Effect of thermal convection in the subsurface molten layer on its thickness

Abstract

Earlier the authors showed that the molten layer thickness can be effectively increased only by raising the accelerating voltage of the electron beam used as a penetrating heat load source for temperature treatment of metal surfaces. This conclusion was drawn on condition that thermal conduction is the only heat transfer mechanism inside the molten layer medium. One can assume that thermal convection in the melt medium, when under the forces caused by the temperature gradient in the molten zone depth, might contribute essentially to heat transfer in a sample increasing considerably the molten layer thickness and, hence, modifying deeper the thermally treated surface.

By comparing the experimental and calculation data on thermal treatment of a double-layer sample (2.5 μm Ni on steel substrate) it is shown that under conditions necessary for hardening of the metal surface layer (intensive and fast heating during a short pulse and maximum cool-down rate within the time comparable with the pulse length) the convective mechanism does not have a marked effect on the thickness of the hardened layer. It is also shown that the thermal convection in the melt, because of its rather slow development, might only enlarge the melt zone after removal of heat load at times longer than the pulse duration by an order of magnitude. But these processes are characterized by much lower temperature rates, that is why they can not change the material crystal structure, as required.

Keywords: subsurface modified layer, grain size, cool-down rate, penetration depth, accelerating voltage, melting depth, recrystallization, thermal convection

Introduction

Transportation of thermal energy deep into a sample is the determining factor in an increase in the thickness of the molten and recrystallized layer. There exist two main ways to bring the heat deep inside a sample: by penetrating electrons releasing their energy volumetrically and by the thermal conduction in material. Besides, the convective flow inside the melt observed during experiments with long-pulses (more than 300 μs) [1] might also transfer the energy inside the sample

The purpose of this study is to investigate the role of this particular mechanism of heat transfer (convective mixing of the melt) in the quasi-adiabatic regimes of materials treatment, which are characteristic for short pulses (not exceeding 50 μs) of heat loading.

For this purpose numerical calculation were done for a double-layer Ni-steel sample where the mixing zone can be found more definitively by defining the Ni material distribution in the depth of the treated double-layer sample.

Numerical Study

The calculation was made for a double-layer sample (2.5 μm Ni layer deposited on 1mm steel C60 substrate). The beam energy in the experiment amounted to 80 keV and 140 keV. The calculations were made in the non-linear and non-steady-state formulation of the thermal conduction problem the mathematical model and the details of which were reported in our previous paper [6]. So attention here is focused only on the basic physical processes which are the main features of the developed model:

- non-equilibrium evaporation of Ni or steel from the sample surface producing a vapour cloud;
- shielding effect by evaporated material;
- material melting/crystallization inside the depth of the condensed material phase;
- temperature dependence of the thermophysical properties of the sample material;
- real distribution of thermal load penetrating in depth of the subsurface layer of a sample.

Heat load distribution in penetration depth (obtained by Monte-Karlo method) is shown in Fig. 1. The distribution was obtained for a beam accelerating voltage of 80keV and a current density of 1 A/cm^2. For other values of current density, with the accelerating voltage remaining constant (80 keV), the heat release distribution in depth remains unchanged, with the absolute value scaled to the ratio of the real beam current density to the value taken as the tabulated one (1 A/cm^2).

As seen from the heat load distribution in Fig. 1, the electron penetration depth defined by the generally recognized method [4] amounts to 10 μm.

