DOI: 10.1515/amm-2016-0216

E. JONDA*,#, Z. BRYTAN*, K. LABISZ*, A. DRYGAŁA*

THE INFLUENCE OF LASER SURFACE ALLOYING ON THE THERMAL FATIGUE RESISTANCE OF HOT WORK TOOL STEELS

The paper presents results of the effect of laser surface remelting and alloying by carbides powders of NbC, TaC, TiC, VC and WC on the structure and thermal fatigue resistance of the surface layer of hot work tool steels X40CrMoV5-1 and 32CrMoV12-28. The laser surface alloying and remelting treatments was performed using a high power diode laser (HPDL ROFIN SINAR DL 020). In order to investigate the effect of applied laser treatments and used alloying powders on the microstructure and thermal fatigue resistance of processed surface layer of hot work tool steels, the microstructure evaluation by light microscopy, hardness test, and dedicated thermal fatigue resistance test were performed. The best results regarding fatigue cracks inhibition was obtained when the surface of hot work tool steels was alloyed with TiC and VC carbides at the laser beam power of 2.0 and 2.3 kW. The grain refinement effect of laser remelting has a lower impact on the thermal crack inhibition, than a strong strengthening effect of matrix saturation in alloying elements and precipitation of fine carbides in the steel matrix.

Keyword: Hot work tool steel, laser surface remelting, laser surface alloying, thermal fatigue

1. Introduction

Existing research on the effects of laser radiation influence on steel properties have been shown that resulting microstructural and chemical composition changes in the surface layer are different from those occurring during a conventional heat treatment. For this reason the workpieces processed by laser radiation can achieve a high hardness, corrosion resistance, abrasion resistance and thermal fatigue of the surface layers [1-4].

Laser enrichment of the surface layer in alloying elements aims to modify properties a narrow surface layer zone of the base material due to dispersing or alloying process. The alloying elements (in a pure form or as compounds) can be preplaced on the metallic surface as a solid layer and then laser treated. The essence of such process is to melt applied layer and the base material by laser radiation, where a rapid heating of a small volume takes place, the materials are intensively mixed and then solidify with very fast cooling rate. As a result, a fine crystalline microstructure is formed and a considerable supersaturation in alloying elements of the solid solution takes place, as well as the metastable phase can be formed. The possibility of precise control of process conditions such as the scanning speed of the laser beam, the laser beam power, the type and thickness of the preplaced alloying layer, the shielding gas applied, etc., allows to achieve the alloyed layer with anticipated properties [5-8].

Apart from the required functional properties of laser treated surface, the laser surface processing is aimed to regenerate worn out machine parts, involving the reconstruction of the worn surface and the fill-up surface cracks or cavities. In case of properly selected processing conditions, it is possible to treat machine parts with high accuracy, virtually “ready to use”, without the need for additional finishing [9-11].

Thermal fatigue as well as creep resistance is one of the crucial factors influencing accelerated wear of metallic parts operating in hot working conditions at elevated temperature [12,13]. The thermal fatigue resistance of hot work tool steel and similar alloys can be greatly improved by laser surface remelting and alloying, thus repairing surface thermal cracks. Moreover, microstructural changes focused on grain refinement and strengthening mechanisms of carbides precipitations or strengthening of the fine non dissolved alloyed particles can produce super thermal fatigue resistance restraining propagation of the thermal cracks [5].

The major interest in the laser surface treatment of hot work tool and other alloyed steels is focused on the laser surface remelting (LSR) and laser surface alloying (LSA) resulting in increased surface thermal fatigue behaviour [5], higher wear resistance, increased surface hardness as well as changing some functional surface properties like adhesion or corrosion resistance [1]. Improved surface layer properties are obtained by LSA using carbide powders like TiC, WC, etc. [8,11], nitrides e.g. CrN [6], ceramic powder or alloyed powders e.g. Cr-Ni, FeCr, Cr-Cr2B [1,4,5,7].

The scope of the present paper is to evaluate the thermal fatigue resistance of two hot work tool steels X40CrMoV5-1 and 32CrMoV12-28 subjected to LSA with carbides NbC, TaC, TiC, VC, WC preplaced on the surface of the base material.

