Investigation of the Thermal Effects of Magnetic Pulse Forming using LS-DYNA®

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Abstract

This paper shows the results o f LS-DYNA simulations and experimental studies of various sources of thermal effects occurring during magnetic pulse forming: theJoule heating of the eddy currents, the work of plastic deformation and the collision with the die. The obtained results allow quantifying the thermal effects and their influence on the mechanism of high-speed deformation: the technological plasticity of the forming process, the level of residual stresses during assembly operations, the mechanism of formation of welded joints, and so forth.

Electro Magnetics

1. Introduction

Technical progress in engineering requires continuous improvement of existing and developing new technological processes that provide quality and reliability. One of the ways of solving this problem is the use of methods of high-speed deformation of metals that can improve labor, productivity, reduce production costs, improve product quality, and open the way for new solutions in the field of design and technology. Among the most actively implemented methods in various industries are the processes of magnetic-pulse processing of metals.

In the basis of this method pulsed magnetic fields of high intensity as a source of load are used, which cause the effects of electro-dynamic forces on the conductive material placed in a magnetic field. Under the action of these forces, the workpiece is accelerated to high speeds (100 to 500 m/s). In the collision of the workpiece with the die or with the mandrel the predetermined forming occurs, and with the collision of two or more parts they are welded together to form a permanent joint [1].

Magnetic pulse treatment of metals is characterized by a high accuracy dosing of energy, a locality application of the load, the lack of contact between tool and workpiece, and environmental safety. The equipment can easily be embedded into the technological lines, thereby improving other high-speed and traditional processing methods [1].

During this processing the workpiece is subject to intense thermal and force effects. This article discusses the thermal effects occurring in the workpiece, which are determined by three main factors:

- heating from the action of eddy currents (Joule heating), which can reach tens and even hundreds of kA;
- heating by the plastic strain;
- heating by high-speed collision of the workpiece with the die or with other workpieces.

The discharge of the current during the magnetic pulse forming creates heat in both the coil and the workpiece. Moreover, the eddy currents over the cross section of the workpiece are not distributed uniformly (skin effect).

When the deformation is done at high speeds and over a small period of time, the heat produced during the deformation process has no time to stand out to the environment or be distributed within the workpiece volume, but remains in the deformation zone. Consequently, the process of high-speed deformation is adiabatic, therefore the deformation of the material is carried out at elevated temperatures.

In addition, most of the processes of magnetic-pulse processing of metals usually end up with a collision with the die. In this case the kinetic energy accumulated at the impact is converted into heat.

All these factors determine the special conditions of metal forming with a pulsed magnetic field, and favorably distinguish it from other pulse methods, because additional heating of the workpiece during the deformation increases the plasticity of the material, determines the mechanism of assembly and welding joints, as well as the properties of the metal after deformation.

Thus the need to incorporate the described thermal effects in the development process of magnetic-pulse processing of metals becomes evident. For example, when the forming, assembling and calibrating operations are carried out.

2. Features of computer simulation of magnetic-pulse processing of metals

For the complex simulation of magnetic-pulse processing of metals coupled problems must be considered. Their complexity is caused by taking into account the phenomena of electromagnetism, heat and mechanics. For today the advanced finite element package for solving such problems is LS-DYNA. This is achieved by using a new unique electromagnetic module, developed by the staff of LSTC.

A new Electromagnetism (EM) module has been introduced in LS-DYNA [2], [3]. This module allows solving the Maxwell equations in the eddy current (induction-diffusion) approximation. This is suitable for cases where the propagation of the electromagnetic waves in the air (or vacuum) can be considered as instantaneous, like in magnetic pulse forming cases. The EM fields are solved using a finite-element method (FEM) in the conductors and a boundary-element method (BEM) for the surrounding air/insulators. Thus no air mesh is necessary and the motion of the conductors can be easily handled. The EM module allows the introduction of a source electrical current into solid conductors and to compute the associated magnetic field, electric field as well as induced currents.

