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Cavitation erosion of laser processed Fe-Cr-Mn and Fe-Cr-Co alloys

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Properties

ABSTRACT

Purpose: Purpose of this paper is attempt explanation how laser beam processing influence on the cavitation performance of the Fe-Cr-Mn and Fe-Cr-Co alloys. This kind of alloys are frequently used in Polish power plants to routine repairs of damaged blades working under cavitation loading.

Design/methodology/approach: Padding welds of investigated alloys were tested for three cases: after laser melting, after laser heating of the solid state and without additional processing. Cw. CO_2 laser was employed as a source of radiation. The rotating disk rig was used in cavitation erosion investigations. The chemical composition, microstructure, and phase identification of the processed and subjected to cavitation loading alloys were examined using light microscopy, X-ray diffractometry and scanning electron microscopy, respectively.

Findings: Phase transformation for processed and unprocessed alloys was observed. Obtained results revealed that laser processing contributes to delaying of austenite → martensite phase transformation. Kinetic of this transformation is different for investigated alloys and depends on the chemical composition and applied laser processing.

Research limitations/implications: Reported research ought to be completed and full cavitation curves (volume loss in time) for laser beam processed alloys must be done.

Practical implications: For low intensity of cavitation loading, like in field conditions laser beam processing can increase of cavitation erosion resistance of investigated alloys due to increase of hardness.

Originality/value: Confirmation that creation of the transformed and hardfacing structures by laser techniques leads in many cases to considerable changes in cavitation erosion properties of the processed materials.

Keywords: Erosion; Cavitation; Laser processing; Fe-Cr-Mn and Fe-Cr-Co alloys

1. Introduction

Cavitation occurs in hydrodynamic systems such as echo sounder membranes, hydraulic turbines, pumps, ship propellers, mechanical heart valves and other. Hydrodynamic systems often create sonic vibration within the fluid which causes pressure fluctuations in the liquid. Whenever the pressure drops below the vapor pressure of the liquid microscopic bubbles nucleate. Next they collapse violently with high pressure, producing stress pulses which exceed yield strength of most metals and their alloys. As a results of cavitation phenomena such a noise, vibration, luck of efficiency of the equipment, and erosion of solid surfaces in contact with the liquid can occur. Damage of material because of cavitation is known in the literature as cavitation erosion. Developing new kinds of materials processing to protect their surface layer is an important method to prolong service life of part machines subjected to cavitation. One of this method is laser beam machining. Laser surface treatment creates of the transformed and hardfacing structures which leads in many cases to considerable changes in cavitation erosion properties of the processed materials [4,5,11,12,15,21,22,25,27,28]. Laser heating and subsequent rapid cooling creates also the state of residual stresses within the processed surface layer [1,3,6,7-9,11,13,30] and leads as a rule to grain refining due to diffusion retarding. Another result of laser beam machining application is the most cases the formation of metastable structures of the materials [23, 33].

Evaluation of materials resistance to cavitation erosion is done by comparison of their cumulative volume loss in time [35]. However measurements of cumulative volume loss due to cavitation loading, to determine such relationships, are labour-consuming. That is why in recent years many authors try to determine resistance to cavitation erosion observing materials in the initial stage of damage [2,16,17,24].
Despite substantial progress in understanding cavitation erosion mechanism, evaluation of cavitation erosion resistance of materials is not still synonymous [18,19].

In the paper influence of the laser processing of the Fe-Cr-Co and Fe-Cr-Mn alloys on their cavitation performance is discussed. The special attention was paid to the damage of materials in the first stage of the erosion. As a criterion of cavitation performance of materials hardening work degree and depth of hardened surface layer were considered.

2. Experimental procedures

The samples (in shape of cylinder 30 x 8 mm) used in investigations were made of chromium-nickel stainless steel of the grades: max 0.08% C, max 2% Mn, 18% Cr, 9% Ni. Fe-Cr-Mn and Fe-Cr-Co electrodes were used to cover tested samples. Table 1 contains chemical compositions electrodes used to obtain padding welds.