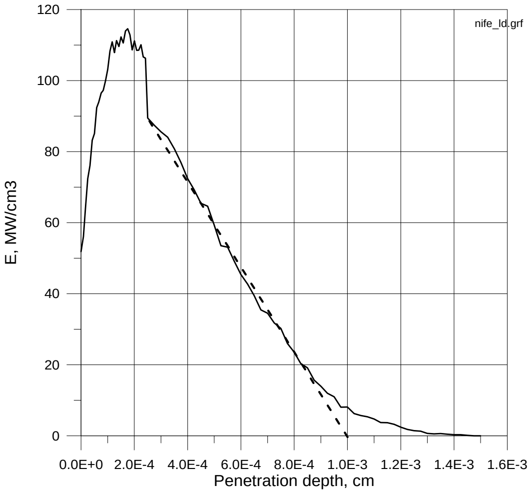


Fig. 1. Heat load distribution in double-layer sample (2.5μm Ni+1mm C60) at 80keV and 1A/cm^2

The temperature dependence (up to 1300 °C) of thermal conductivity and heat capacity for Ni is presented in Figs. 2 and 3, for steel C60 (up to 1000°C) in Figs. 4 and 5. Since the reliable data at higher temperature are lacking, the values of Ni and steel C60 properties were taken as constant in this temperature range.

