

# Analysis of the initial cavitation erosion period of selected nickel alloys

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**Abstract.** Cavitation wear resistance, of four different nickel-based alloy during the incubation period was investigated with the use of stream-impact device and results are presented in this paper. Four nickel alloys with excellent resistance corrosion very high corrosion resistance and very good mechanical properties were selected for the tests: Monel 400, Inconel 600, Incoloy 800H and Hastelloy C22. Nickel alloys examined for the period of 600 minutes. Mechanism of formation and destruction of the surface layer under working liquid influence is described. It was noticed, that first microcracks are formed on the grain boundaries, especially in the triple contact points. Effects of plastic strain were also noted on the surface of samples as a uplifting and collapsing in boundary area. It was stated, that among nickel alloys examined, a better resistance to cavitation erosion in initial period of cavitation damage has the alloys: Hastelloy C22 and Incoloy 800H.

## 1 Introduction

Nickel-based alloys are construction materials characterized by very high strength and high corrosion resistance [1-7]. Due to their properties, nickel-based alloys are used in the construction of aircraft gas turbines, steam turbine power plants, nuclear power systems, chemical and petrochemical industries. Nickel-based alloys are known by their trademark names such as: Monel®, Hastelloy®, Inconel®, Incoloy® and Nimonic®.

Monel® alloys are a nickel-copper alloy with high strength and excellent corrosion resistance in a range of media including sea water, hydrofluoric acid, sulfuric acid, and alkalis. It is used by marine engineering, chemical and hydrocarbon processing equipment, valves, pumps, shafts, fittings, fasteners, and heat exchangers. There are three Monel® alloys are: Monel 400, Monel K500 and Monel R-405

Hastelloy® - the name of a group of corrosion-resistant nickel alloys, namely the Ni-Mo and the Ni-Cr-Mo alloys. Depending on the desired combination of properties, Hastelloy® alloys contain varying amounts of Mo (up to 30%), Cr (up to 23%), Fe (up to 29%), Hastelloy® alloys are characterized by high resistance to hydrochloric, sulfuric, phosphoric, acetic, and formic acids, to media containing ions of chlorine and fluorine, and to many organic media. The most popular among Hastelloy® alloys are: Hastelloy B2/B3, Hastelloy C22 and Hastelloy C-276.



Inconel® alloys are a group of austenitic nickel-chromium-based superalloys. Inconel® alloys characterized by excellent mechanical properties at both extremely low and extremely high temperatures, outstanding resistance to pitting, crevice corrosion and intercrystalline corrosion high resistance to oxidation at elevated temperatures and good resistance to acids, such as sulfuric, phosphoric, nitric, and hydrochloric. Inconel 600, Inconel 625, Inconel 690, Inconel 718 and Inconel 751 are alloys used in gas turbine blades, seals, and combustors, as well as turbocharger rotors and seals, high temperature fasteners, chemical processing and pressure vessels, heat exchanger tubing, steam generators and core components in nuclear pressurized water reactors.

Incoloy® and Nimonic® is registered trademark name of Special Metals Corporation. Incoloy® alloys are a nickel-chromium-iron alloys, which used in chemical and petrochemical processing, nuclear fuel reprocessing, acid production, in power plants for super-heater and reheater tubing, oil and gas well piping, in industrial furnaces and for heat-treating equipment. The most popular among Incoloy® alloys are: Incoloy 800H/800HT/800AT, Incoloy 825, Incoloy 925 and Incoloy 945.

Nimonic® alloys typically are a nickel-chromium or nickel-chromium-cobalt alloys. Nimonic® alloys consist of more than 50% nickel chromium (up to 30%) and cobalt (up to 32%) with additives such as titanium (up to 6%) and aluminum (up to 6%) and molybdenum (up to 5%). Nimonic® alloys use is in gas turbine components such as turbine blades and exhaust nozzles on jet engines and extremely high performance reciprocating internal combustion engines, where the pressure and heat are extreme. Nimonic® alloys characterized by very good corrosion and oxidation resistance at high temperatures and easy machined. In Nimonic® alloys are: Nimonic 75, Nimonic 80, Nimonic 86, Nimonic 90, Nimonic 105, Nimonic 115.