* SILESIAN UNIVERSITY OF TECHNOLOGY, INSTITUTE OF ENGINEERING MATERIALS AND BIOMATERIALS, FACULTY OF MECHANICAL ENGINEERING, 18 A KONARSKIEGO STR., 44-100 GLIWICE, POLAND

Corresponding author: ewa.jonda@polsl.pl

2. Experimental conditions

Investigations were carried out on the test pieces from the X40CrMoV5-1 and 32CrMoV12-28 hot work tool steels of the compositions according to PN-EN ISO 4957 standard. The studied steels were melted in the electric vacuum furnace at the pressure of about 1 Pa, cast into ingots weighing about 250 kg, and were roughed at the temperature range 1100-900ºC into the O.D. of 76 mm bars and 3 m long, which were soft annealed. The samples of the investigated steels were subjected to heat treatment consisting of quenching and tempering according to PN-EN ISO 4957 standard – as delivery state of hot work tool steel. Next, a powder layer of the NbC, TaC, TiC, VC and WC carbides with the inorganic binding agent was preplaced on the degreased base metal surface. The siliceous liquid glass consisting of the Na_4SiO_4 orthosilicate and $Na_2Si_2O_5$ sodium disilicate was used as a binding agent in the form of dens syrup.

The Rofin DL 020 high power diode laser (HPDL) was used for remelting and alloying with carbides of the X40CrMoV5-1 and 32CrMoV12-28 steels. The laser surface treatment was carried out using constant remelting and alloying scanning rate of laser - 0.5 m/min and laser beams power of 1.2, 1.6, 2.0 and 2.3 kW. The laser remelting and alloying were carried out under an argon shielding gas to prevent oxidation of preplaced a powder layer and the base metal surface. Metallographic investigations were made on the Leica MEF4A light microscope with the Leica-Qwin computer image analysis system at magnifications of 100 -1000x. Hardness tests were made on specimens subjected to laser surface remelting (LSR) and alloying (LSA) using the HPDL laser; making 10 measurements for each condition and calculating their average value. Hardness was measured on the ground and polished center of the face surfaces using Zwick ZHR 4150TK hardness tester, according to the standard PN-EN ISO 6508-1.

a)

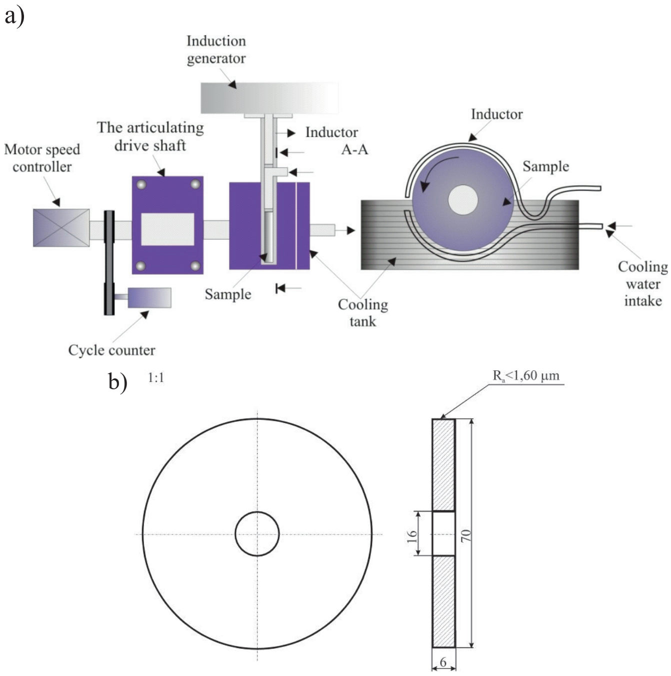


Fig. 1. a) Scheme of the stand for thermal fatigue investigations, b) Shape and size in [mm] of the sample for thermal fatigue investigations with the correspond roughness of the surface in [µm]