Table 1.
Chemical composition of used electrodes

	C	Mn	Si	P	S	Cr	Co
Fe-Cr-Mn	0.35	8.31	0.26	0.069	0.012	10.93	-
Fe-Cr-Co	0.31	0.55	0.30	0.016	0.010	16.5	6.07

Padding welds thickness ranged from 1-2.5 mm. Next prepared samples were superficially heated by laser beam. As a power source continuous work CO_2 laser MLT 1.2 was used. The padding welds surface were melted or heated in solid state along two parallel paths (Fig. 1). Argon of purity 99.998 % was used as a shielding gas to protect the molten material from oxidation and the focusing optics from the fumes. The diameter of the beam spot on the processed surface was 3.6 mm in case of laser heating and 1.6 mm in case of laser melting and the velocity of the sample subjected to laser processing was 0.6 cm/s. There were no cracks in the laser treated samples. In order to level roughness remained after the laser processing their surfaces before cavitation investigations on the rotating disk stand have been polished. The processed samples were subjected to cavitation at the rotating disk rig [20] (see Fig. 2). Cylinders situated on a disk surface on the circle 300 mm (see Fig. 3) generated cavitation loading. The rotation speed was 3000 r.p.m. Tested samples were inlaid in the disk downstream of the cavitator. As an active medium the water of temperature 20°C was used. The resulting mean gauge pressure was 155 kPa. The duration of cavitation test was 70 minutes. A light microscope Neophot 32 and scanning electron microscope Philips 30/ESEM were used for visualization of microstructures in the plane normal to the processing path. Energy dispersive spectroscopy EDAX was used to chemical composition analysis. The analysis of the chemical composition at the accelerating voltage of 25 kV was done at the surface of the tested samples. X-ray diffractometry (XRD) was using to examine phase identification of the modified layers.

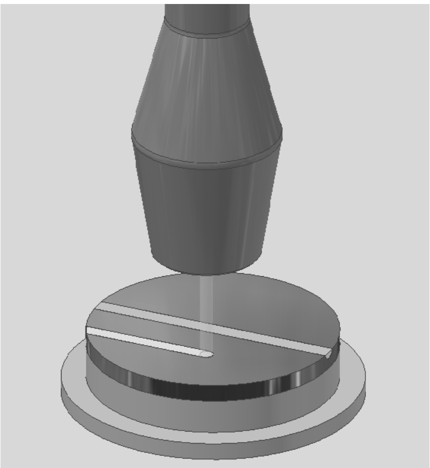

Fig. 1. The view of laser processed padding weld

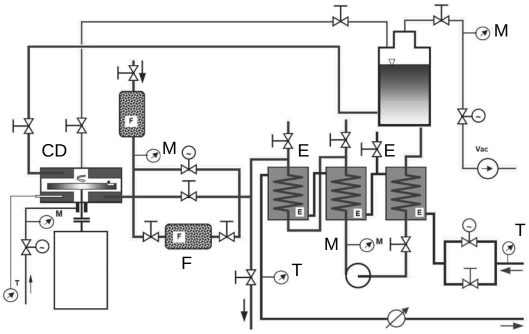

Fig. 2. Scheme of the cavitation test stand in IMP PAN Gdansk. CD – chamber with rotating disk, E – heat exchanger, F – filter, M- manometer, T- thermometer

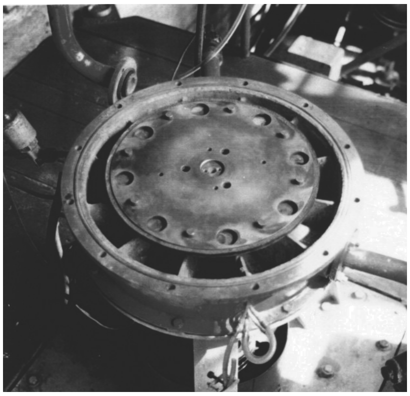

Fig. 3. Opened chamber with rotating disk

The hardness measurements within the processed zone and hardened surface layer detected at the load of 2 N were done by means of a Vickers tester.