It is coupled with the mechanical solver, the Lorentz forces being added to the mechanics equations of motion as well as with the thermal one, the ohmic heating being added to the thermal solver as an extra source of heat.

3. Investigation of the process of beading of a plane workpiece under the action of the pulsed magnetic field

To conduct experimental investigations of thermal effects arising in the process of beading of a workpiece from Aluminum alloy 5754 through the use of the pulsed magnetic field (Fig.1), a measuring stand has been assembled (Fig.2) involving the pulse generator (МИУ-15), the infrared camera "Thermovision A20M" with high-speed response of 20 μs, the oscillograph "LeCroy 44 Xs" and technological attachments. Besides a high-speed digital camera "Cordin 505"was used for recording the kinematics of the process.

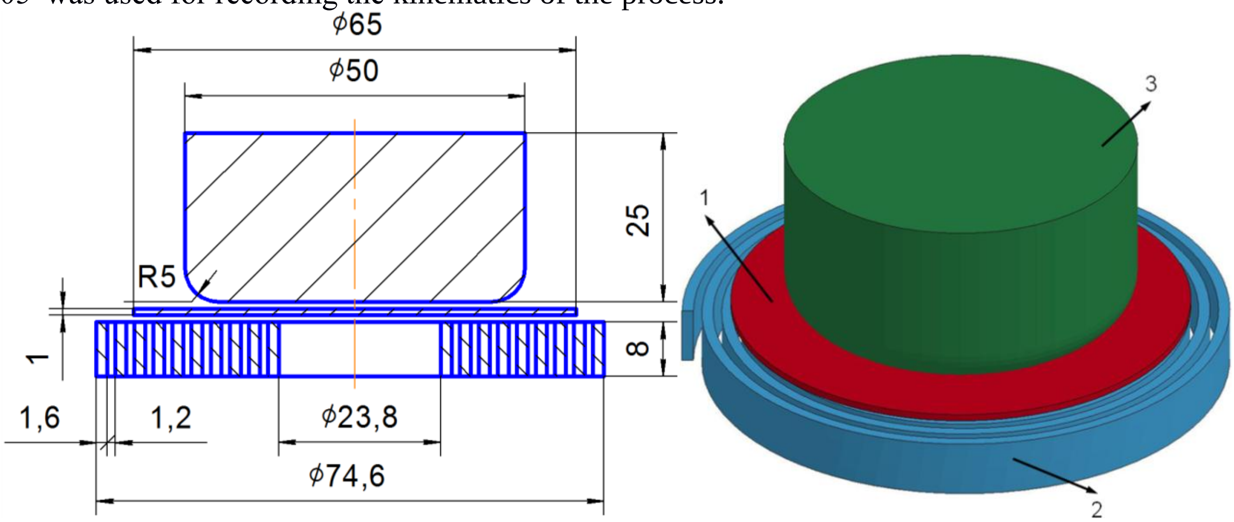

Fig. 1. Scheme and simulation model of the process of beading of a plane workpiece under the action of the pulsed magnetic field created by a spiral pancake coil.
1 – workpiece; 2 – coil; 3 – die

