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Aleksander Siwek*

LASER MELTED STEEL FREE SURFACE FORMATION

1. INTRODUCTION

Many phisical phenomena happen on the surface of worked object in the time of laser recasting. Only a part of laser beam energy, which is absorbed by the worked object, vouches for a recasting process. A portion of energy is lost for radiation, free convection and evaporation of the alloy elements. The amount of absorbed energy depends on a great deal of factors such as length of laser radiation, type and shape of the surface as well as presence of plasma beyond worked surface. As a result of heating a liquid is being formed and temperature distribution in the recasting zone is assigned, with its shape and properties. The energy that was supplied to the surface conveys up the material by convection is caused by Marangoni's effect. As a result of heating the substance in the zone of laser beam action a pool of liquid appears. The shape, depth, chemical composition and solidified layer structure, as an effect of cooling, depend on the factors already mentioned. Modelling of phenomenon that proceed during laser recasting allows to decrease amount of requisite experiments as well as prediction the course of process.

By dint of conducted computer simulations of laser recasting it was ascertained that the main force which causes the liquid convection is the Marangoni force [1, 2]. The results of computations confirm the influence of heat convection upon the recasted zone shape. The direction of liquid stream on surface is determined by the Marangoni effect. Temperature gradient as well as liquid chemical composition cause the alteration of sign of a temperature surface tension factor $\partial\gamma/\partial T$, which promotes the creation of two contrary oriented liquid streams [3, 4].

In hitherto calculations [1, 2, 4] both the surface velocity and surface temperature were calculated with the assumption that the surface of melted zone is not free. The possibility of predicting surface shape is important on account of observation of its topography while

* Ph.D., Faculty of Metals Engineering and Industrial Computer Science, AGH University of Science and Technology, Krakow, Poland; asiwek@agh.edu.pl

heating and cooling. The flows of liquid with free surface and moving transition boundary in a liquid state are the exceptionally complicated flows category. The position of surface is well-known in initial moment only. Later position of this surface might be predicted with numeric methods.

The following boundary conditions one should consider while assuming absence of phase change:

– Kinematic conditions constraining the mass transfer

$$\left[\left(\mathbf{v}-\mathbf{v}_{\mathrm{g}}\right)\cdot\mathbf{n}\right]_{ps}=0 \tag{1}$$

where:
ps – free surface,
$\mathbf{v}, \mathbf{v}_g$ – velocity of a liquid and border, respectively,
$\mathbf{n}$ – normal vector.

This states that normal component of liquid velocity on the free surface equals to velocity translocation of free surface.

– The dynamic conditions comming from principle of the momentum conservation impose the balance of forces, which influence the liquid phase on the free surface. Components perpendicular to free surface are equal in their size and directed opposite, while components tangential to the forces are equal in their magnitude as well as direction.

The position of free surface has to be calculated as part of general solution and it usually is not known in advance. It is supposed that flux of mass in elements lying on free surface equals zero and preasure is equal to air-preasure. One of the conditions might be used to apply as boundary condition, while the remaining one could serve to determination of free surface position. Iterative methods are used in aim of sufrace position assignation. It additionaly enlarges the problem complexity.

Introduction of function H is necessary in the free surface shape calculations. This function equals to value of surface elevation in relation to unperturbed position

$$z=H\left(x,y,z,t\right) \tag{2}$$

where: x, y and z are the coordinates of free surface point and t marks time.

The kinematic equations of boundary conditions become transformed into equation which describes the local change of height

$$\frac{\partial H}{\partial t}=u-v\frac{\partial H}{\partial x}-w\frac{\partial H}{\partial y} \tag{3}$$

where: u, v and w are the velocity components in x, y and z directions on the free surface.

The equation (3) can be integrated with respect to time. The liquid velocity on the free surface can be obtained by extrapolation of values calculated for the liquid phase or using dynamic boundry conditions. For flow computations a number of authors uses finite element method and for computations of function H a finite difference method with both of the boundary conditions [5].