Machine parts made of nickel alloys very often operate under extreme conditions and are exposed to corrosive and erosion phenomena caused by aggressive environments. Nickel alloys used in marine engineering, chemical and petrochemical processing, pulp and paper industry, food processing, nuclear engineering are exposed to cavitation erosion caused by cavitation.

Cavitation is the process of formation, growth and implosion of bubbles containing steam, gas or steam-gas mixture due to cyclic pressure changes in the flowing liquid. The cavitation implosion is an effect of pressure change from the area of its low value to a region of elevated pressure, causing condensation of steam filling the cavitation bubble. Implosion phenomenon occurs at very high velocity (exceeding 100 m/s), and in such case time of growth and decay of cavitation bubble is

in milliseconds. The dynamics of the formation and sealing of bubble is dependent on the physicochemical properties of liquid and the distance between the wall and the interaction of bubbles. In the vicinity of the wall, a microstructure implosion bubble forms, which can reach speeds of 300 to 500 m/s. Microstreams formed during the implosion of cavitation bubbles transmit on the wall pressure impulses in the order of 1-4 GPa. Multiple repetitive cavitation implosion causes material destruction [8-13].

The aim of the paper to analyze of the initial cavitation erosion period of selected nickel alloys.

## 2 Investigated materials

The detailed examinations of resistance to cavitation wear was carried out on four deliberately selected nickel-based alloys:

- Monel 400 – alloy is a solid solution alloy that can only be hardened by cold working. This nickel alloy exhibits characteristics like good corrosion resistance, good weldability and high strength. A low corrosion rate in rapidly flowing brackish or seawater combined with excellent resistance to stress-corrosion cracking in most freshwaters, and its resistance to a variety of corrosive conditions led to its wide use in marine applications.
- Inconel 600 - alloy used for applications that require corrosion and high temperature resistance. It is non-magnetic, has excellent mechanical properties, and presents the desirable combination

of high strength and good weldability under a wide range of temperatures. The high nickel content in Inconel 600 provides excellent resistance corrosion.

- Incoloy 800H - alloy with good strength and excellent resistance to oxidation and carburization in high-temperature exposure. Incoloy 800H is intend for high temperature structural applications. The nickel content makes the alloys highly resistant to both chloride stress-corrosion cracking and to embrittlement from precipitation of sigma phase.
- Hasteloy C22 - alloy with enhanced resistance to pitting, crevice corrosion and stress corrosion cracking. The high chromium content provides good resistance to oxidizing media while the molybdenum and tungsten content give good resistance to reducing media. This nickel alloy also has excellent resistance to oxidizing aqueous media including wet chlorine and mixtures containing nitric acid or oxidizing acids with chlorine ions.

Chemical composition and mechanical properties of tested nickel alloys are shown in Table 1.

**Table 1.** Chemical composition and mechanical properties of tested materials

Chemical element [% Wt.]	Nickel alloys			
	Monel 400	Inconel 600	Incoloy 800H	Hasteloy C22
Ni	bal.	bal.	30.67	bal.
Fe	2.07	8.95	bal.	4.09
Cu	29.94	-	0.32	-
Si	0.25	0.28	0.46	0.048
Mn	1.18	0.20	0.87	0.31
C	0.14	0.06	0.071	0.009
Cr	-	18.96	19.57	21.48
Co	-	0.021	0.10	0.03
Mo	-	-	0.26	13.78
Ti	-	0.020	0.60	-
Al	-	0.22	0.42	-
V	-	-	-	0.018
W	-	-	-	3.20
Mechanical properties	Monel 400	Inconel 600	Incoloy 800H	Hasteloy C22
Rm [MPa]	616	713	554	780
Re [MPa]	335	361	219	426
A [%]	41	44	44	50