3. Results and discussion

Light microscope and XRD investigations (see Figs. 4-5) revealed that microstructure of both not processed padding welds have consisted in martensite, austenite, and $Cr_{23}C_6$ carbides. For chemical compositions presented in Table 1, this kind of microstructure stay in accordance with the Schaffler diagram.

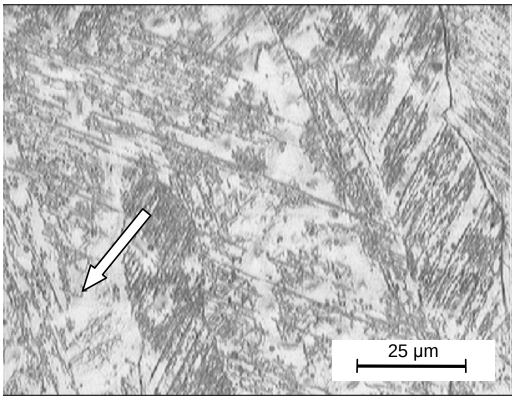

Fig. 4. Microstructure in surface layer of the not processed Fe-Cr-Co alloy. Martensite and austenite phases and also $Cr_{23}C_6$ carbides (depicted by arrow) are visible. Light microscope

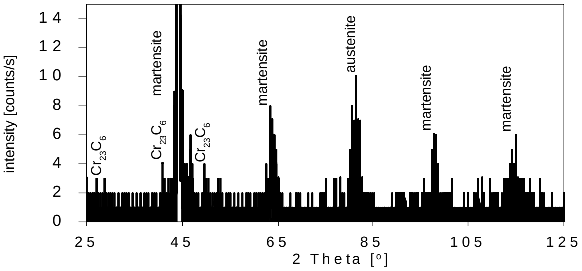

Fig. 5. Results of XRD analysis for the not processed surface of Fe-Cr-Mn padding weld

Microstructure changes within the investigated alloys due to laser beam machining have found. Laser heating in solid state and laser melting resulted quench annealing of some amount of $Cr_{23}C_6$ carbides (see Figs. 6-7) because of high degree of underheating. The content of the martensite within processed regions was also increased due to laser heating and rapid cooling particularly for laser melted zones. Besides micropores in microstructure were observed (Fig. 8) particularly in melted padding welds. Cavitation erosion resistance of processed materials can decrease because of present of micropores which lead to decrease of fatigue strength. But laser beam processing creates also the state of residual stresses within the processed surface layer. Tensile stresses can decrease of cavitation erosion resistance of processed materials while compressive stresses can increase this resistance. Laser processing has also resulted grain refining (Figs. 6-7).

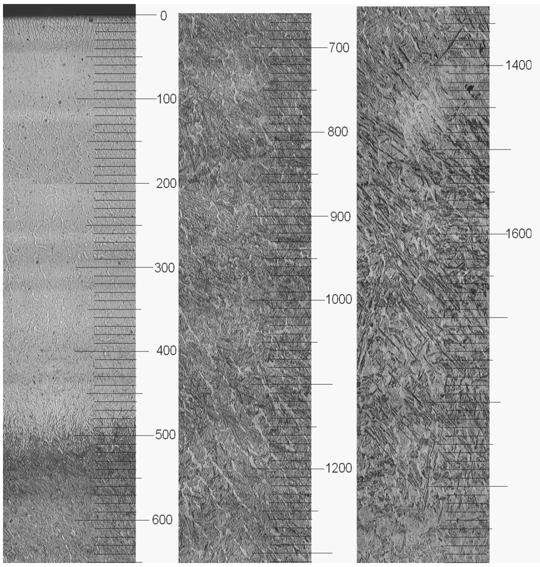

Fig. 6. Microstructure in plane normal to the melted path for Fe-Cr-Co padding weld. Light microscope