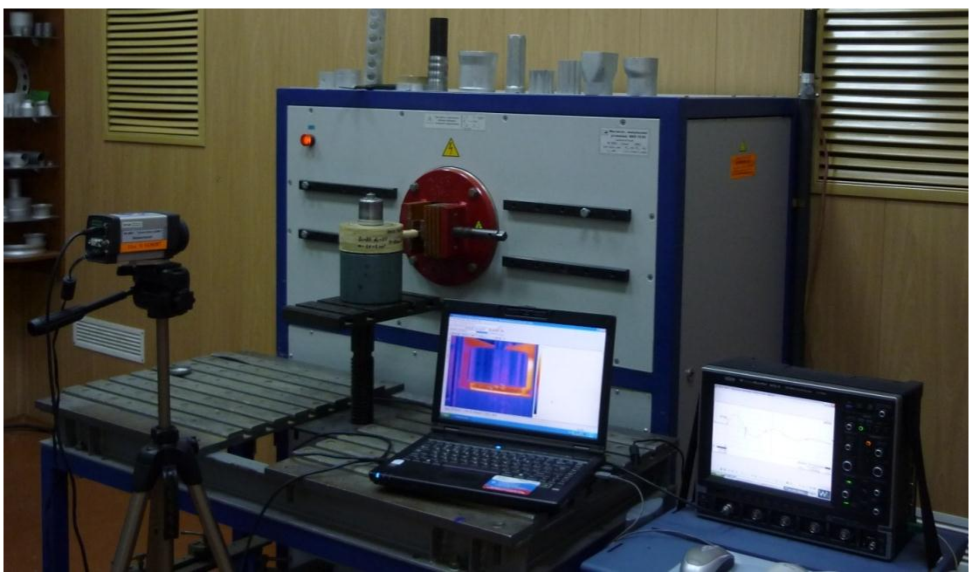

Fig.2. Measuring stand

Main parameters of the equipment used:

- Pulse generator МИУ-15:

- Maximum energy to be stored: 19,3 kJ;
- Voltage of charging of energy accumulators – 19,5 kV, it is regulated discretely with a step of 0,5 kV;
- Capacity of an energy accumulator, total,: 101,6 μF;
- Frequency of the discharging current under the regime of shorting at output terminals, no less than – 53 kHz;
- Time of charging of the accumulator to the stored energy of 15 kV, no more than – 5 s.

- Thermal imaging infrared camera «ThermoVision A20M»:

– Temperature range: - 20…+ 900°C;
– Temperature sensitivity: < 0,1°C of 25°C;
– Error: ± 2°C;
– Matrix: 160x120 pixels;
– Rate of action: 20 ms;
– Frequency of frames: 50/60 Hz.

- High-speed digital camera «Cordin 505»:

– Number of frames (in the process of one realization of shooting): 16;
– Maximum shooting speed: 200 000 f/s;
– Time separation between frames at the maximum speed: 5 μs.

The oscillogram of the current curve obtained during the process of discharging of the pulse generator is shown on Fig. 3. Sensitivity of the current sensor is S= 7,34 kA/m. The same current curve with considerations for transformations was used for performing the LS-DYNA simulations.