Thermal fatigue tests of the X40CrMoV5-1 and 32CrMoV12-28 steels were carried out on a dedicated test stand of the Institute of Engineering Materials and Biomaterials (Fig. 1a). The test pieces of flat cylindrical shape (Fig. 1b) were induction heated by a heating coil encompassing half of the test piece perimeter powered by the ELCAL REL – 15 induction generator with the current frequency of 400 kHz and maximum power of 15 kW. The test pieces subjected to 5000 thermal cycle were cut to metallographic examination along the main axis and the fatigue cracks were analyzed on the cross-section of the cylindrical sample. The average crack depth, (calculated as an average from 3 deepest cracks) and the number of cracks per 1 mm of the test piece length were assumed as criteria specifying the thermal fatigue resistance of the investigated steels.

3. Results and discussion

Investigations of hot work tool steels X40CrMoV5-1 and 32CrMoV12-28 revealed a clear effect of applied laser beam power, for tested laser beam power: of 1.2; 1.6; 2.0 and 2.3 kW, on the surface layer shape and the thickness of the laser treated zone (Figs. 2 and 3).

a)
b)

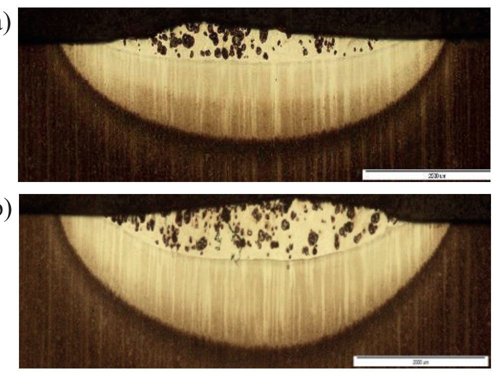


Fig. 2. The cross - section of the surface layer of X40CrMoV5-1 steel alloyed with WC powder, a) laser power 1.2 kW, b) laser power 2.3 kW

a)
b)

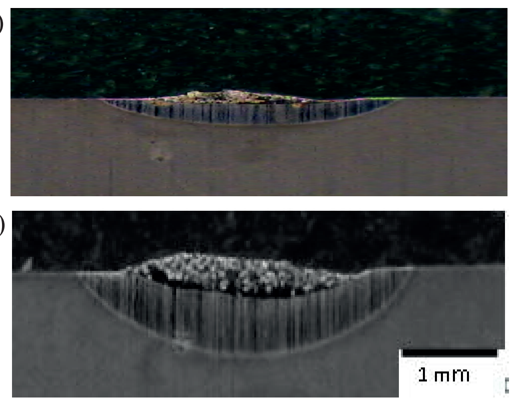


Fig. 3. The cross - section of the surface layer of 32CrMoV12-28 alloyed with WC powder, a) laser power 1.6 kW, b) laser power 2.3 kW

The laser surface alloying using carbide powders preplaced on the base metal surface in a form of paste results in a surface layer composed of different zones. Starting from the top of laser treated surfer, the first zone located at the top layer is rich in non-dissolved powder particles (Fig. 6a). The second zone identified as the melting zone (RZ) is enriched in alloying material (depending on the type of applied powder WC, VC, TaC, TiC, NbC). The third zone is a heat affected zone (HAZ). Next, the transition zones between the remelting zone and the heat affected zone, and between the heat affected zone and the base metal can be observed (fig. 6b). The thickness of the melted zone (RZ) and heat affected zone (HAZ) on a constant laser scanning rate of the laser beam and a constant paste thickness of preplaced layer mainly depends on the applied laser power (Fig.4). The powders characteristics associated with absorption of energy generated by the laser beam also plays an important role influencing achieved remelting depth. The laser beam power affects also the shape of the bottom of remelted zone and the convexity of laser weld bead, which is influenced by strong movements of the solidifying metal, gas pressure, the amount of supplied powder material as well as the laser beam power. When using higher laser beam power during laser surface alloying there appears a strong convexity of laser weld bead face surface, and on the fusion line forms a numerous spatters and discontinuities (Figs. 5 and 6).

