Electric current pulse driven liquid metal flow studied by the multi-dimensional Ultrasound Doppler array technique

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The electric current pulse (ECP) technique is an effective method of applied MHD to be used for promoting grain refinement in the macrostructure of metal alloys during the solidification process. However, the physical mechanism of the ECP grain refinement technique has not been fully understood until now because of a shortage of knowledge of the forced flow induced by current pulses. In a comprehensive study, experimental investigations were performed considering the configuration of two parallel electrodes immersed through the free surface into a liquid metal column of GaInSn. A melt flow is driven by the Lorentz force resulting from an interaction of the electric current between the electrodes and its induced magnetic field. By means of the ultrasonic Doppler array technique the time-dependent flow field structure induced by DC and pulsed currents under various conditions and parameters was investigated. The measuring results of the study will be presented and discussed.

Keywords: electric current pulse, ultrasound Doppler method, ultrasonic array sensors, liquid metal flow, magnetohydrodynamics

1 INTRODUCTION

Today’s attention of the metallurgical industry is turned to the optimization of metallurgical processes to improve the mechanic properties of metallic products and simultaneously to reduce energy consumption. In this connection, electromagnetic processing of materials (EPM) gains in importance. Various approaches have been performed during the last decades to control the solidified macrostructure and grain refinement of metals during the solidification process and, to adjust material properties by electric and magnetic fields [1, 2]. One particular method was found by *Nakada* [3] in the electric current pulse (ECP) technique.

Many studies have shown that beneficial effects like a distinct grain refinement or the promotion of the transition from a columnar to an equiaxed dendritic growth can be achieved [2-4]. However, the physical mechanism of the grain refinement effect caused by ECP has not been understood so far. Various effects are under discussion, such as the fragmentation of dendrites induced by the electric current [1], the reduction of the nucleation activation energy [2], or the break out and the transport of little grains from the boundary by the periodic Lorentz force [3]. However, the previous studies did not consider the possibility that intense Lorentz forces resulting from the interaction between the strong electrical current and the self-induced magnetic field can create significant melt flows.

This paper presents an experimental study which focuses on the forced melt flow induced by a strong electric current. A set of experiments was conducted to obtain quantitative information about the isothermal flow field exposed to various electrical parameters like the frequency and amplitude of the current as well as the pulse length. Flow measurements were carried out by the ultrasound Doppler method.

2 EXPERIMENTAL SETUP AND PROCEDURE

2.1 Flow mapping measurement system

The pulsed ultrasound Doppler method has proved as a reliable and attractive flow measuring technique for non-transparent fluids including liquid metals [5]. A detailed study of transient flow structures often requires the measurement of instantaneous flow velocity fields instead of merely velocity profiles. However, previous approaches of flow field measurements with the ultrasound Doppler method suffer from a lack of sufficient spatial and temporal resolution for such studies [6]. Recently, a two-dimensional measurement method based on the application of linear ultrasonic transducer arrays in interaction with specific array driving techniques was developed to overcome these drawbacks [8, 9]. The linear array is composed of 25 plane transducer elements (transmission frequency 8 MHz) of $2.3 \times 5\ mm^2$ with an element pitch of 2.7 mm (fig. 1) spanning a measuring field length of 67 mm. A single array facilitates the measurement of the flow velocity component perpendicular to the transducer surface.

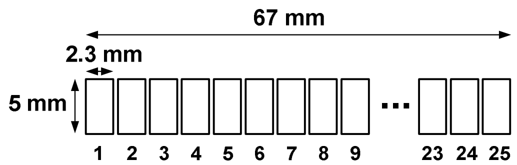

Figure 1: Configuration of linear transducer array

Multiple array arrangements are feasible allowing e.g. the measurement of both, velocity components in a plane or the measurement of several planes side by side.

A modified electronic traversing by means of a specific time-division multiplex scheme enables an improved spatial as well as a temporal resolution. A suitable spatial resolution is achieved by the operation principle of segmental arrays: During operation two adjacent transducer elements are interconnected to operate as one transducer of approx. 5 × 5 mm² resulting in a reduced beam divergence over the measuring depth. The active transducer pair can be traversed by one pitch length. This additionally facilitate the acquisition of intermediate measuring lines thereby taking account of the self-focusing effect of plane transducers which makes the ultrasonic beam smaller than the transmission plane over a specific depth [7-9].