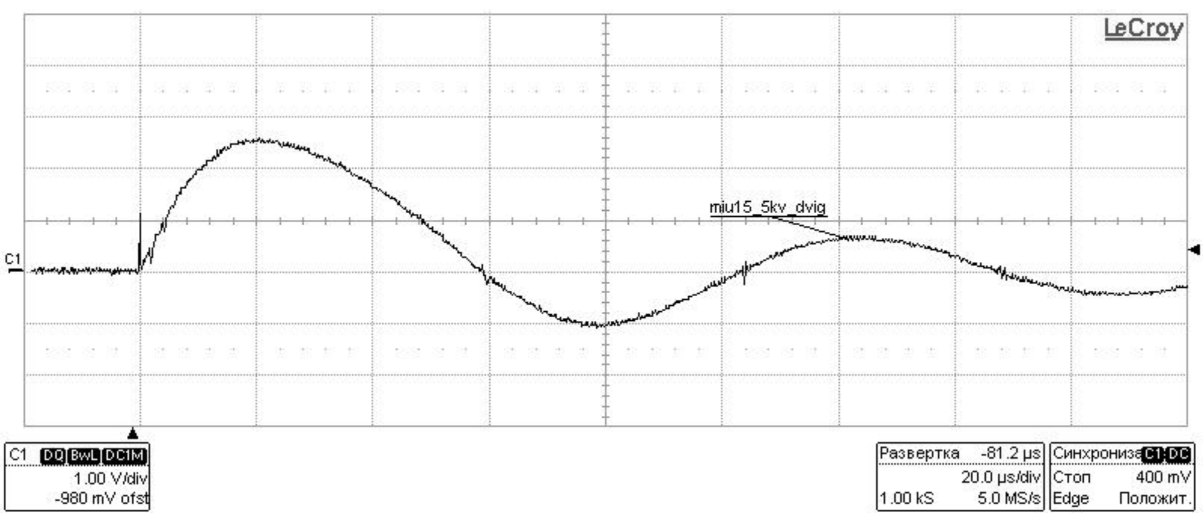

Fig.3. Oscillogram of the current

3.1. Kinematics of the beading process

Fig.4 shows comparison between several stages of kinematics of the plane workpiece beading process obtained with a help of the high-speed camera (experimentally) and the LS-DYNA simulation (digitally).