Euler's method for two-dimensional arrangement, where calculations are carried out for time $t_{n,}$ is the simplest way of solution of equation (3). It is assumed that derivatives with respect to x and y are approximated with the use of central difference. A grid used for the solution in direction x i y is homogeneous. The new value of H_i^{n+1} variable is counted according to the following formula

$$H_i^{n+1} = H_i^n + \left[u - v \frac{H_{i+1}^n - H_{i-1}^n}{2\Delta x} \right] \Delta t \tag{4}$$

where:

H_i^n – elevation of grid node i in relation to unperturbed surface in n-th iteration,

Δx – a grid nodes distance,

Δt – a time step.

In case of large time steps Δt this methods is not sufficient, for example for slowly changing solutions or solutions achieving a stationary state. Instability is a problem in this method. In the aim of solution assurance Courant and Friedrichs [5] have proposed exchange of central difference in equation mentioned above by difference between two neighbouring points *i–1* and *i*

$$H_i^{n+1} = H_i^n + \left[u - v \frac{H_i^n - H_{i-1}^n}{\Delta x} \right] \Delta t \tag{5}$$

The additional limitation of time step is required in aim of stability assurance

$$\Delta t < \frac{\Delta x}{v} \tag{6}$$

A leapfrog method is different method which is commonly used. According to this method integration is proceeded in a time iterval $2\Delta t$. The use of this pattern for function H results in

$$H_i^{n+1} = H_i^{n-1} + \left[u - v \frac{H_{i+1}^n - H_{i-1}^n}{2\Delta x} \right] 2\Delta t \tag{7}$$

Analysis of this computational schema stability shows that it is unstable and therefore useless for nonstationary numeric problems. In the aim of stabilization an additional approximation is used

$$H_i^n \approx \frac{1}{2}\left(H_i^{n-1} + H_i^{n+1} \right) \tag{8}$$

2. MODELING THE PROCESS OF RECASTING

The mathematical model for two-dimensional arrangement [1, 4] of recasting steel with laser was used in this research. The area whereupon laser beams light becomes heated violently. The structure melts-through. A quick liquid movement accelerates heat transportation to areas distant from the heat source. The size and shape of melted zone depends on chemical composition of the substance and power of laser beam.

Table 1. Thermophysical Properties of Steel HS6-5-2

Characteristic values	Symbol	Unit	Value
Density	ρ	kg/m^3	8100
Viscosity	μ	kg/(m·s)	$6 \cdot 10^{-3}$
Coefficient of thermal expansion	β	1/K	$1 \cdot 10^{-4}$
Latent heat of fusion	L_H	J/kg	$250.8 \cdot 10^3$
Solidus temperature	T_s	K	1620
Liquidus temperature	T_l	K	1740
Absorbtivity	η	%	11
Emissivity	ε	–	0.4
Temperature coefficient of surface tension	$\partial\gamma/\partial T$	N/(m·K)	$-5 \cdot 10^{-4}$

Two-dimensional model 2×2 mm sized laser recasting steel HS6-5-2 (Tab. 1) with the regard on arrangement symmetry includes only a half of laser beam. A sample was divided into triangular elements. On the sample surface, in the area, where great temperature gradient exists, the network was thickened to elements having size $\sim 7 \cdot 10^{-6}$ m. On bottom sample surface the size of network was $\sim 7 \cdot 10^{-5}$ m. The plane in which laser beam axis lies was establish as a symmetry axis. The liquid phase movement on the surface of melted zone was mainly controlled by value and direction of surface tension, which was taken into consideration in boundary conditions of the model. Great temperature gradient on the surface of melted metal results in Marangoni flow as an effect of surface tension gradient (Fig. 1).

Field of velocity and temperature were ascertained in calculations [1, 2, 4] performed with the assumption that the surface of recasted zone is not free. Nevertheless the assumption of stiffness surface in recasted zone in hitherto calculations of convection, in reality the liquid surface freely relocates. The possibility of predicting of surface shape during process and after cooling would enable to control more accurately course of the process.

In this paper marching function H given by equation (2) was introduced into the model. It allows the calculation of shape of recasted zone surface. In order to solve differential equation (3) the iterative scheme (4) was applied with an additional solution stabilising equation (8).

