Inclusions in metallic materials as origin for microcraters formation at a pulsed electron-beam surface melting

D A Shepel, A B Markov, E V Yakovlev and V I Petrov
Tomsk Scientific Centre SB RAS, 10/4, Akademichesky Ave., Tomsk, 634055, Russia

E-mail: dashepel@lve.hcei.tsc.ru

Abstract. In the present work, the effect of difference between thermal properties of the base material (matrix) and inclusion on the temperature behavior of the target in the regions of inclusion locations has been considered. The calculations were based on the solution of two-dimensional nonlinear nonstationary heat equation. It has been shown that the most strong effect on the temperature field takes the difference between heat conductivities of the matrix and inclusion. The simulations of temperature fields have been carried out on the real systems matrix-inclusion, namely, stainless steel 316 L/manganese sulfide (SS 316L/MnS), TiNi/Ti2Ni, TiNi/TiC. The results obtained allows suggestion on the origin of microcraters appearing at the irradiated surface as a result of thermocapillary convection in overheated sites of location of inclusions.

1. Introduction
The low-energy high-current electron beams (LEHCEB) are promising instrument for the applications in various branches of industries [1, 2]. The purpose of the LEHCEB treatment is to improve the surface properties, for example, to increase the corrosion or wear resistance as well as the level of breakdown fields between conductive surfaces in vacuum [3]. However, the application of the LEHCEB technologies has some difficulties, the reason is the uncontrollable microcraters formation at the treated surface. Earlier it has been determined that microcraters are formed at the places of the locations of second phases inclusions. However, the mechanisms and processes of microcraters formation are still intensively investigating and discussing [4-6].

From viewpoint of both theoretical and experimental investigations, it is important to know the temperature field of the target irradiated by LEHCEB. This knowledge is important in many cases, for instance for revealing the thicknesses of hardened and heat-affected zones when treating of steels or for prediction of thermomechanical stresses arising in materials, which can lead to its destruction [7]. Obviously in common materials which are not super-pure ones there is always some share of impurities located, as a rule, in the form of inclusions. This inclusions presenting in the near-surface layer can affect noticeably both on temperature distribution and dynamics of melting process at the local surface areas [8].

Mathematically the presence of the inclusions of second phases in the near-surface layer means that it is necessary to use the two sets of thermal properties: (1) for matrix material and (2) for inclusion material when solving the heat diffusion equation. There is the ratio between these sets of properties, which determines how significant the inclusions will affect on heat regimes induced by LEHCEB irradiation. The purpose of the work was to investigate the influence of the ratio between the sets of...
thermal properties on temperature distribution along the irradiated surface and dynamics of the melting.

2. Method and parameters of calculation

The calculation algorithm used in the work has been utilized earlier for prediction of temperature fields for the following systems 316L stainless steel (matrix) – manganese sulfide (inclusion) (SS 316L/MnS), (TiNi/Ti$_2$Ni) and described elsewhere [8,9].

We picked for the calculations the 316L stainless steel. Its properties as well as the properties of the other elements used in calculations are listed in table 1. At the first stage of the calculations we assumed that all thermal properties of the matrix (316L) and the inclusion are the same except for one that varied over a wide range. In such a way, we have investigated the impact of each property, namely, heat capacity, heat conductivity, and latent heat of melting on the heat regime of LEHCEB irradiated target, in particular, on temperature distribution over the irradiated surface.

The beam parameters were as follows: pulse duration 4 $\mu$s, electron energy 30 keV. The values of the beam current density were chosen in such a way that the initial melting regime was realized. The letter is characterized by the formation of a layer of molten material with a thickness of ~1 $\mu$m on the irradiated surface. The initial melting mode was realized at the LEHCEB energy densities of 3, 2.4, and 2.5 J/cm$^2$, for SS 316L/MnS, TiNi/Ti$_2$Ni TiNi/TiC systems, respectively. It was assumed that the beam parameters remain constant during the irradiation process.

Table 1. Thermal properties of materials.

| Material   | $\rho$, kg/m$^3$ | $c$, J/(kg K) (at 300 K) | $k$, W/(m K) (at 300 K) | $T_m$, K | $L_m$, kJ/kg |
|------------|-----------------|--------------------------|--------------------------|----------|--------------|
| SS 316L    | 8000            | 500                      | 16.3                     | 1693     | 247          |
| MnS        | 4000            | 582.8                    | 2                        | 1803     | 287          |
| TiNi       | 6450            | 438.6                    | 18                       | 1583     | 318.8        |
| Ti$_2$Ni   | 6000            | 485.4                    | 15                       | 1288     | 406.74       |
| TiC        | 4900            | 697                      | 10                       | 3400     | 1095         |

3. Results and discussion

Figure 1 shows the temperature distribution curves calculated for different ratios of the heat capacities of the matrix and the inclusion. For the case of equal heat capacities (curve 3), the temperature distribution is homogeneous (straight line), which obviously and should be observed. With an increase the heat capacity of the inclusion (curves 1 and 2), the temperature in the region of its location is lower than that far from the inclusion, i.e. underheating of the inclusion is observed. If, however, the heat capacity of the inclusion decreases with respect to the matrix, then an overheating of the inclusion is observed (curves 4 and 5). It can be seen from the figure that curves 1, 2, 4 and 5 are located almost symmetrically with respect to curve 3. However, the maximum temperature deviation $\Delta T$ with respect to curve 3 corresponding to the curve 1 is 47 K or 2.5% only.

