), that provokes the suction of the sand that falls in the funnel (c), which is the arrival of the particles feeder (d). The particles mixed to the flow are then accelerated by the high-speed of the air that passes through a nozzle (e) before they impact the sample (f).

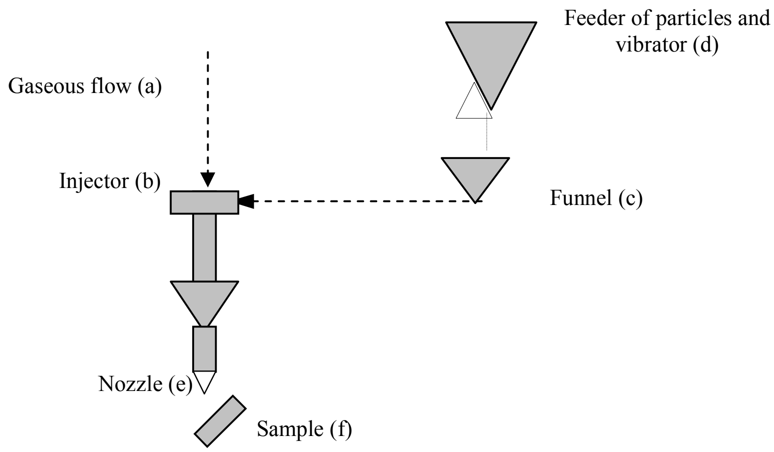

Figure1. Representation of the device of erosion by solid particles in gaseous flow of the type air-sand jet impingement.

The erosion tests following the methodology:

- Cleaning of the samples before the test, with ultrasonic cleaner, to remove dirt.
- Weighting of the erosion sample before the test, determining initial mass.
- Erosion test with the parameters previously established.
- Cleaning of the samples after the test l, with ultrasonic cleaner, to remove dirt.
- Weighting of the erosion sample after the test, determining final mass.

The erodent rate (E) is commonly given in terms of mass or volume of material removed per unit mass of erodent impacted, volume being preferred because it permits thickness loss comparisons between materials of different density.

3. Results and Discussion

Analyzing the medium erosion resistance of the superalloy Inconel 600, in relation to the reference material, the steel PS 67, in Fig. 2, in function of the impact angles of the solid particles flow, in an impact angle of 15º, an inferiority of the medium erosion resistance of the superalloy Inconel 600 was observed. For the impact angle of 30º, 60º and 90º, a superiority of the medium erosion resistance of the superalloy Inconel 600 was observed. From these observed considerations, it is verified that the superalloy Inconel 600 showed a maximum erosion rate in low impact angles (15º to 30º), with a subsequent decrease until the impact angle of 90°, presented a probable behavior of ductile materials. In other words, larger erosion rates for low impact angles and smaller erosion rate for larger impact angles, as observed by several researchers, among them Finnie (1960) and Kosel (1995). However, the results showed small differences for all impact tested, where the reliable intervals of 95% (t-student) have been superimposed for almost all of them, except for the impact angle of 30º.

The great ductility of the superalloy Inconel 600 (A=25%) in relation to the reference material, the steel PS 67 (A=8%), in Fig. 2, didn't show significant influence on the erosion rate for low impact angles 15º, where the cut mechanism operates and hardness shows a preponderant role in the erosion mechanism. However, for larger impact angles, such as of 90º, where the mechanism of plastic deformation begins to prevail, the ductility showed a larger influence on the erosion rate, which is observed by Sundararajan (1995) in copper alloys, however, alone the ductility didn't explain the resistance to the erosion.

In spite of the great difference among the work hardening exponent ‘n’ of the superalloy Inconel 600 (n = 0,24) and of the steel PS 67 (n = 0,1), in Fig. 2, it is verified that the work hardening cannot be considered a fact that explains the difference of the erosion rate in the analyzed materials, differently from of Sundararajan (1995), that his found some correlation between the work hardening and erosion rate for the systems nickel (Ni, Ni-Cr, Ma 754) and system (17-4 PH SS).