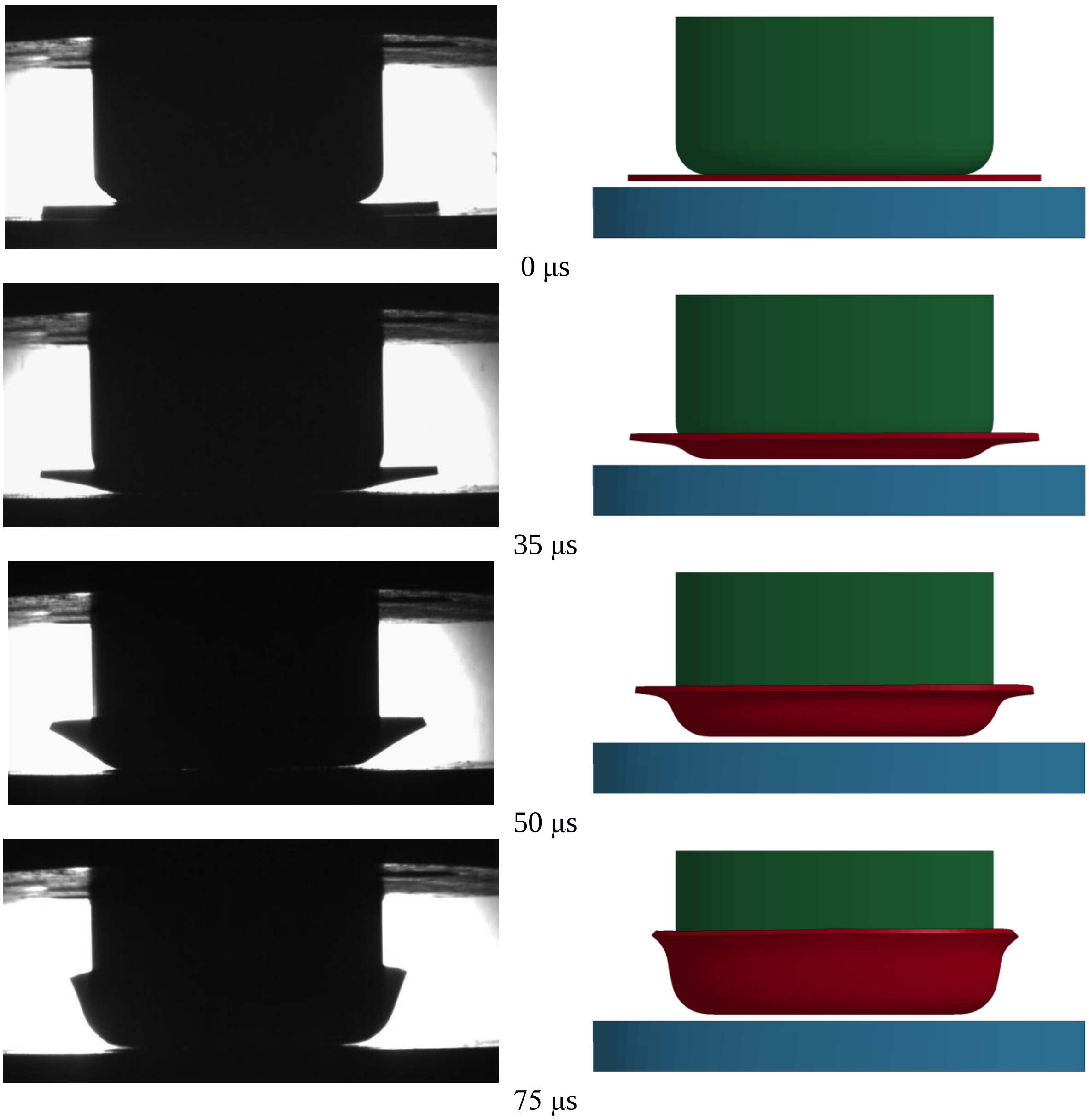

Fig.4. Kinematics of the plane workpiece beading process:
Left: experimental data, right: LS-DYNA simulation.

Fig. 5 presents the exterior view of the obtained detail.

Fig.5. Exterior view of the detail:
Left: experiment, right: LS-DYNA simulation

3.2. Assessment of thermal effects

Fig. 6 and 7 present experimental and calculated data showing the changes in temperature with consideration for thermal effects arising in processes of pulse-magnetic processing. In comparison of the results, consideration must be given to the low quick-operation of the infrared camera (2 ms range) compared to the actual time of the process and potentialities of the software LS-DYNA (0.2 ms range). This explains different nature of temperature change curves.