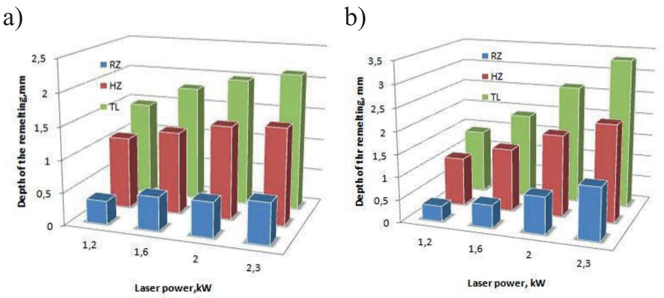


Fig. 4. Influence of the laser beam power on the thickness of individual zones in LSA X40CrMoV5-1 steel surface, where RZ - the remelting zone, HZ - heat affected zone and TL - top layer, a) alloying with WC, b) alloying with NbC powders

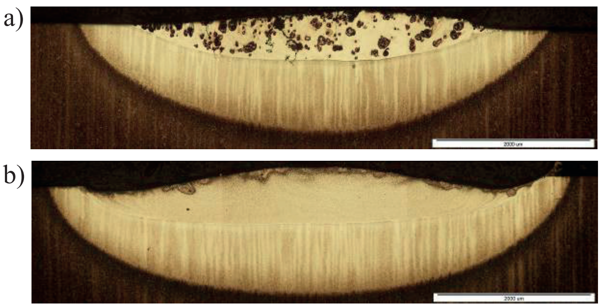
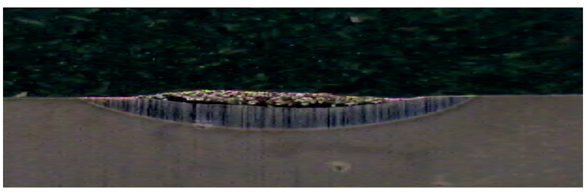


Fig. 5. The cross - section of laser surface alloyed X40CrMoV5-1 steel after laser alloying with a) WC powder and b) VC powder at laser beam power of 2.3 kW

a)



b)

Fig. 6. The cross - section of laser surface alloyed 32CrMoV12-28 steel after laser alloying with a) WC powder and b) VC powder at laser beam power of 2.3 kW

Studied hot work tool steel after laser remelting (Fig. 7a) and laser alloying (Fig. 7b) shows fine dendritic microstructure where on the fusion line the epitaxial grows of newly formed crystals can be observed and the dendrites main axis are oriented along the direction of the heat transfer. The specific band of fine dendrites (Fig. 8b) occurring between the remelted zone (RZ) and the heat affected zone (HAZ) was solidified at the beginning of the crystallization process, just after the stop of the laser beam radiation during laser treatment and one the fusion line is composed of partial melted grains of heat affected zone. The small grain size in this region can be associated with the initiation of solidification process that's beginning on dissolved carbide particles. The direction of crystal grows replay the direction of the greatest temperature gradient connected with heat removal through the entire mass of the sample that transfer the heat from the laser remelting process.

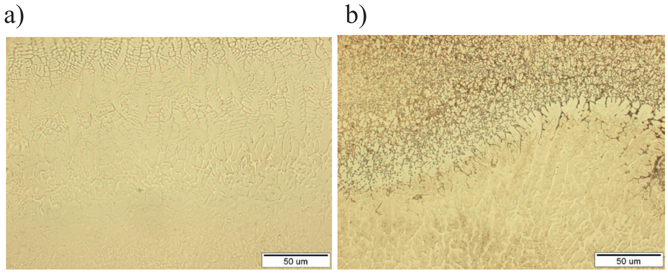


Fig. 7. The fusion line of laser threated X40CrMoV5-1 steel, a) after laser remelting, laser beam power of 1.6 kW, b) after laser alloying with TiC powder, laser beam power of 1.6 kW