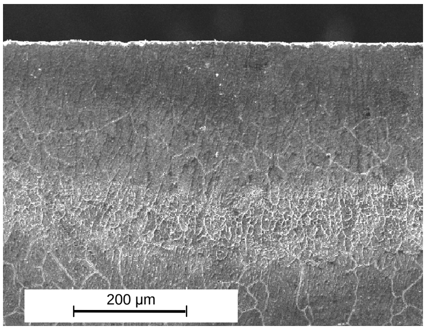

Fig. 7. Microstructure in surface layer heated in solid state Fe-Cr-Co padding weld reveled on the cross section (SEM)

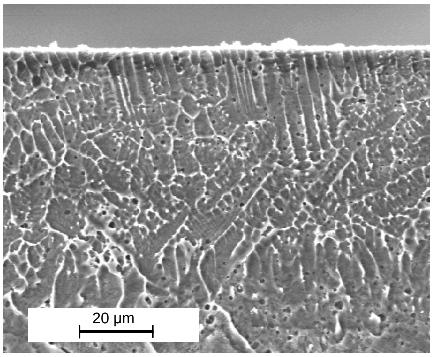

Fig. 8. Refining dendritic structure in surface layer of melted Fe-Cr-Mn padding weld reveled on the cross section (SEM). Amount of micropores is visible

In consequent laser processing of the padding welds led to an increase of the surface hardness due to reasons mentioned above. Figs. 9-10 present microhardness profiles prepared after 70 minutes of cavitation loading. By examining of those figures can notice that laser beam processing as well as cavitation loading increase hardness in surface layer. Hardness increase after laser beam heating and melting is not obliged to lead to brittleness increase because of decrease amount of carbides. In other hand increase of hardness due to work hardening causes increase of dislocation density and lead to toughness decrease especially in presence of micropores. On the contrary stress relaxation proceeds by crack formation or/and by plastic deformation. Therefore high cavitation erosion resistance guarantees susceptibility of surface layer to work hardening. Kinetic of work hardening will influence on the damage progress due to cavitation. Cavitation erosion progress depends also on the depth of work hardening. If surface layer of eroded sample is hardened deeper due to cavitation loading material is split off on the bigger particles and volume loss rate is higher. For reasons mentioned above work hardening degree and depth of work hardening will be considered as a parameters describing cavitation erosion resistance of the laser processed samples and they will be compared with those parameters for not processed padding welds.

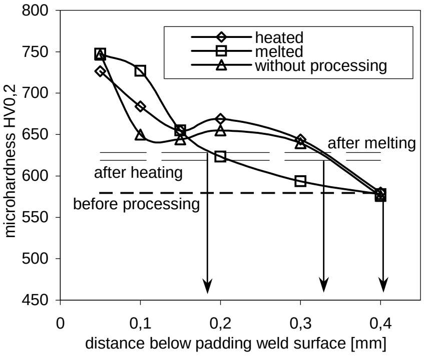

Fig. 9. Microhardness profiles of Fe-Cr-Mn padding weld after different kind of laser processing and 70 min of cavitation loading. Broken lines indicate hardness after laser processing and before cavitation erosion test

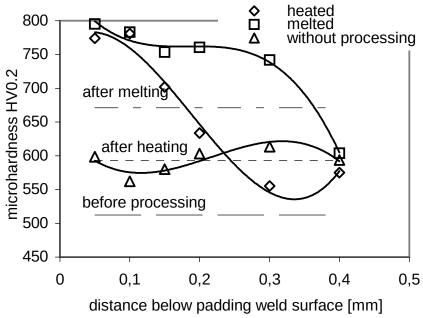

Fig. 10. Microhardness profiles of Fe-Cr-Co padding weld after different kind of laser processing and 70 min of cavitation loading. Broken lines indicate hardness after laser processing and before cavitation erosion test

Figs. 11-12 present microhardness changes due to laser processing and after 70 min of cavitation loading. Analysing those figures can notice that increase of hardness is much more due to work hardening, as a rule, than caused by laser processing.