Two novel approaches are applied to extend the temporal resolution [9]. The first method implements a multi-beam operation which targets to scan as many profiles measuring lines (respectively transducer pairs) in parallel as possible, thereby taking into account a low crosstalk. The second method is related to the pulsing strategy: As generally known the choice of pulse repetition frequency of the ultrasound Doppler method complies with the maximum velocity range as well as the maximum measuring depth. For small scale experiments with moderate flow velocities the required measuring time (according to the measuring depth) is much lower than the pulse repetition time inducing an idle time between end of one echo acquisition and the begin of the following one. Contrary to previous multiline systems our approach applies this idle time for the echo acquisition of further measuring lines according to the multiplex pattern in fig. 2 (in combination with the multi-beam operation).

A more detailed description of the technical implementation is reported in [7-9].

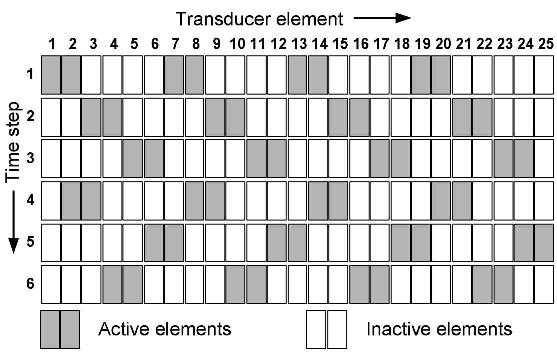

Figure 2: Multiplex pattern of one array

2.2 ECP setup

Apart from other electrode arrangements the configuration using parallel electrodes at the ECP technique is often found in literature [1, 2, 3]. This kind of ECP setup will also be treated in the present discussion.

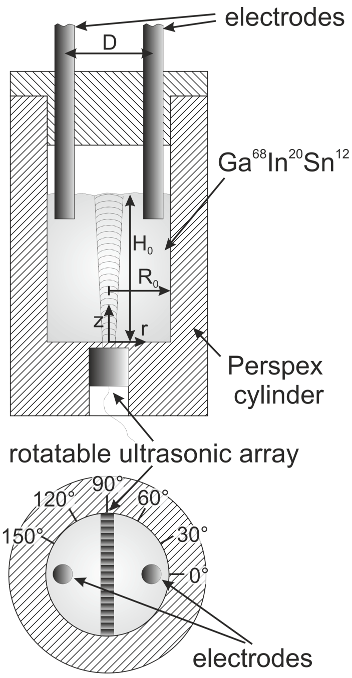

Figure 3: ECP setup with parallel electrodes

The experimental setup is shown in fig. 3. A cylindrical vessel made of Perspex is filled with the eutectic alloy $Ga^{68}In^{20}Sn^{12}$ which is liquid at room temperature. The liquid metal column has a height of H_0 = 60 mm and a radius of R_0 = 25 mm. Two circular rod electrodes with a diameter of 8 mm are mounted at opposing radial positions of D/2 = 18 mm parallel to the cylinder axis. The electrodes are immersed from top to a depth of 10 mm below the free liquid metal surface. The ultrasonic array is installed radially at the bottom of the cylindrical vessel (fig. 3) to measure the axial flow component in the radial-meridional plane of the liquid metal column. The ultrasonic array resolves the measuring plane into 18 velocity measuring lines. The lid of the vessel fixing the parallel electrodes is pivoted with respect to the cylinder and the ultrasonic array, respectively. This facilitates the field measurement of planes in various angles toward the parallel electrodes.

2.3 Measurement parameters and procedures

The measurements were performed with a burst length of 8 cycles following in at best an axial resolution of about 1.4 mm (c_{GaInSn} = 2740 m/s, f_S =8 MHz). The temporal resolution ranges from 200 ms to 50 ms.

A pulse reverse power supply *from plating electronic GmbH* delivers the rectangle pulse current as well as the direct current (DC). The pulse current is specified by the peak current I_{peak}, the pulse frequency f_c and the duty cycle τ. The effect of both pulse currents with different parameters and direct currents is mainly governed by the root mean square (RMS) current. The RMS value of pulse currents is defined as:

$$I_{RMS} = I_{peak}\sqrt{\tau \cdot f_c} \qquad (1)$$

Since the expected flow structure is non-axisymmetric the flow field was acquired in radial-meridional planes at different angles with respect to the plane of the parallel electrodes. As a criterion for the evaluation of the effect of different current configurations the mean flow intensity is determined. As a measure of flow intensity the axial velocities determined on the measuring planes are averaged across the volume of the liquid metal column by

$$\bar{u}_z = \frac{1}{H_0 R_0^2 T_m \pi} \int_0^{T_m}\int_0^{\pi}\int_0^{H_0}\int_{-R_0}^{R_0} r\left|u_z(r,z,\varphi,t)\right| \, dr\,dz\,d\varphi\,dt \qquad (2)$$

where T_m is the measurement duration.