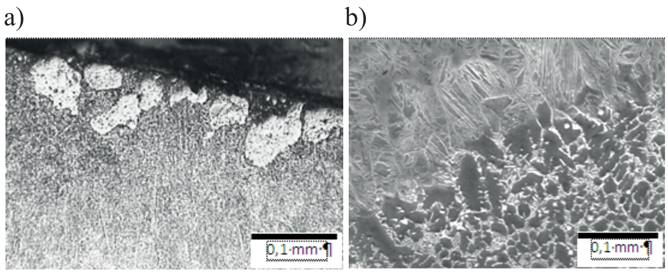


Fig. 8. The cross-section of laser surface alloyed of X2CrMoV12-28 steel at laser beam power of 1.6 kW, a) the top layer after alloying with TaC powder, b) the fusion line after alloying with TiC powder

Basing on hardness test for X40CrMoV5-1 steel after laser surface remelting and alloying it was revealed that maximum hardness of about 62 HRC was obtained for surface alloyed with TiC carbide for the highest studied laser beam power of 2.3 kW (tab. 1). Similar high hardness was achieved for VC carbide at laser beam of 2.0 kW. Comparing the hardness of hot work tool steel in delivery state (53.9 HRC), and after surface remelting and alloying it was found that hardness increase proportionally to applied laser beam power. For all analyzed carbide powders the higher hardness (60 to 62 HRC) was achieved for the highest analyzed laser beam power of 2.3 kW.

In most cases, the hardness of the surface layer of hot work tool steel 32CrMoV12-28 subjected to laser alloying with carbide powders increased in comparison to the delivery state and steel surface subjected to a laser surface remelting (tab. 2). The highest increase in hardness (67 HRC) for 32CrMoV12-28 steel was achieved when alloyed with TaC carbide. The exception to the rule that laser alloying with studied carbides increase the surface hardness was observed for TiC carbide at laser beam powers of 2.0 and 2.3 kW. This phenomenon can be correlated to the high reactivity of titanium that easily combine with oxygen and argon to form titanium oxides that will evaporate from the welded pool at high laser beam energy (2.0 and 2.3 kW). The shielding gas applied seems insufficient for these laser treatment conditions. The overall amount of remaining titanium seems to be too small to effectively precipitate titanium carbides in order to strengthen the alloy matrix. Additionally, the weak strengthening effect is deepened by reaching aging temperature in the alloyed zone, thus the quenching and aging effects of the hot work tool steel at delivery state were fully eliminated and steel surface shows lower hardness values than in as delivery state (after quenching ad aging heat treatment).

Investigations concerning thermal fatigue resistance of the laser treated hot work tool steels has shown that the laser remelting and alloying with different carbide powders have a significant impact on increasing the resistance to thermal fatigue process of hot work tool steels. This conclusion can be drawn based on the crack depth measurements (Fig. 9).

a) b)

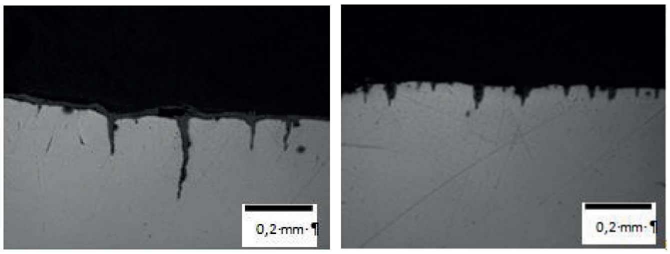


Fig. 9. The cracks on the surface layer cross section after thermal fatigue test of X40CrMoV5-1 steel after laser surface alloying with WC powder with the laser beam power of a) 1.6 kW and b) 2.0 kW

Basing on the crack length measurements after laser surface remelting the amount of surface defects is slightly reduced when compared to the surface after laser alloying with different carbides (Fig. 10). The lowest thermal fatigue resistance shows the surface layers modified by laser remelting and alloying with WC powder, within the entire range of studied laser beam power. The grain refinement effect of the remelting process has a lower impact on the