### 3 Methods of investigation

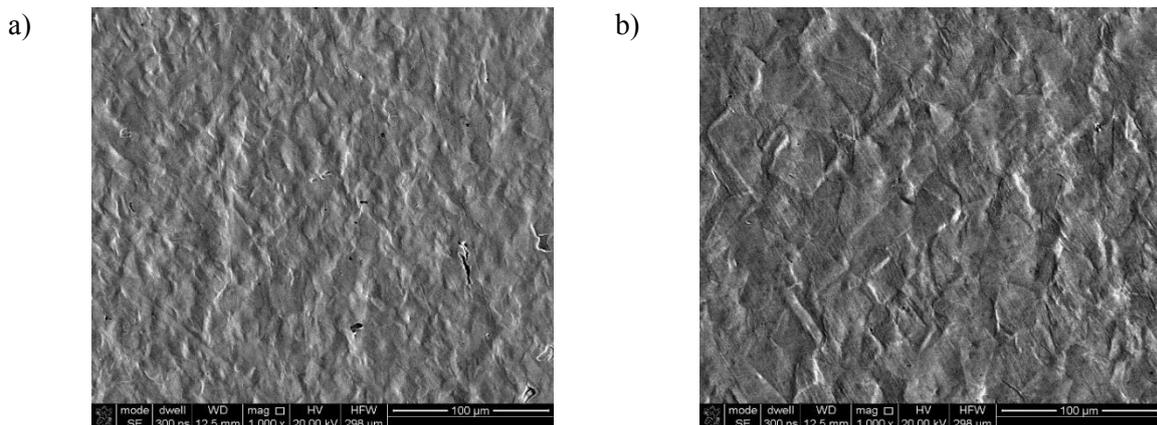
The examination of cavitation erosion was carried out on stream-impact device [14]. This device consists of rotating arm, equipped with a sample holder. The samples rotate with high speed and are subjected to the impact of a liquid, flowing through a nozzle. The impact of flowing liquid simulates cavitation impulses. The intensity of destruction primarily depends on rotational speed of the samples, the distance between nozzle and samples, the flow rate and the physio-chemical properties of the liquid. Examined samples had cylindrical shape with 20 mm diameter and  $6 \pm 0.5$  mm height. Surface roughness of samples before the experiment, measured by PGM-1C profilometer, was in range

of  $0.010 \div 0.015$   $\mu\text{m}$ . The samples were vertically mounted in rotor arms, parallel to the axis of water stream, pumped continuously at 0.06 MPa through a 10 mm diameter nozzle located 1.6 mm from the edge of the sample. The rotating samples were hitting by the water stream. The samples were tested for the period of 30 minutes, took out from the fixtures, de-greased in an ultrasonic washer for 10 minutes at 30°C, dried in a laboratory drier for 15 minutes at 120°C and weighed, than mounted

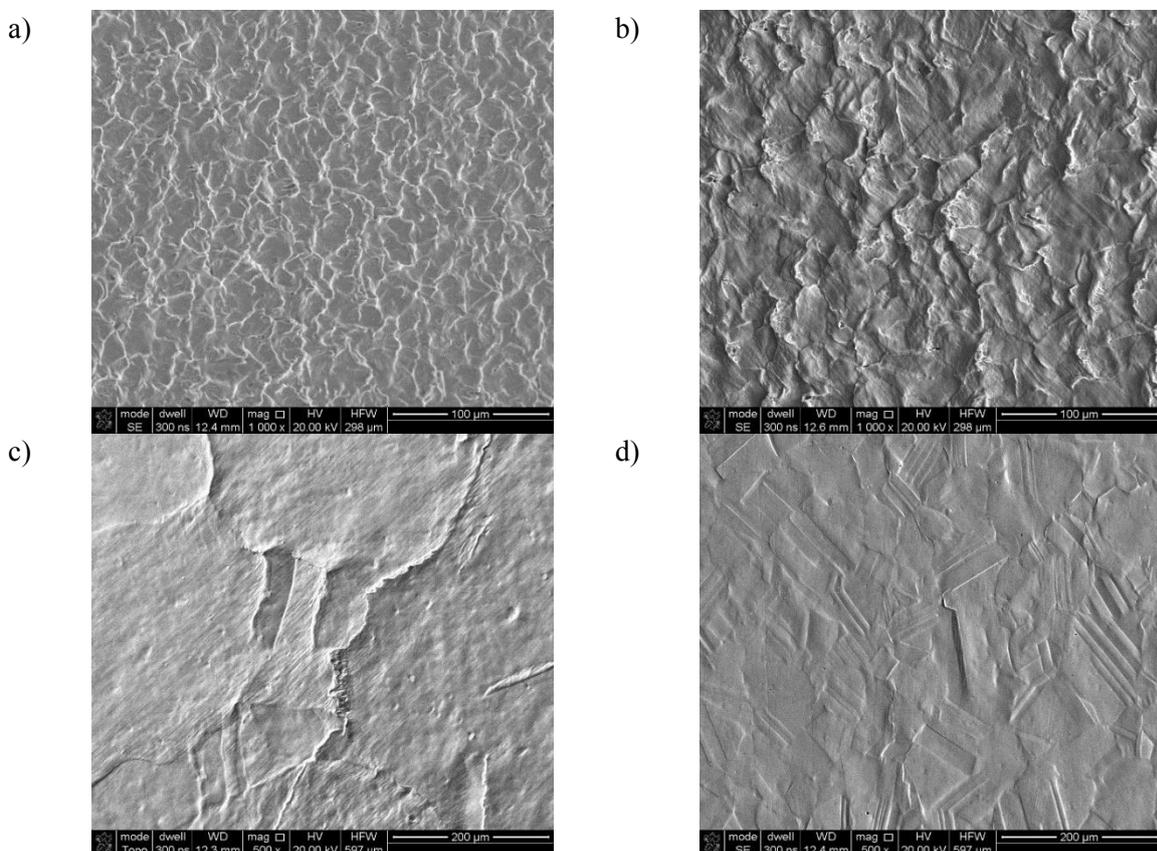
again in the rotor arms, maintaining the initial position in relation to the water stream. The analyses included 4 samples of each alloy, examined for the period of 600 minutes.

