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Material properties essential for cavitation erosion of laser produced surface alloys

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Cavitation erosion of metal surface is a problem the designers and exploiters of hydraulic machinery must cope with. Therefore, search for new efficacious materials and methods for the solid body protection or cavitation damage repair is of high importance. One method of improving the wear properties of metals consists in employing a surface layer of high cavitation erosion resistance [1]. Results have shown that alloying, cladding, melting or transformation hardening of the ferrous alloys by laser beam led to substantial improvement of the materials performance under the cavitation conditions, e.g. [2, 3]. Especially, alloying of steel surface layers with Co, Mn, AlNi and TiC compounds were found to be effective in combating cavitation wear [4].

As a rule, grains refining and formation of hard phases (e.g., martensite) due to rapid cooling in the course of laser processing contribute to the increase in cavitation resistance of the materials. Precipitation of hard phases (such as carbides) and formation of residual stress fields may be either beneficial or detrimental [5]. The latter is the case when laser processing is accompanied by an increase in brittleness. Specific properties of laser manufactured layers may cause a deviation from the rule proved in [6] that material deformation and destruction under the cavitation loading is of fatigue nature, regardless of the material type. Therefore, it is vital to discover what properties of laser produced alloys are essential for cavitation resistance. This may make it easier to predict the material performance under the cavitation loading, although one should keep in mind that material performance depends strongly on the intensity of the cavitation loading. Parameters affecting the cavitation resistance of the material should link to its ability to scatter or absorb energy. Among others properties that may be of importance are hardness and impact toughness. Also, the relationship between the material ability to work harden and its resistance to cavitation damage seems to be relevant [7]. The latter is important due to dynamics of the erosion, i.e., the progress of the damage deeper and deeper into the material.

In the present work the cavitation performance of samples with various mechanical proprieties was investigated. Four groups of laser produced alloys were selected due to following properties: (1) hardness of the level of tool hardened steel, low impact toughness and low work hardening capability—sample 1; (2) relatively low hardness—of the level of gray iron tempered martensite, high impact toughness and high work hardening capability—sample 2; (3) hardness of the level of gray iron untempered martensite, mid-impact toughness and high ability to work hardening—sample 3; (4) high hardness of the level of high speed hardened steel, mid-impact toughness and mid-ability to work hardening—sample 4.

The samples for investigations were made of 0.45% carbon steel (samples 1 and 4) of grade: Fe-0.45C-0.65Mn-0.25Si-0.30Cr-0.30Ni-0.30Cu-0.04P-0.04S and 13% chromium steel (samples 2 and 3) of grade: Fe-0.2C-13Cr-0.6Mn-0.5Si-0.2Ni and subsequently alloyed with appropriate additive powders (AlNi, Nb, Cr, B, Ni, Si, Mn, Ti, Co, Mo). Continuous wave CO_2 laser Triumph TLF 6000 was used as a power source. The main parameters of the devices as well as the conditions of the processing are presented in Table I. During the experimental runs the specimens were moved across the laser beam along a single 1 cm wide path. Chemical compositions and the microstructures of the manufactured surface layers are presented in Table II. Their average thickness was 0.55 mm.

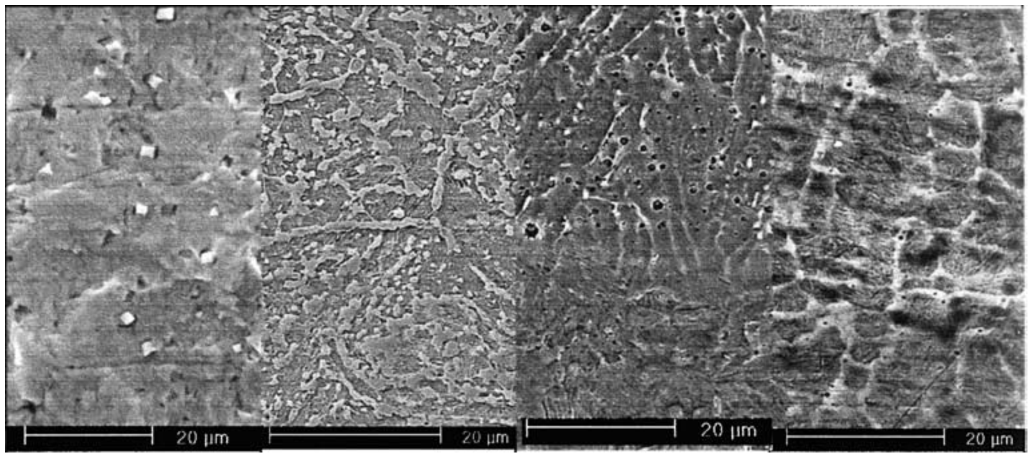
Impact toughness was qualitatively determined by following procedure: a steel ball of 4.12 g weight and 67 HRC was let down onto the alloyed sample of thickness 0.7 mm in an area of 1 cm × 1 cm square. Impacts were applied repetitively to both sides of the prepared layer until cracking occurred along the edges of the area. Values shown in Table II are relative as this was not a standardized method of impact toughness assessment. Preparation of the sample required for a standard test was obviously impossible.