TABLE 1

The hardness results of laser surface remelted and alloyed X40CrMoV5-1 steel

Laser beam power, kW	Hardness of the surface layer, HRC						
	Base material X40CrMoV5-1						
	Delivery state	As remelted	Alloyed with:				
			WC	VC	TiC	TaC	NbC
1.2	53.9	53.9-54.7	54.6-56.9	55.1-56.2	54.7-56.3	55.9-57.9	53.9-55.9
		54.5	55.6	55.1	55.3	56.7	55.1
1.6		54.9-57.6	56.8-58.1	60.3-62.1	55.6-57.8	57.5-59.6	54.2-57.5
		56.0	57.5	55.5	56.4	58.8	55.5
2.0		56.3-57.1	57.1-58.6	61.9-63.4	56.5-59	57.9-58.9	55.4-58.7
		56.8	57.9	62.6	57.5	58.4	56
2.3		57.2-58.4	57.8-59.6	61.6-63.1	61.5-63	59.4-61.5	57.3-60
		57.5	58.7	59.3	62.1	60.3	59.3

TABLE 2

The hardness results of laser surface remelted and alloyed 32CrMoV12-28 steel

Laser beam power, kW	Hardness of the surface layer, HRC						
	Base material 32CrMoV12-28						
	Delivery state	As remelted	Alloyed with:				
			WC	VC	TiC	TaC	NbC
1.2	51.8	53.6-55.4	56.3-58.9	56.3-58.3	52.1-54.6	64.5-66.7	54.6-56.8
		54	58	57	53	64	56
1.6		54.5-56.8	57.1-59.1	56.3-57.9	51.3-53.8	64.3-67.4	54.8-58
		55	58	57	52	64	57
2.0		55.8-57.8	57.4-60.4	56.8-59.8	39.3-45.8	65.5-67.8	59-61.3
		57	59	58	43	64	59
2.3		55.4-58.4	58.5-61.4	57.2-59.7	39.2-41.3	66.5-67.8	59.3-61.5
		57	59	59	40	67	60

thermal crack inhibition, than a strong strengthening effect of matrix saturation in alloying elements and precipitation of fine carbides in the steel matrix. Precipitations of fine and uniformly distributed carbides in remelted zone delay crack propagation. This effect was most noticeable for VC, TiC and TaC carbides when laser alloying with the highest laser beam power of 2.3 kW was applied.

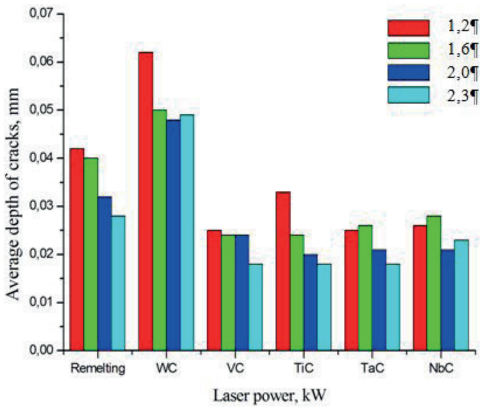


Fig. 10. Comparison of average crack depth in X40CrMoV5-1 steel surface layer after laser remelting and alloying with different carbide powders

Regarding the steel 32CrMoV12-28 the highest resistance to thermal fatigue was observed for surface layers alloyed with VC powder and TiC powders. In this case only small and difficult to observe cracks were revealed. The best thermal fatigue resistance of tested steels was observed for surface layers alloyed with WC, TaC and NbC powders. It was also found that there is a relationship between applied laser beam power and the size and number of forming cracks. When alloying X40CrMoV5-1 steel the lowest crack depth was registered for laser beam power of 2.0 kW for all kinds of tested carbide powders, while in case of 32CrMoV12-28 steel it was similar with two exceptions for NbC and WC carbides. Figure 11 shows the average depth of the cracks for the 32CrMoV12 -28 laser alloyed steel with carbide powders subjected to the thermal fatigue test.