#### 4 Study results and their analysis

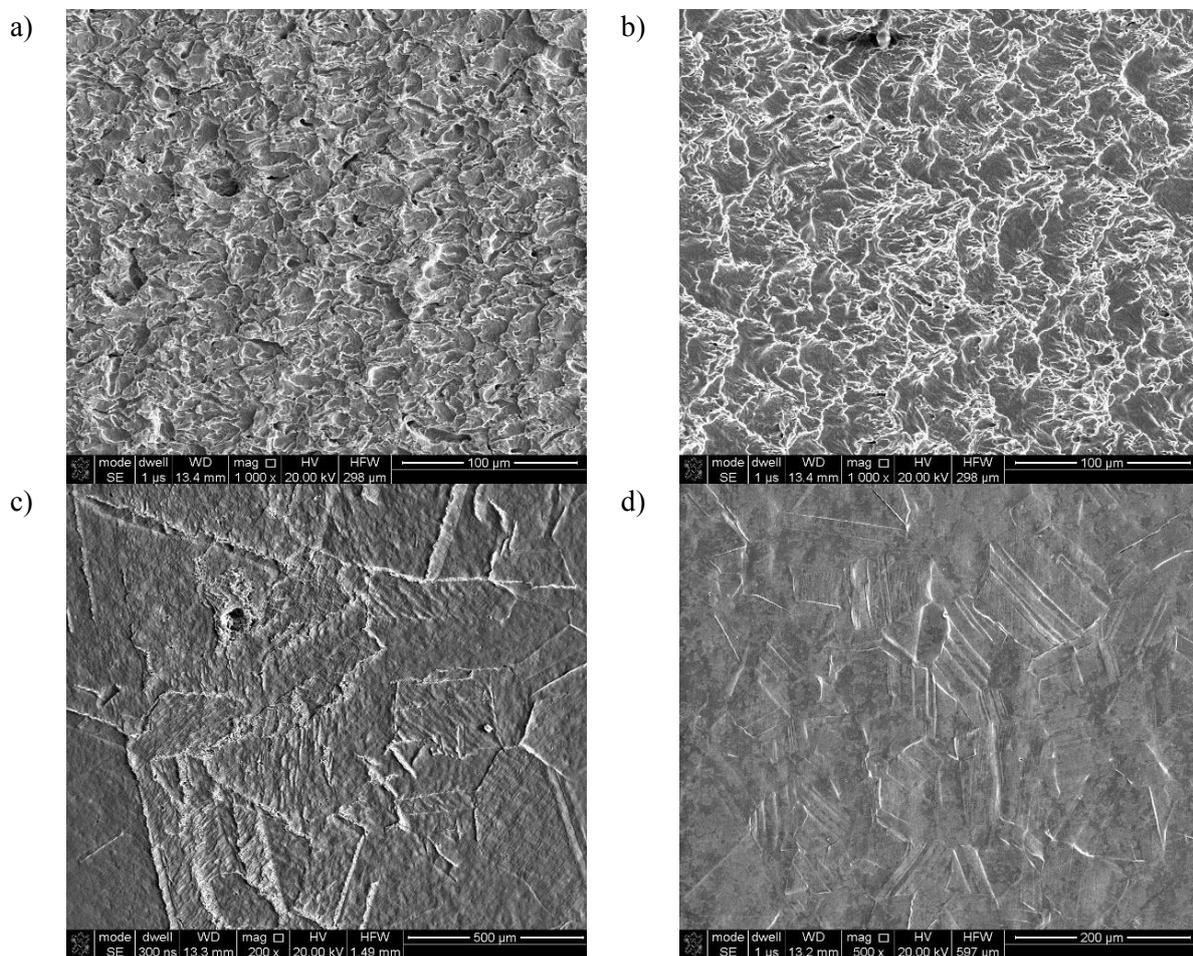
Microscopic observations of cavitation process effects have shown that the main reason of alloys destruction was mechanical interaction between water stream and surface of specimen. First minutes of the test show, that water stream action on the surface of samples induces the strengthening of surface layer and the increase of micro-hardness. The plastic strain and single pits was observed on the surface of all nickel alloys samples. The plastic deformation on Monel 400 and Inconel 600 alloys surface are showed in figure 1.