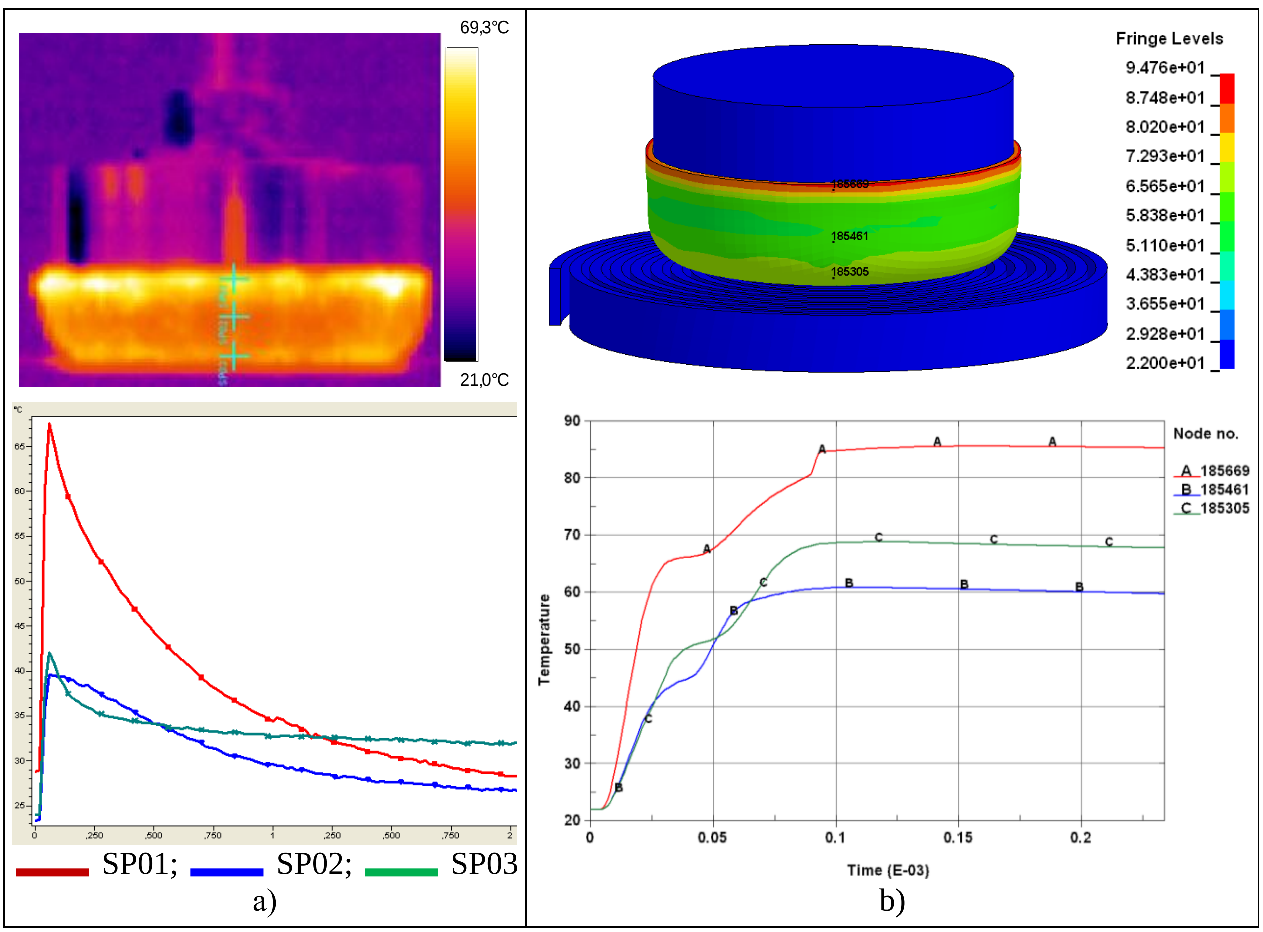

Fig.6. Distribution of temperature with height of the workpiece:
a – experimental data (time range: 2ms); b – LS-DYNA data (time range: 0.2 ms)