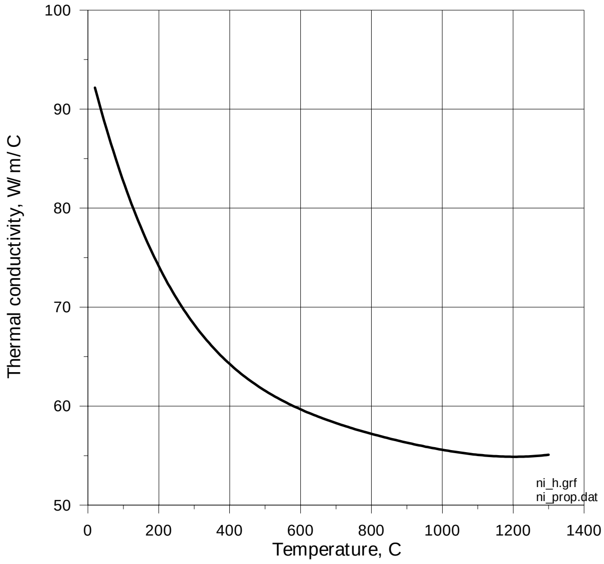


Fig. 2. Temperature dependence of thermal conductivity for Ni

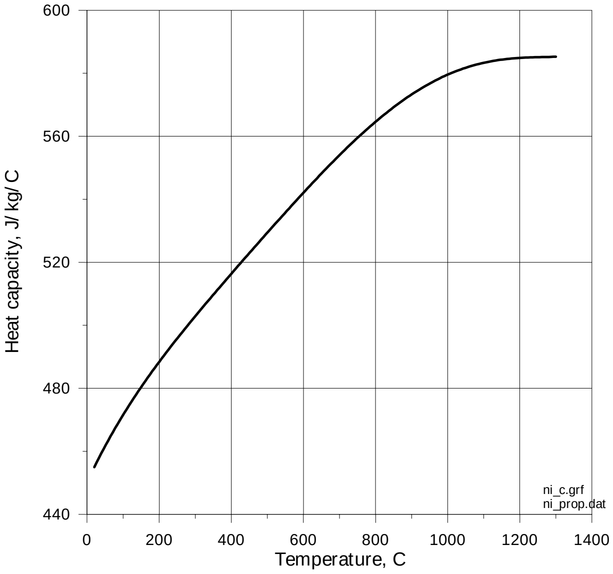


Fig. 3. Temperature dependence of heat capacity for Ni

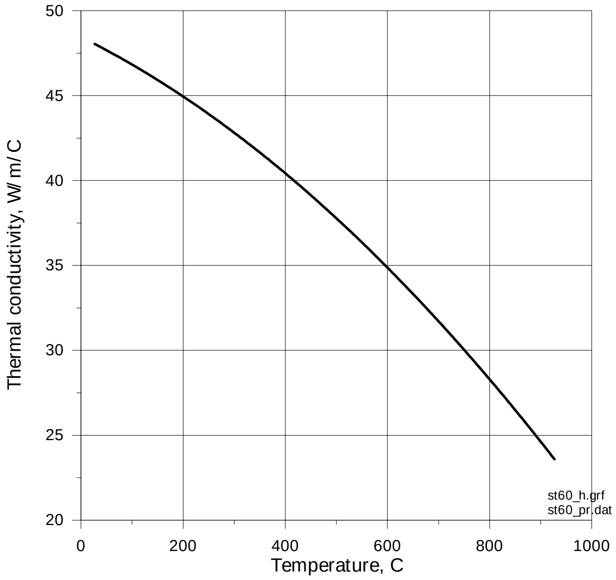


Fig.. 4. Temperature dependence of thermal conductivity for steel C60

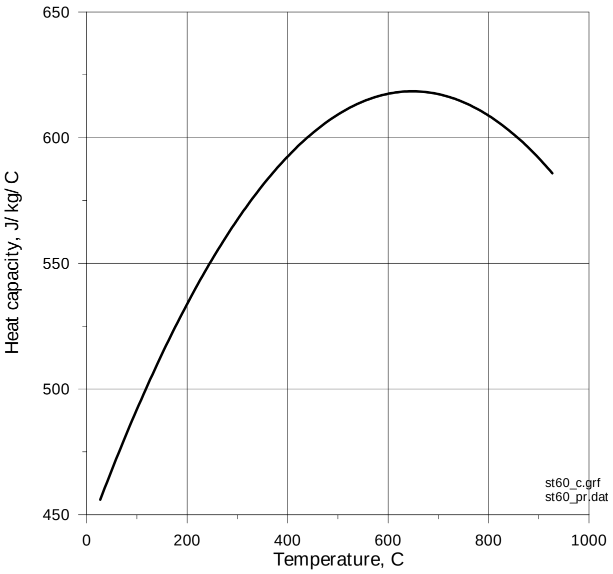


Fig. 5. Temperature dependence of heat capacity for steel C60

The values of thermophysical properties of Ni and steel C60 taken as temperature-independent are given below [3]:

	Ni	steel C60
Density, kg/m^3	8900	7700
Emissivity factor	0.6	0.28
Sound velocity, m/s	5000	6680
Evaporation heat, J/kg	$7.2\cdot10^6$	$6.30\cdot10^6$
Melting heat, J/kg	$3.05\cdot10^5$	$2.70\cdot10^5$
Boiling temperature, °C	2800	3030
Melting temperature, °C	1450	1540

Numerical simulations were performed for the following e-beam parameters:

Current density, A/cm^2	0.5 ÷ 2.0
Accelerating energy, keV	80 ÷ 140
Pulse duration, µs	25

The above formulated problem was solved by the specially developed calculation program package.

Test Results

Fig. 6 shows the results of computation of the tested sample temperature state for two moments: (a) at the end of the pulse and (b) at the time when the molten zone is maximum.