The processed workpieces were subjected to cavitation impingement in a rotating disk rig [8]. The

TABLE I Experimental conditions of metal surface processing

Laser beam power (W)	6000
Laser beam mode	TEM 0.1
Laser beam diameter (cm)	2.5
Laser beam divergency	1.5 mrad
Focussing element	Mirror optics for the formation of the laser beam field uniformly on the area 1 × 10 mm.
Focal length (cm)	20
Diameter of the beam spot on the surface (cm)	Rectangular 1 × 10 mm
Sample velocity (cm/s)	0.8
The shielding gas	Argon (99.998%)
Gas velocity (m/s)	60

TABLE II

Sample designation/substrate	1/45	2/2Cr13	3/2Cr13	4/45
Average chemical composition of the matrix in a surface layer (wt%)[a]	73.25Fe/5.04Nb/6.29Ni/3.8Al/3.01Mn/1.91Si/0.7Ti/0.6C	86.55Fe/5.47Ni/6.46Al/0.2C/0.4Cu/0.92Mn	78.65Fe/12.12Cr/3.89Co/3.98Ni/1.02Mn/0.19Ti/0.15C	75.55Fe/9.6Ni/6.42Co/5.51Mo/1.4Mn/0.54Cr/0.41Ti/0.37Si/0.19Al/0.02C
Repetitive impact toughness[b]	1×	2.3×	1.5×	1.3×
Average microhardness (HV0.2)	644	449	570	800
Ability to work hardening[c] (%)	0	39	22	18
Microstructures[d]				
	Fig. 1a	Fig. 1b	Fig. 1c	Fig. 1d

[a]analysis carried out by means of electron dispersive spectroscopy EDAX.
[b]values normalized to the value of the sample 1. Measurements done according to the method described in the text.
[c]an increase of hardness detected after 20 min of cavitation.
[d]visualization made by scanning electron microscope Philips 30/ESEM.

cavitation was generated there by cylinders situated on the surface of a disk of 300 mm diameter. The rotation speed was 3000 r.p.m. Water of temperature 20 °C was used as an active medium. The tests were performed in runs 2–5 min long following one after another, lasting 20 min in total. The intensity of cavitation impingements loading was very high, but the duration of each run was less than the time needed to achieve the steady state cavitation intensity. After each run, the decrease in surface brightness (η) caused by the increase in indentations size and amount was detected and quantified by a multi scan system. Relevant time variations for the four investigated alloys and for unprocessed steel 2Cr13 are presented in Figs 1 and 2. The inaccuracy in assessment of brightness values is within the experimental points depicted in the plots. Curves in Figs 1 and 2 pertain respectively to the cases of relatively low and high intensity cavitation.

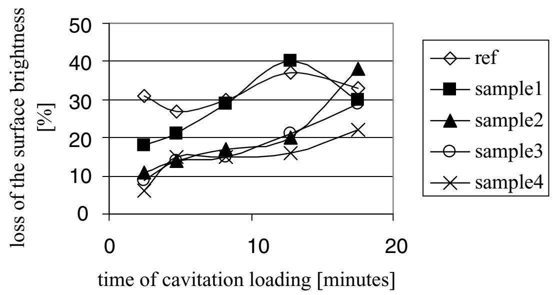


Figure 2 Loss of the surface brightness of the investigated samples due to high intensity cavitation loading.

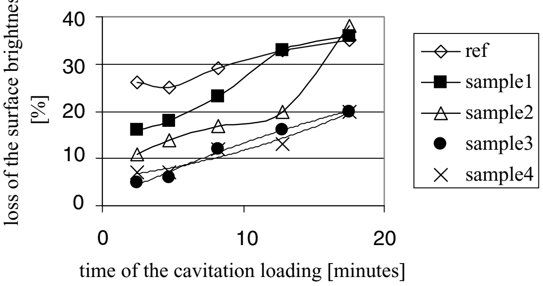


Figure 1 Loss of the surface brightness of the investigated samples due to low intensity cavitation loading.

The results indicate that all processed samples displayed considerably less wear at the beginning of cavitation action than the reference one (sample made of corrosion resistant 13% chromium steel of 256 HV0.2). The best resistance was exhibited by samples 3 and 4, both of high ability to work hardening and mid-impact toughness. Their performance under the low intensity cavitation was almost the same. The horizontal segments of the curve of sample 4, especially the plateau visible in Fig. 2 are the effects of the work hardening of the material. The low gradient of the curve of sample 2 in Fig. 1 observed after 10 min of cavitation seemed also to be caused by work hardening effect. Subsequent rapid increase of the gradient of the curve was the result of intensive development of deformation inside the holes because of increased plasticity of the material. A decrease in η for reference sample after 5 and 15 min of high intensity cavitation may be ascribed to the extraction of material pieces from the surface layer resulting in the surface smoothing. The same trend is seen in the curve of sample 1. In the latter case, material loss is facilitated by the high brittleness of the alloy.

Although there is a correlation between cavitation resistance of the material and its ability to work hardening, the intensity of the erosion of particular alloys cannot be regarded as a function of a single parameter. On the other hand, it seems that a material with a low ability to work hardening cannot achieve optional resistance to cavitation, regardless of its hardness or impact toughness levels. It may be inferred from the results obtained that a high level of work hardening capacity should be accompanied by increased hardness and impact toughness if substantial and durable increase in material resistance to cavitation erosion is to be achieved. Samples of high hardness, but with reduced impact toughness and work hardening capability, exhibit poor erosion resistance in the late stage of damage. The cavitation performance of the samples of high toughness—not coupled with significant hardness and work hardening capability—is also not satisfactory.

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