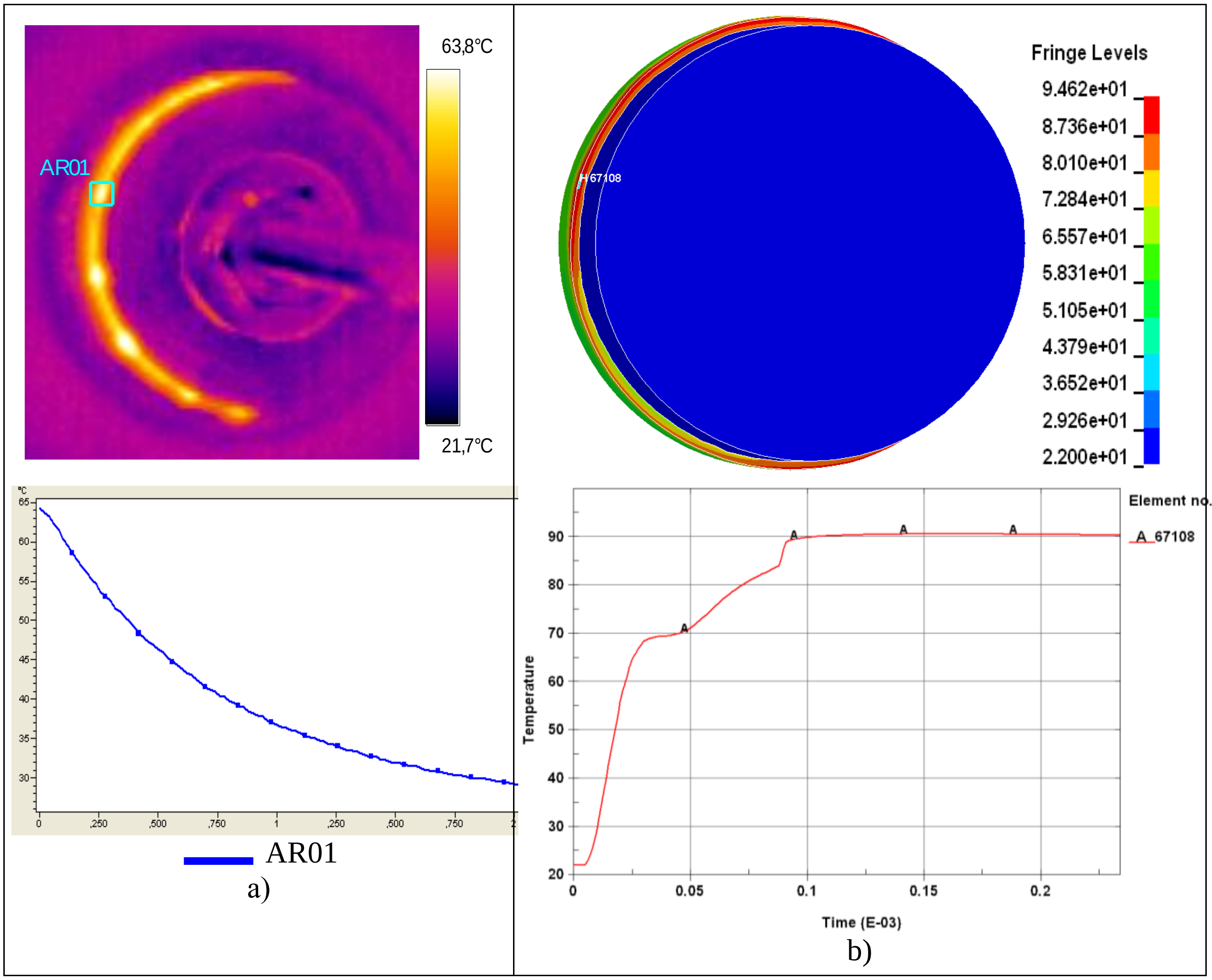

Fig.7. Temperature at the end of the workpiece after the completion of the beading process
a – experimental data (time range: 2ms); b – LS-DYNA data (time range: 0.2 ms)

The presented patterns and plots obtained with the infrared camera confirm wide potentialities of the software complex LS-DYNA which make it possible to take account of heating of the workpiece caused by action of factors of pulse-magnetic deforming of a metal.

Fig.8 shows calculated values of the distribution of the temperature through the thickness of the workpiece. By this means heating of the skin layer and further distribution of temperature with thickness of the workpiece can be assessed which is very important, for example, in processing of thin-walled workpieces or obtaining of facing details since fusions of them are possible at high values of current.

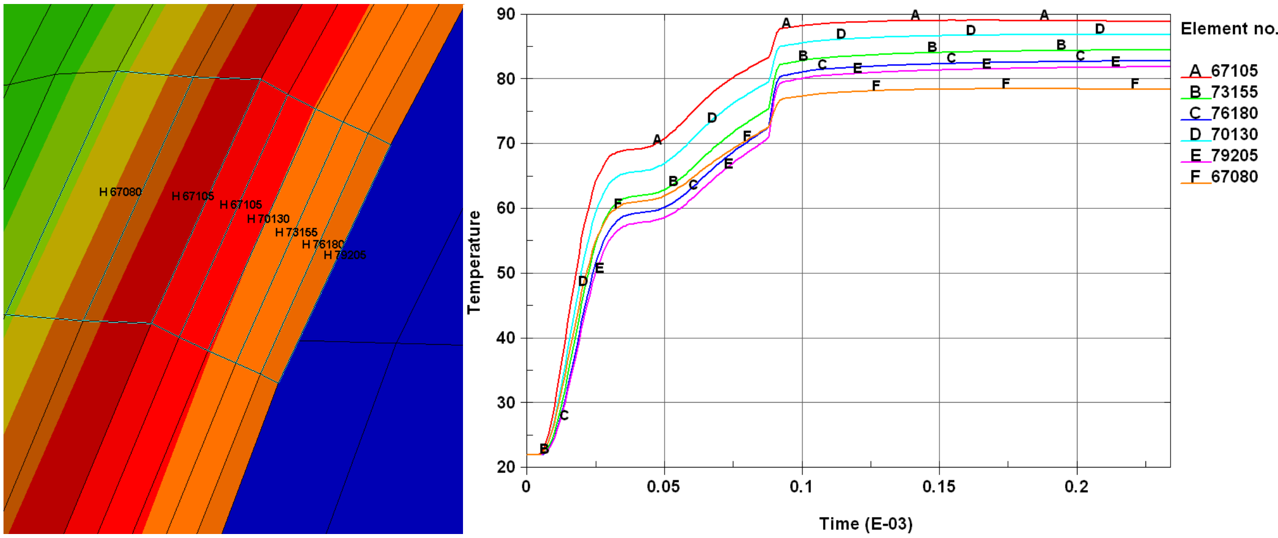

Fig.8. Calculated values of distribution of temperature through the thickness of the workpiece