The influence of the ratio of the thermal conductivities of the matrix and the inclusion on the temperature distribution along the irradiated target surface is shown in figure 2. For the case of equal thermal conductivities (curve 3), the distribution is homogeneous, as in the case of heat capacity. With an increase in the thermal conductivity of the inclusion, the temperature in the region of its location is lower than that far from the inclusion, i.e. underheating of the inclusion (curves 1 and 2) is observed. If, however, the thermal conductivity of the inclusion decreases with respect to the matrix, then the overheating of the inclusion is observed (curves 4 and 5). It can be seen from the figure that the symmetry of curves 1, 2 and 4, 5 relative to curve 3 is absent in this case and the observed overheating is several times higher than underheating. The maximum temperature deviation $\Delta T$ with respect to curve 3 corresponding to the curve 5 is 425 K or 22.5%, which is an order of magnitude larger than that for the heat capacity.
Figure 1. Temperature distribution over the irradiated surface depending on ration of heat capacities of matrix and inclusion ($c_{\text{incl}}/c_{\text{matrix}}=2;1.5;1;0.5$ and 0.25 for curves (1-5), respectively).

Figure 2. Temperature distribution over the irradiated surface depending on ration of heat conductivities of matrix and inclusion ($k_{\text{incl}}/k_{\text{matrix}}=4;2;1;0.5$ and 0.25 for curves (1-5), respectively).

Figure 3 shows the temperature distribution curves calculated for different ratios of the latent heats of melting of the matrix and the inclusion. For the case of equal latent heats of melting (curve 3), the distribution is homogeneous. When the latent heat of melting of inclusion is increased, the temperature in the region of its location is lower than that far from the inclusion, i.e. underheating (curves 1 and 2) is observed. If, however, the latent heat of melting of the inclusion decreases with respect to the matrix, then the overheating of the inclusion is observed (curves 4 and 5). It can be seen from the Figure that the symmetry of curves 1, 2 and 4, 5 with respect to curve 3 is also absent in this case, and the observed underheating for latent heat of melting is several times greater than overheating. The maximum temperature deviation $\Delta T$ with respect to curve 3 corresponding to the curve 1 is 197 K or 10.4%, which is less than for thermal conductivity, but several times greater than for heat capacity.

Thus, the results of calculations carried out for estimation of the effect of each of the thermal properties on thermal regime have shown that they have a significant effect on the temperature distribution along the irradiated surface, especially the thermal conductivity and latent heat of melting.

The calculated curves of overheating for real matrix-inclusion systems are shown in figure 4. Figure shows the temperature distribution along the LEHCEB irradiated surface for the systems (1) matrix of 316L stainless steel with inclusion of manganese sulfide (SS 316L/MnS), (2) matrix of titanium nickelide with inclusion of titanium carbide (TiNi/TiC), (3) matrix of titanium nickelide with
The inclusion of Ti$_2$Ni (TiNi/Ti$_2$Ni). It can be seen that all three curves have a temperature maximum in the location of the inclusion. The maximum overheating for SS 316L/MnS is 283 K (curve 1) is explained by the fact that the thermal conductivity of the inclusion is substantially lower than that for the steel. For TiNi/TiC target, the overheating value is 45 K (curve 2), which is explained by the lower thermal conductivity of the inclusion, but its higher heat capacity relative to that for titanium nickelide. The overheating of the target TiNi/Ti$_2$Ni at the location of the inclusion is insignificant and equals 12 K only (curve 3), which is explained by the slight difference in the values of the thermal properties of these materials. Thus, it can be seen that the ratio of the thermophysical properties of the matrix and the inclusion has a significant effect on the thermal regime of the target.

Figure 3. Temperature distribution over the irradiated surface depending on ration of latent heat of melting of matrix and inclusion ($L_{\text{incl}}/L_{\text{matrix}}=4;2;1;0.5$ and 0.25 for curves (1-5), respectively).

Figure 4. Temperature overheating distribution over the irradiated surface for SS 316L/MnS (1), TiNi/TiC (2) и TiNi/Ti$_2$Ni (3).

The results obtained allows suggestion on the origin of microcraters appearing at the irradiated surface as a result of thermocapillary convection in overheated sites of location of inclusions.

4. Conclusions
As a result of simulation of the temperature fields, it was shown that the effect of inclusion on the target heat regime depends strongly on the ratio of the thermal properties of the matrix and the inclusion. It was found that different thermophysical properties to varying degrees affect the
temperature distribution. The greatest influence on the temperature distribution is due to the thermal conductivity and the latent heat of melting.

Detailed calculations of the temperature fields under the influence of the LEHCEB for three systems have been carried out: SS 316L/MnS, TiNi/Ti2Ni, TiNi/TiC.

In addition, on the basis of the analysis carried out in this paper, knowing the thermal properties of matrix and inclusion, one can predict in detail the degree of influence of the inclusion on the heat regime of the target. The results obtained are consistent with the results of experiments presented in the literature [6].

The results obtained allows suggestion on the origin of microcraters appearing at the irradiated surface as a result of thermocapillary convection in overheated sites of location of inclusions.

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