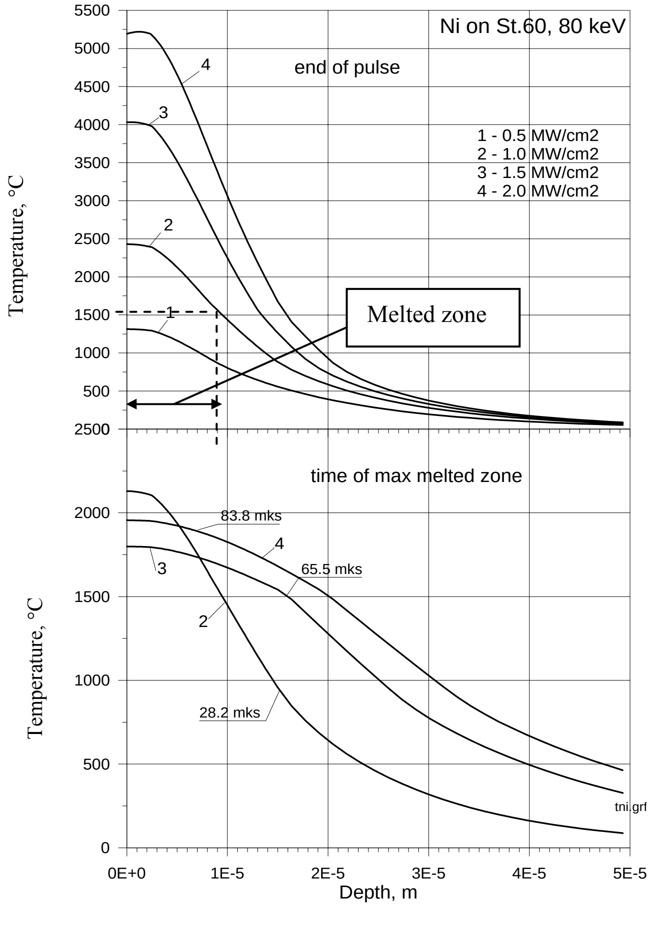


Fig. 6. Temperature state of the double-layer sample for different heat fluxes (a) at the end of the pulse and (b) at the time when the molten zone is maximum.

Fig. 7 shows the melting depth corresponding to the above-shown temperature distribution (see Fig. 6) as a function of beam power density for the same two time moments: (a) at the end of the pulse and (b) at the time when the molten zone is maximum.

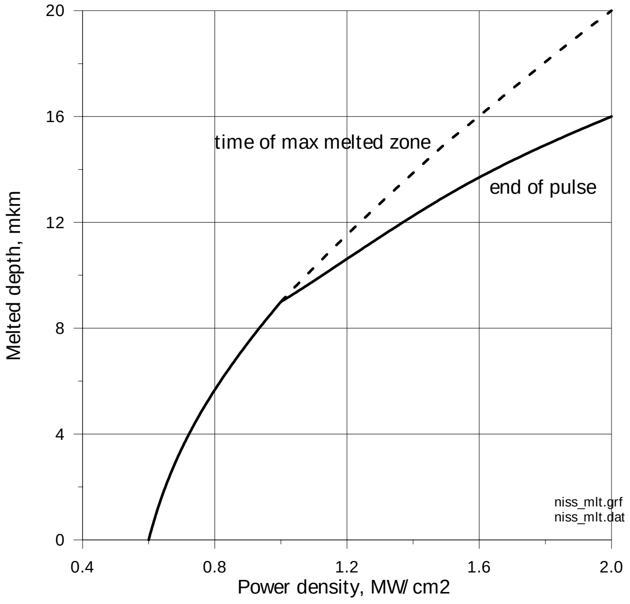
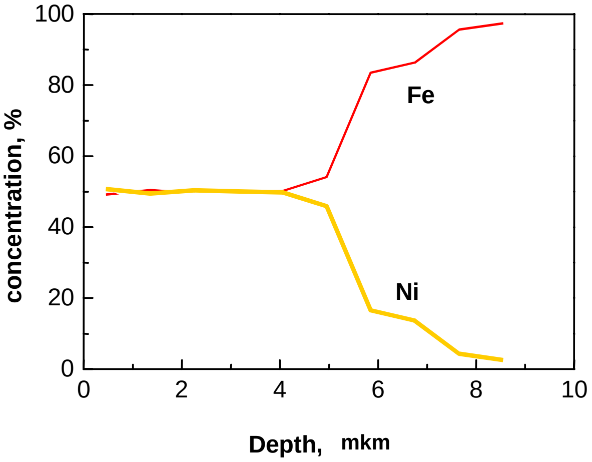