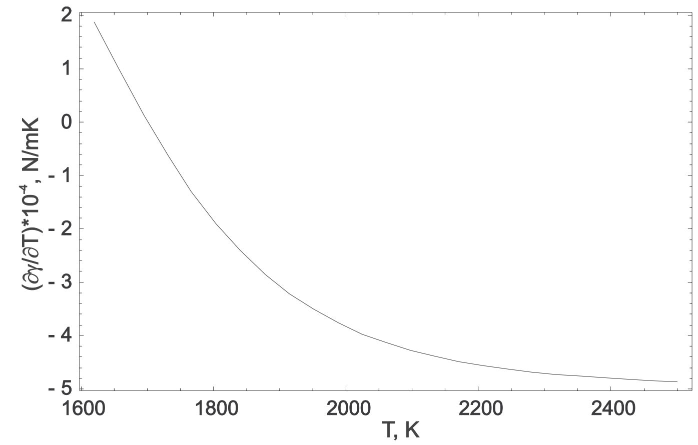

Fig. 1. *Dependence of temperature coefficient of surface tension (∂γ/∂T) for steel HS-6-5-2 containing 20 ppm of the sulfur*

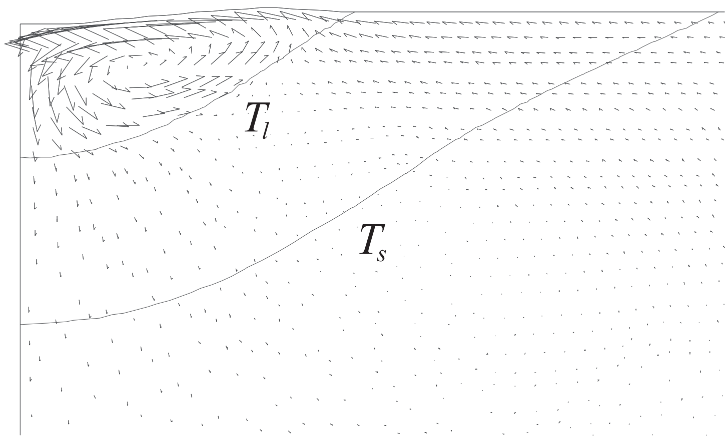

Fig. 2. *Calculated temperature and velocity field for steel HS6-5-2 when the pool surface is considered free*

The shape of recasted free surface by laser beam with 500 W power and after 0.15 s is presented on the Figure 2. In axis of laser beam a strong liquid stream, which is directed from surface interior sample, is visible. In this area a liquid steel reaches maximum value of perpendicular velocity component, which is equal to 0.1 m/s on depth of $2.5{\cdot}10^{-5}$m (Fig. 3). Because of iterative scheme applied in this model, which permits the deformation of free surface, the liquid stream directed to the surface in the area where the temperature is nearing the liquidus temperature (T_l), results in bending of the surface above initial level of the upper sample surface (Fig. 2). However an inversely directed liquid phase stream in the axis of laser beam creates cavity in this place. On the upper sample surface the liquid stream is directed into laser beam axis (Fig. 4). The maximum liquid phase velocity on this boundary rises ~0.35 m/s. The perpendicular liquid velocity component on the same surface changes its sign (Fig. 5) extreme values of its velocities reach –0.05 m/s and 0.03 m/s respectively.

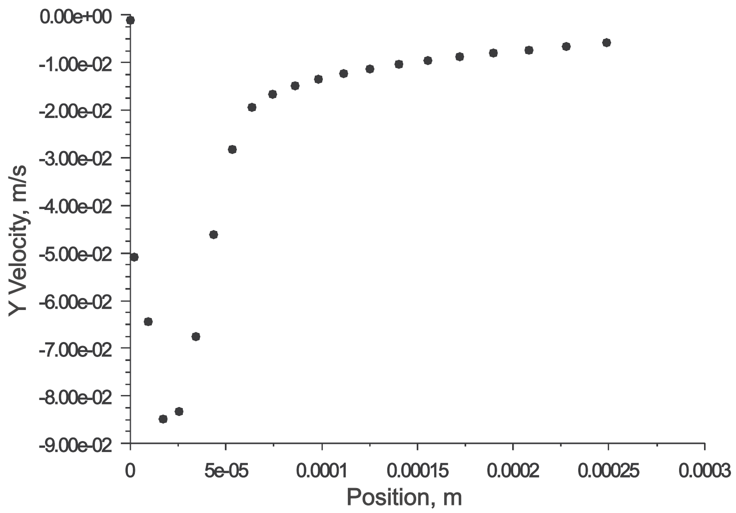

Fig. 3. *Plot of liquid velocity perpendicular component (v) in the axis of sample symmetry*