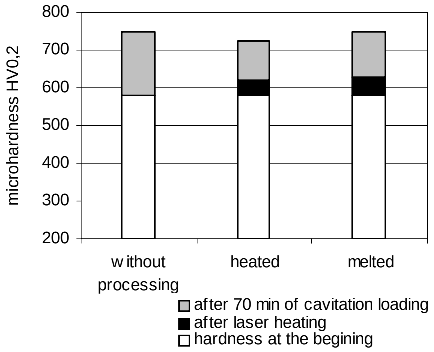

Fig. 11. Microhardness changes due to laser beam processing and cavitation loading for Fe-Cr-Mn padding weld

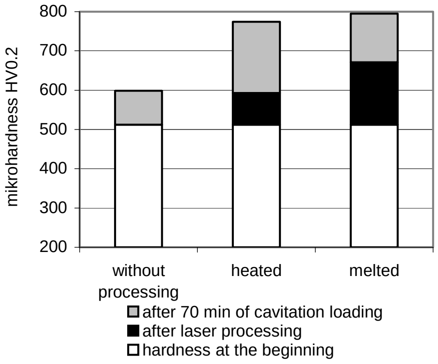

Fig. 12. Microhardness changes due to laser beam processing and cavitation loading for Fe-Cr-Co padding weld

Particularly high increase of hardness was revealed (Fig. 13) for not laser processed Fe-Cr-Mn padding weld subjected on the cavitation loading. Phase transformation can play significant role in this case. Many alloys do undergo phase transformation due to cavitation loading [13,32]. High susceptibility to transformation of manganese austenite in martensite was also reported in [22,31,34]. The martensitic transformation depends on the temperature, strain rate, stress state and composition of alloys [29]. That is why in many cases no simple quantitative correlation could be established between mechanical properties of eroded materials and their cavitation erosion resistance. Cavitation loading intensity influences also on the mutability of mechanical properties due to phase transformation. It should be noted that bubble collapse impingement is different from shock loading cases and acts only on a localizes surface of material.

For laser processed Fe-Cr-Mn padding weld decrease of work hardening degree was also observed. XRD diffraction measurements (Fig. 15) revealed that refinement of structure due to laser processing resulted delaying phase transformation. Laser

heating in solid state of surface resulted lower degree of fineness than laser melting and austenite transformation rate was higher. Faster phase transformation for the grinded surface of stainless steel, in comparison with remelted by TIG welding method was also reported in [33]. For laser melted regions of Fe-Cr-Mn padding weld work hardening was almost the same like for heated area (Fig. 13). So it could be inferred that work hardening degree of laser melted regions depends more from dislocation density increase than in laser heated case.

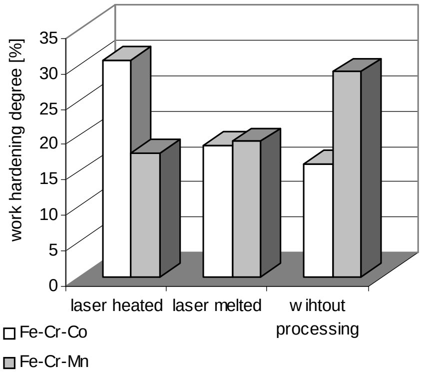

Fig. 13. Work hardening degree due to cavitation loading for Fe-Cr-Co and Fe-Cr-Mn padding welds after different kind of laser processing

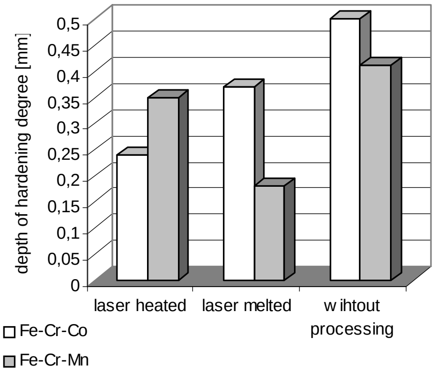

Fig. 14. Depth of work hardening due to cavitation loading for Fe-Cr-Co and Fe-Cr-Mn padding welds after different kind of laser processing