Fig. 7. Melting depth vs. beam power density

The experimental data shown in Figs. 8, 9 were obtained on the GESA facility [5]. As seen from Fig. 8, after treatment of the Ni-C60 double-layer sample by a 80keV 25μs single pulse, Ni atoms are detected at a depth of 8 μm, this bearing witness to the value of the melt zone. On the one hand, the melt depth measured experimentally agrees well with the calculated value, i.e. 9 μ m (Fig. 6, curve 2) and, on the other hand, it is close to the electron penetration depth, i.e. 10 μ m, and hence, to the characteristic size of heat release in sample depth. This consistency of the heat release zone size with the melt zone points to the fact that the heating conditions are close to the adiabatic ones, this being actually characteristic of short pulses (20 ÷ 50 μs) at a sufficiently low heat conductivity (~20 W/m/C). The observed good agreement of the calculated data was obtained on condition that the heat conductivity in the melt is maintained at about 20 W/(m·K), that is, as for the solid phase at the melting temperature. In other words, the experiment results show that a sharp increase in the effective heat conductivity, which is typical of the convective mixing of the melt, is not observed, at least, in short load pulses (< 50 μs). This fact is likely to be explained by a certain response time of the thermal convection development the settling time of which is much longer than the length of the pulses in question. That the intensive convective mixing is lacking is verified also by the well-marked gradient of the Ni atom content distribution in depth of the recrystallized zone (Figs. 8 and 9).

As additional calculations revealed, account of the thermal convection in the molten zone should increase its size several times. However, for the 25μs pulses investigated this is not observed. Fig. 9 presents the experimental results of loading of the similar sample by a four-fold 25μs 140keV pulse. In this case no convection transfer of the thermal energy deep into the sample is observed, and the melt 25 μm deep (as compared with 8 μm at 80 keV, see Fig.8) is attributed only to an increase in the electron penetration depth caused by a change in the accelerating voltage (from 80 keV to 140 keV).



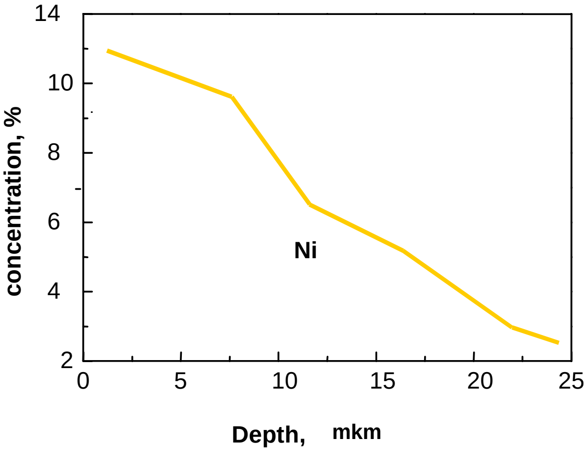


Fig. 8. Distribution of Ni and Fe concentration in the sample after loading by one 80 keV, 25μs pulse.

Fig. 9. Distribution of Ni and Fe concentration in the sample after loading by four-fold 140keV, 25μs pulse

Summary

The analysis of the presented experimental and calculated data allows the general conclusion to be made that the convective mechanism of the thermal energy transfer into the sample material is absent in case of short pulses which are required to provide the quasi-adiabatic conditions for melt zone heating necessary to maintain high-temperature gradients on the boundary between the melt and the solid phase. The depth of the recrystallized zone is determined only by the electron penetration depth.

Since the time necessary for the thermal convection to develop is more than the characteristic time of pulses of the quasi-adiabatic loading of the melt zone, an increase in the melt zone caused by convection is possible either in case of longer pulses (> 100 μm) or considerable overheating of the melt relative to the melting temperature, which will provide the necessary energy stored after completion of even a shorter pulse (Fig. 6, curve 4). But in this case the temperature gradient on the boundary between the melt and the solid phase is essentially lower than during the quasi-adiabatic heating decreasing drastically the crystallization rate of the molten zone and, hence, deteriorating the strength characteristics of the thermally treated layer. This is verified in [1], where the authors draw the conclusion that an appreciable overheating of the melt zone by a long loading pulse enlarges the recrystallization zone reducing simultaneously the strength characteristics of the modified layer, while considerable overheating of the loading zone provides the existence time sufficient for development of the intensive thermal convection.