**Figure 1.** SEM microphotographs present the surface changes after 120 min, a) Monel 400 alloy, b) Inconel 600 alloy.



- Figure 2.** SEM microphotographs present the surface changes after 300 min, a) Monel 400 alloy, b) Inconel 600 alloy, c) Incoloy 800H alloy, d) Hasteloy C22 alloy. Further exposition of the alloy surface on water stream has caused:
- higher plastic deformation of the surface of Monel 400 and Inconel 600 alloys led to roughness increase. Higher surface roughness of the tested samples changed the angle of the water stream interaction and accelerated the process of cavitation destruction;
  - first microcracks are formed on the grain boundaries, especially in the triple contact points of the surface of Incoloy 800H alloys;
  - effect of material uplifting and collapsing in a boundary area of the surface of Hasteloy C22 alloys.
- These changes on surface condition of nickel alloys samples are showed in figure 2.



**Figure 3.** SEM microphotographs present the surface changes after 600 min, a) Monel 400 alloy, b) Inconel 600 alloy, c) Incoloy 800H alloy, d) Hasteloy C22 alloy.

- In further stage of tested nickel alloys there were observed below mentioned processes:
- slow erosion of the Monel 400 and Inconel 600 alloys surface;
  - destruction of uplifted grain boundaries on the Incoloy 800H alloys surface;
  - first microcracks and first single losses were formed on twins grain boundaries of the Hasteloy C22 alloys surface

These changes on surface condition of nickel alloys samples are showed in figure 3. After 600 minutes of examination the average mass loss of four samples of each nickel alloys was: 0.5, 0.4, 0.2 and 0.1 mg for Monel 400, Inconel 600, Incoloy 800H and Hasteloy C22 respectively.

## 5 Summary

First period of cavitation destruction - incubation period – was characterized by no mass decrement (mass decrement rate was equal to zero), fatigue processes and plastic strain effects occurred and micro-cracks developed on the surface. All these phenomena were observed on tested samples of nickel alloys. Tests of resistance to cavitation erosion proved, that materials with a long incubation period have a very good resistance to this type of destruction. Determination of the resistance to cavitation erosion of the nickel alloys tested would be possible in case of the studies continuation. The analysis of initial period of tested nickel alloys cavitation erosion process has proved, that two alloys have the highest resistance to cavitation erosion: Incoloy 800H and Hasteloy C22.

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