For laser processed Fe-Cr-Mn padding weld decrease of work hardening degree was also observed. XRD diffraction measurements (Fig. 15) revealed that refinement of structure due to laser processing resulted delaying phase transformation. Laser heating in solid state of surface resulted lower degree of fineness than laser melting and austenite transformation rate was higher. Faster phase transformation for the grinded surface of stainless steel, in comparison with remelted by TIG welding method was also reported in [33]. For laser melted regions of Fe-Cr-Mn padding weld work hardening was almost the same like for heated area (Fig. 13). So it could be inferred that work hardening degree of laser melted regions depends more from dislocation density increase than in laser heated case.

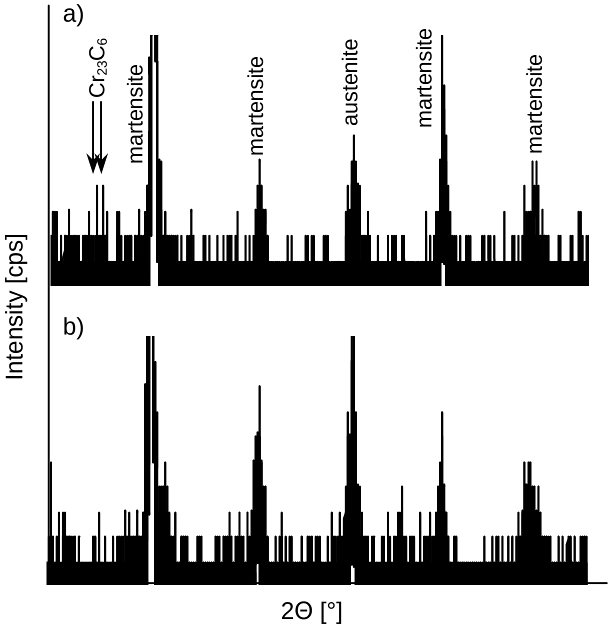

Fig. 15. Results of XRD diffraction measurements for Fe-Cr-Mn padding weld after 70 min cavitation erosion with (a) laser heated and (b) laser melted surfaces

Phase transformation for not processed Fe-Cr-Mn alloy was also observed. Mechanism of austenite - martensite transformation is identifiable by a triangular structures, resulting from sliding (see Fig. 16). The relaxation mechanism is equivalent to a stacking fault created as every two adjoining $(111)_{fcc}$ atomic planes displayed towards the $[112]_{fcc}$ direction. The triangular geometry is built up from three cross {111} planes [21] as a consequence of this relaxation mechanism.

Analysing Fig. 14 can notice that depth of hardening due to cavitation loading is the highest for not processed Fe-Cr-Mn alloy and the lowest for the laser melted one. This is because of higher initial hardness of laser melted padding weld than the Fe-Cr-Mn alloy without laser beam machining. Harder microstructure better resists cavitation loading especially in the first stage of cavitation erosion that is why depth of hardening is lower for laser processed material.

Observing case of Fe-Cr-Co alloy (Figs. 13-14) can notice that for not laser processed padding weld work hardening degree of surface layer subjected to cavitation loading is the lowest and the depth of work hardening is similar like for Fe-Cr-Mn alloy. Austenite → martensite transformation (see Fig. 17) is also responsible for work hardening of this alloy but its kinetic is different. In this case cobalt presence contributes to microstructure stabilization. Earlier investigations revealed (see Fig. 18) [26] that incubation time for both not processed alloys was the same. Nevertheless cavitation erosion of Fe-Cr-Mn alloy in second stage was faster. The faster damage under cavitation loading of this alloy could be induced by higher content of phosphor (0.069% for Fe-Cr-Mn and 0.016% for Fe-Cr-Co alloy) which resulted increase of Fe-Cr-Mn brittleness.