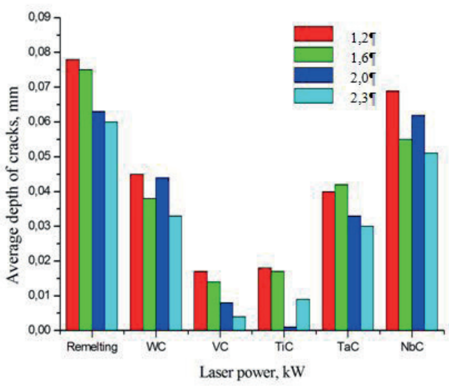


Fig. 11. Comparison of average crack depth in 32CrMoV12-28 steel surface layer after laser remelting and alloying with different carbide powders

4. Summary

Basing on the presented studies of laser surface remelting and alloying of hot work tool steels X40CrMoV5-1 and 32CrMoV12-28 it was found that in surface layer exists: a remelted zone (RZ), the heat affected zone (HAZ) and transient zones between remelted layer and heat affected layer and between HAZ and the base material. The thickness of remelted layer and heat affected zone depends on the applied laser beam power. Together with the increase of laser beam power the thickness of remelted and heat affected zone increase, that is connected with the absorption of laser beam radiation be the sample surface. In both cases X40CrMoV5-1 and 32CrMoV12-28 steels, the hardness of the laser remelted and alloyed surface layer increases compared to the hardness of the steels in as delivery state, and its growth depends on the laser beam power and thus the energy of laser remelting and alloying. The lowest resistance to thermal fatigue was revealed in surface layers of X40CrMoV5-1 after laser alloying with WC carbide in the entire range of applied laser beam power, when compared to steel in as delivery state. A similar effect was observed for 32CrMoV12-28 steel where the least resistance to thermal fatigue show the surface layers obtained by alloying with NbC and WC carbides. The best results regarding fatigue cracks inhibition effect was obtained when the surface of hot work tool steels was alloyed with TiC and VC carbides at high laser beam power of 2.0 and 2.3 kW. The grain refinement effect of laser remelting has a lower impact on the thermal crack inhibition, than a strong strengthening effect of matrix saturation in alloying elements and precipitation of fine carbides in the steel matrix.

Acknowledgments

The author gratefully acknowledges the financial support from the National Science Centre granted based on the decision number DEC-2011/01/B/ST8/06648. This publication was co-financed by the Ministry of Science and Higher Education of Poland as the statutory financial grant of the Faculty of Mechanical Engineering SUT.

REFERENCES

[1] Z. Brytan, M. Bonek, L.A. Dobrzanski, Adv Mat Res **291-294**, 1425-1428 (2011).

[2] M. Brown, C.B. Arnold, Springer **4**, 91-121 (2010).

[3] W.M. Steen, J. Mazumder, Laser Material Processing, Springer, 2010.

[4] X. Tong, M.J. Dai, Z. Zhang, Appl Surf Sci, **271**, 373-380 (2013).

[5] C. Dalong, H. Zhou, R. Hong, Z. Zhenan, R. Haifeng, M. Luquan, W.Ch. Chao, Opt Laser Eng, **54**, 55-61 (2014).

[6] M.S. Rahman, T. Katsuma, D. Yonekura, R.I. Murakami, Int J Mod Phys B, **24**, (15-16), 2502-2505 (2010).

[7] M.K. Zhang, G.F. Sun, Y.K. Zhang, C.S. Liu, X.D. Ren, A.X. Feng, W. Zhang, Laser Eng, 27, (3/4), 231, (2014).

[8] D. Janicki, Sol St Phen, **199**, 587-592 (2013).

[9] T. Tanski, E. Jonda, K. Labisz, L.A. Dobrzanski, Toughness of laser treated surface layers obtained by alloying and feeding of ceramic powders (Chapter 5) in: Sam Zhang (Ed.) Advances in Materials Science in Engineering, Nanyang Technological University, Singapore (2015).

[10] M. Bonek, L.A. Dobrzański, Mater Sci Forum. **654-656**, 1848-1851 (2010).

[11] L.A. Dobrzański, M. Bonek, A. Klimpel, A. Lisiecki, Mater Sci Forum. **437-438**, 69-72 (2003).

[12] L.A. Dobrzanski, M. Czaja, W. Borek, K. Labisz, T. Tanski, Int J Mater Prod Tec. 51, (3), **264-280**, (2015).

[13] A. Zieliński, G. Golański, M. Sroka, Kovove Mater. **54**, (1), 61-70 (2016).