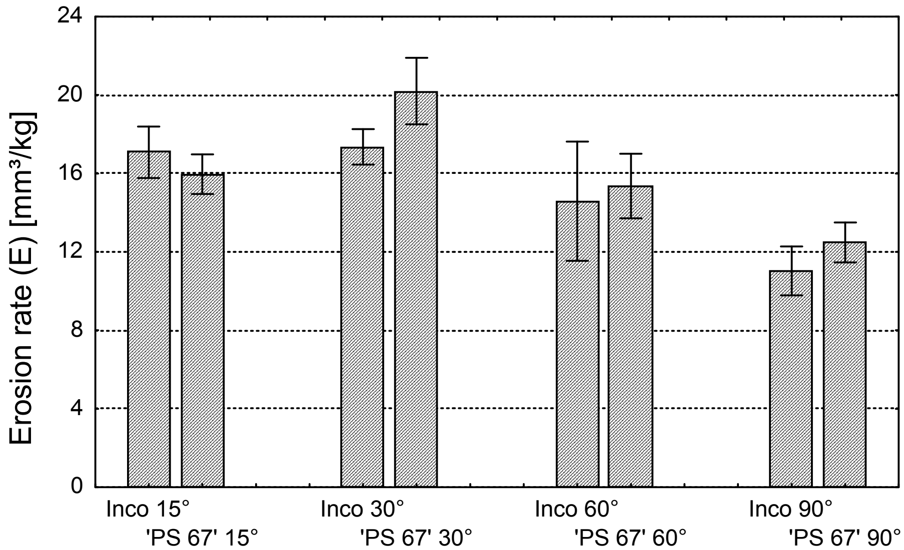

Figure 2. Erosion rate of the superalloy Inconel 600 and of the steel PS 67, in function of the impact angle of the of solid particles flow, for a reliable interval of 95% (t-student).

It is taking into account the yield and ultimate tensile strength of the superalloy Inconel 600 (σe = 418 MPa, σt = 701 MPa) and of the steel 'PS 67' (σe = 744 MPa, σt = 996 MPa), it is verified that the superiority of the yield and ultimate tensile strength of the steel PS 67 in relation to the superalloy Inconel 600, in Fig. 2, didn't show significant influence on the erosion rate for the angles of 15º, 30º, 60º and 90º, differently from of Sundararajan (1995), that showed a better resistance to the erosive wear in materials with intermediate to low mechanical resistance.

4. Conclusions

(a) The medium erosion rate of superalloy Inconel 600, in function of the impact angles of solid particle flow, presented a probable behavior of ductile materials, however the reliable intervals have been superimposed for the angles 15º, 30º e 60º, it was not possible to establish some correlation with the ductile material.

(b) Being the superalloy resistant to high temperatures and the erosion a process of material deformation where is developed temperatures high during the particles impact, we can verify that, the superalloy Inconel 600, presented a superior erosion resistance in relation to the reference material, the steel PS 67, only in the impact angle of 30º. For the angles of 15º, 60º and 90º, the reliable intervals have been superimposed for all of them, in spite of great differences among the mechanical properties of the superalloy and steel.

(c) This study demonstrated that it is very difficult to correlate mechanical property with erosion rate. The erosion should be correlated with a combination of material properties and impingement and particle variables.

4. References

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM G76-95, 1995, "Standard test method for conducting erosion tests by solid particle impingement using gas jet". Philadelphia, pag.1-5.

BITTER, J.G.A, 1963, "A study of erosion phenomena, part. I". Shell International Research, Amsterdam, The Netherlands, Wear, vol.6, pag.5-21.

BLAU, P.J., 1995, "Glossary of terms and definitions in the field of friction, wear and lubrification", *In:* ASM Handbook - Friction, lubrification and wear tecnology. Oak Ridge National Laboratory, 1995, vol.18, pag.1-21.

DONACHIE, M. J., 1985, "Superalloys. *In:* Metals Handbook - desk edition – ASM", Ohio, Metals Park, pag. 16/5.

FINNIE, I., 1960, "Erosion of surface by solid particle", Emeryville, California, Wear, 1960, vol.3, pag.87-103.

FINNIE, I., 1995, "Some reflections on the past and future of erosion", University of California, Berkeley, California, Wear, 1995, vol.186-187, pag.1-10.

HUTCHINGS; LEVY, 1989, "Thermal effects in the erosion of ductile metals", Wear, vol.131, 105-121.

KOSEL, T.H. 1995, "Solid particle erosion", *In:* ASM Handbook, University Notre Dame, Wear, 1995, vol.18, pag.199-213.

LEVY, A. V; MAN, Y.F. 1986, "Elevated temperature erosion-corrosion of 9Cr – 1Mo steel". University of California, Berkeley, California, Wear, vol.111, pag.135-159.

SUNDARARAJAN, G., 1995, "The solid particle erosion of metallic materials: The rationalization of the influence of material variables", Defense Metallurgical Research Laboratory, Kanchaanbagh, Hyderabad 500258, India., Wear, vol.186-187, pag.129-144.

6. Responsibility notice

The authors are the only responsible for the printed material included in this paper.