3 MEASUREMENTS AND RESULTS

3.1 Basic flow structure

Figure 4 shows the typical flow structure of the axial flow velocity in the 0°-plane (fig. 4a) and the 90°-plane (fig. 4b) around 7 s after powering on the pulse current. The current induces two intense, downwards-directed jet streams beneath the electrodes which are well-balanced (fig. 4a). The jet streams are caused by the electric current in and between the electrodes generating circular magnetic fields which evolve a dominant field component perpendicular to the electrode plane. This field component aligned orthogonally to the electric current between the electrodes induces a downward-directed Lorentz force. Since the current density is most intense in the region beneath the electrodes the Lorentz force drives the two jet streams. Figure 4b reveals an upward-directed back flow which is particularly intense in the upper part of the liquid metal column. With progressively ongoing evolution, the flow exposes an increasingly unsteady nature; the jet streams begin to oscillate after about 20 s (fig. 5).

3.2 Parameter study

The variation of the pulse current parameters is supposed to influence the grain refinement in a solidifying alloy. The present investigation is intended to investigate differences in the flow of various current configurations (Table 1) carried out at the same RMS current (according to Eq. 1) of I_{RMS} = 48 A.

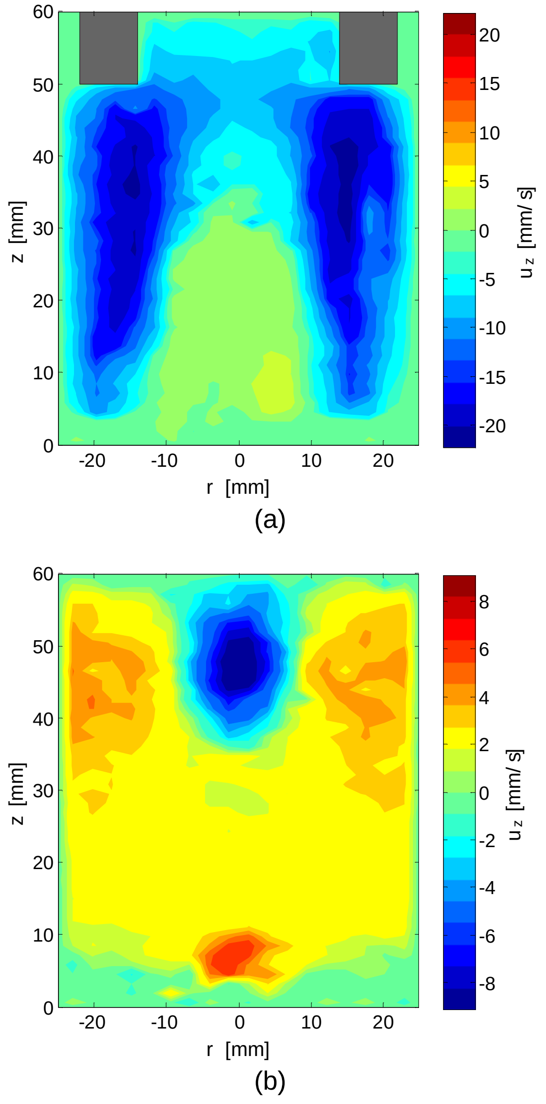

Figure 4: Flow field of electric pulse current (a) in the electrode plane (0°-plane) and (b) in the plane between the electrodes (90°-plane) (at t = 7 s, I_{peak} = 151.8 A, f_c = 50 Hz, τ = 0.1, temporal resolution Δt = 143 ms)