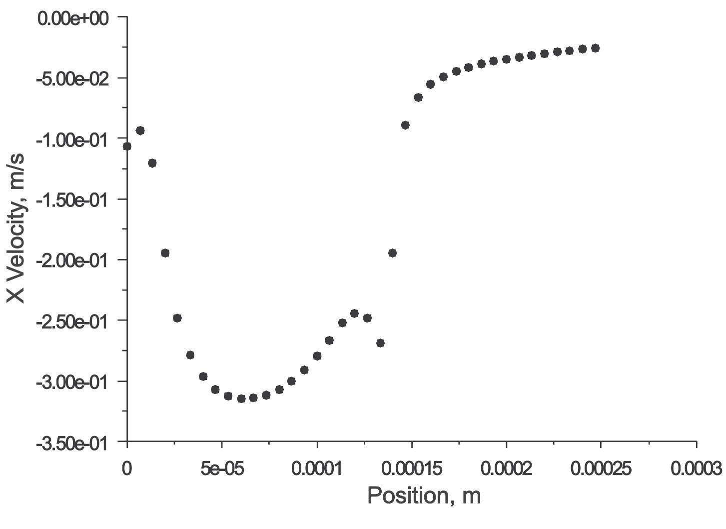

Fig. 4. *Plot of liquid velocity horizontal component (u) on the recasted zone of free surface*

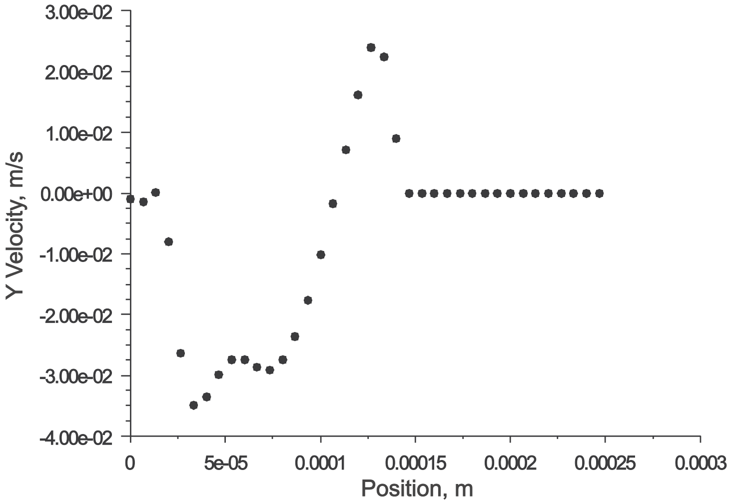

Fig. 5. *Plot of liquid velocity perpendicular component (v) on the recasted zone of free surface*

Almost imperceptible surface deformation (Fig. 6) is caused by computations for sample which was doped with sulfur (20 ppm). In comparison to previous case the horizontal and perpendicular components (u i v) of the liquid phase velocity vector on the liquid surface (Figs 7, 8) are properly 1–2 orders smaller. Therefore their influence upon lifting H_i^n of free surface calculated with iterative scheme with the use of (4) is inconsiderable.