For the most pictorial presentation of influence of each factor affecting the heating of the workpiece, the temperature evolution of a typical node of the workpiece surface is divided conditionally into several sections (Fig.9).

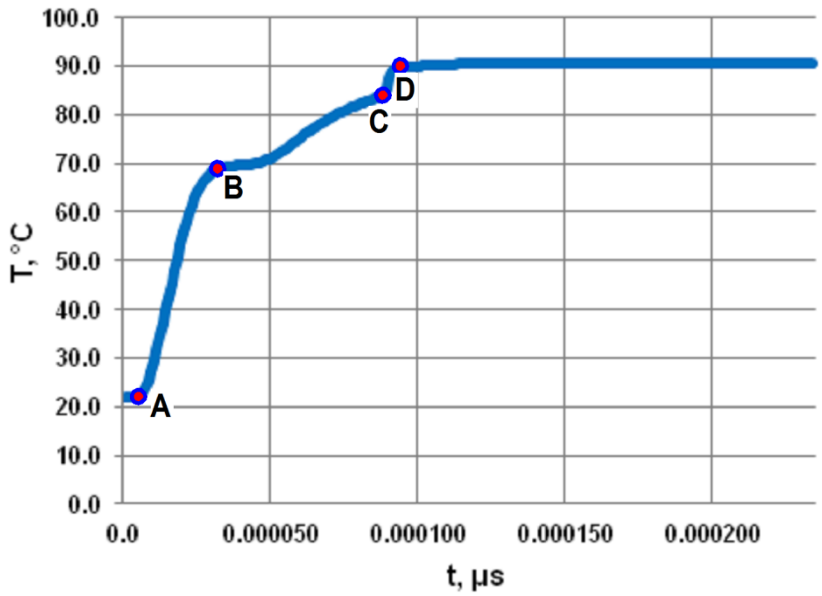

Fig.9. LS-DYNA result showing the different stages in the heating process of the exterior of the workpiece:
A-B: Joule Heating; B-C: Plastic heating, C-D: Heating due to collision with the die.

At the section A-B the main factor of heating the workpiece is Joule heating due to the induced eddy currents, in this case heating the workpiece owing to plastic deformation may be ignored. By contrast, the section B-C is characterized by essential reduction in influence of eddy currents on heating of the workpiece because of increase in the distance between the inductor and workpiece and heating by plastic deformation of workpiece material mainly. At the section C-D the prevailing factor of workpiece heating is its high-speed collision with the die. This plot in association with Fig.4 gives detailed idea of the process of beading of a plane workpiece under the action of the pulsed magnetic field.

4. Conclusions

Thus, possibilities of the electromagnetic module of the software complex LS-DYNA make it possible to take into account different factors of pulse-magnetic processing of metals including thermal factors which in their turn are of great technological importance.

For example - in realizing of different assembling joints. In this case thermal stresses, arising in the process of workpiece heating with its concurrent squeezing, essentially add integrity of such joints [4]. It is possible to manage these thermal stresses by repeated loading.

Thermal effects aid to proceeding of “warm” deformation in shaping operations of pulse-magnetic processing [5]. This leads to increase in technological plasticity which makes it possible, for example, to reduce the number of steps.

Moreover the thermal effects must be taken into account also in the case of workpiece with the counter-part during the formation of assembly or welding joints. The most heated and accordingly most plastic workpiece fills micro-irregularities of other workpiece, forming in this case the solid interface [4].

References

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