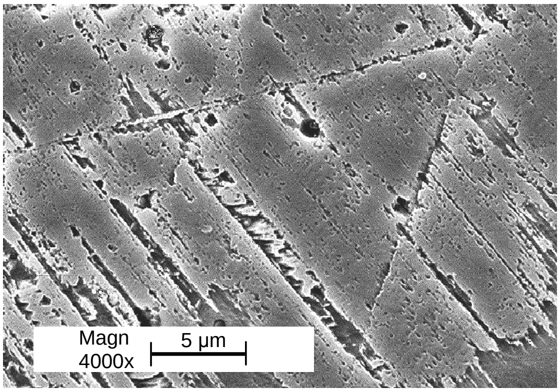

Fig. 16. Appearance of surface layer microstructure after 70 min of cavitation loading raveled for Fe-Cr-Mn padding weld

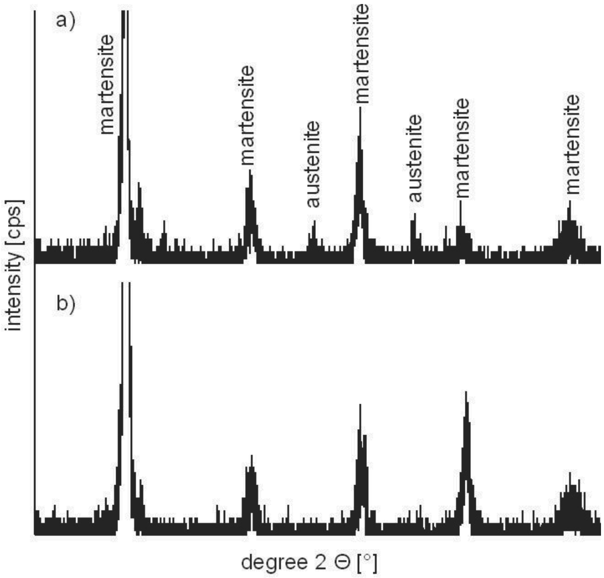

Fig. 17. Results of XRD diffraction measurements for Fe-Cr-Co not processed padding weld (a) before cavitation erosion test and (b) after 70 min of cavitation loading

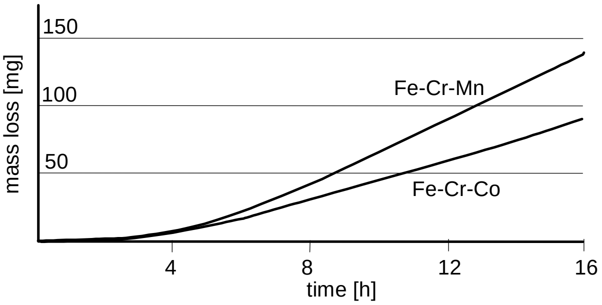

Fig. 18. The erosion curves mass decrease in time for samples covered with the Fe-Cr-Mn and Fe-Cr-Co coatings

4. Conclusion

Made investigations allow to draw some general conclusions concerning influence of laser beam processing and chemical composition on the cavitation erosion of Fe-Cr-Co and Fe-Cr-Mn padding weld:

1. Laser beam processing of Fe-Cr-Mn padding weld decrease of susceptibility to work hardening in comparison with not processed alloy.
2. Results revealed that for both alloys structure refinement due to laser processing contributes to delaying of austenite → martensite phase transformation. Kinetic of this transformation is different for investigated alloys and depends on the applied laser processing and chemical composition.
3. Laser melting of Fe-Cr-Co alloy results the highest increase of hardness in processed surface layer and decrease of susceptibility to work hardening in comparison with laser heating in solid state. Nevertheless in both cases of laser beam processing, depth of hardened surface layer was lower and susceptibility to work hardening was higher than for not processed alloy.

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