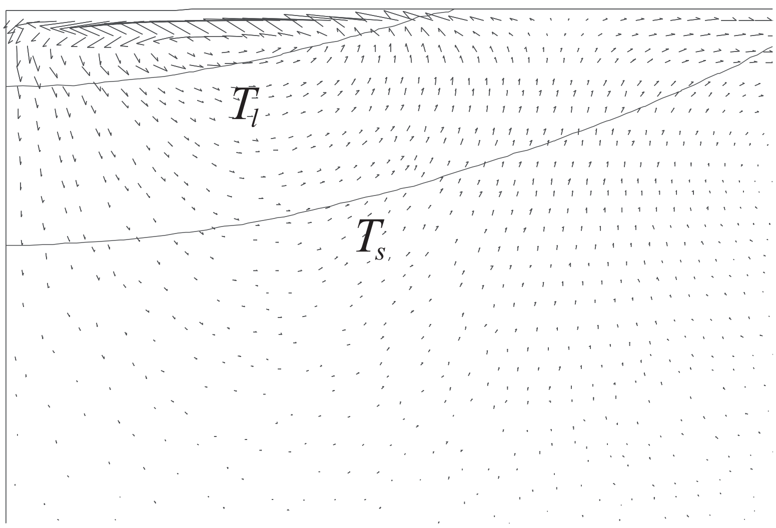

Fig. 6. *Calculated temperature and velocity field for steel HS6-5-2 doped with 20 ppm sulfur when the pool surface is considered free*

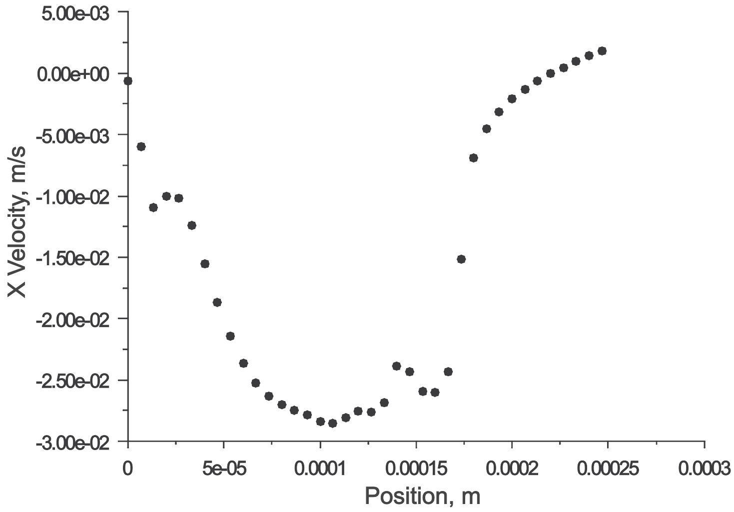

Fig. 7. *Plot of liquid velocity horizontal component (u) on the recasted zone of free surface of a sample consisting 20 ppm of sulfur*

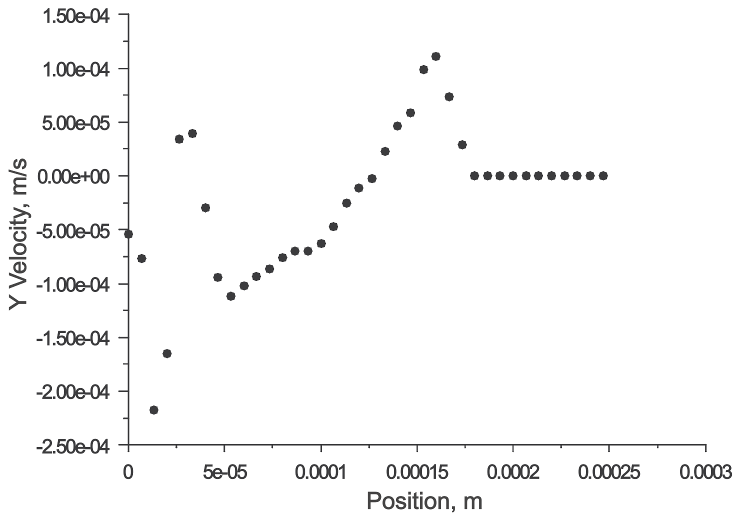

Fig. 8. *Plot of liquid velocity perpendicular component (v) on the recasted zone of free surface of a sample consisting 20 ppm of sulfur*

3. SUMMARY AND CONCLUSIONS

Theoretical calculations of heat and mass transfer by using two-dimensional energy, momentum conservation and stream continuity equations were presented in this paper. The schema of calculating the surface location by introducing an additional iteratively counted function was proposed. The use of computer simulation for laser recasting enables prediction of influence of processing parameters (laser beam power and diameter, chemical composition of the material, surface parameters) upon the shape of recasted zone and liquid phase free surface. The temperature gradient is a propelling force of surface liquid flow, which is highest on the beam circuit. This results in very intensive mixing of melted phase in this area. Steel doped with the sulfur causes decrease of unevenness of liquid steel free surface.

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