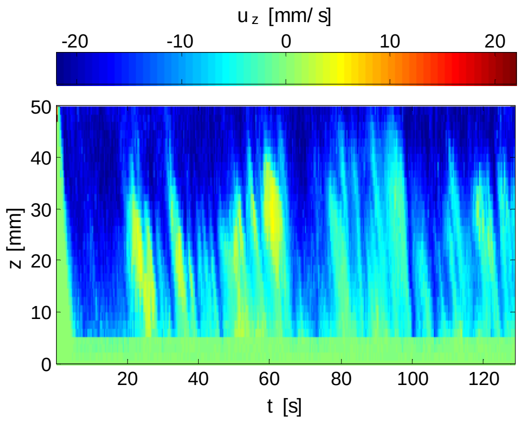

Figure 5: Spatio-temporal map of velocity profile below the electrode (r = -17 mm in 0°-plane) of pulse current (I_{peak} = 151.8 A, f_c = 50 Hz, τ = 0.1)

Figure 6 displays an instantaneous flow field (t = 7 s) induced by a direct current of I_{DC} = 48 A which indicates an equivalent flow structure compared to the pulse current flow of fig. 4a. The spatio-temporal map of the direct current (fig. 7) reveals a similar transient character of the flow as found for the case of the pulsed current (fig. 5).

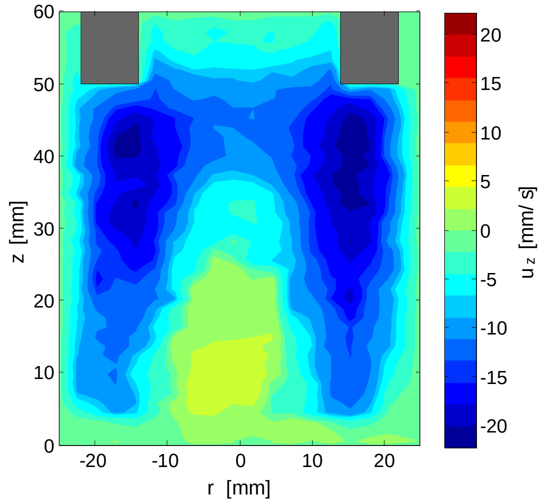

Figure 6: Flow field of DC current (I_{DC} = 48 A) in the 0°-plane (at t = 7 s, temporal resolution Δt = 143 ms)

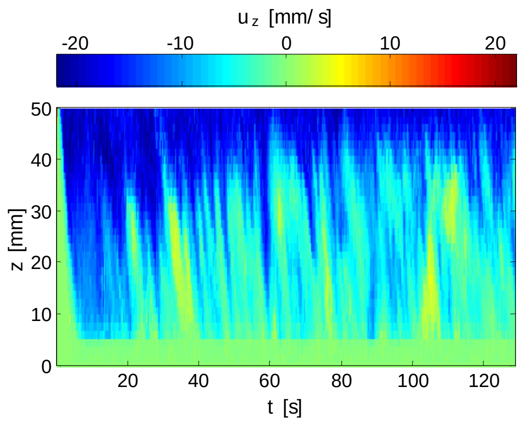

Figure 7: Spatio-temporal map of velocity profile below the electrode (r = -17 mm in 0°-plane) of DC curren t (I_{DC} = 48 A)

Table 1: Sets of parameter study of root mean square current I_{RMS} = 48 A

I_{peak} [A]	f_c [Hz]	τ	$\bar{u}_z$ [mm/s]
151.8	50	0.1	1.29
151.8	100	0.1	1.27
151.8	200	0.1	1.23
214.7	50	0.05	1.28
214.7	100	0.05	1.21
303.6	50	0.025	1.25
48	DC		1.31

In addition, the mean flow $\bar{u}_z$ is determined (according to Eq. 2) as a measure of flow intensity for various current configurations. For this purpose the mean flow field is measured at 6 angular positions. The results are exposed in Table 1 demonstrating that the current modulation has no detectable influence on the flow intensity.

4 SUMMARY AND CONCLUSIONS

By means of the ultrasound array measurement system the transient flow field of the electric current pulse method with parallel electrodes was investigated in a liquid metal column of GaInSn. The flow structure comprises two intense jet streams directly beneath the electrodes and the back flow in the residual. Various configuration of pulse currents as well as the equivalent direct currents are applied and compared with respect to the resulting flow structures.

The measurement results reveal that no significant differences of pulsed and direct current flows obviously exist neither at the global flow structure nor at the transient behaviour. Potentially arising differences of grain refinement or rather macroscale structure of direct and pulse currents are not caused by differences in flow characteristics.

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