

EXPERIMENTAL STUDY OF STEEL BEHAVIOUR IN PROCESS OF MUSHY STATE DEFORMATION

EKSPERIMENTALNI ŠTUDIJSKI PROCES DEFORMACIJE JEKLA V KAŠASTEM STANJU

JAROSLAV HORSKÝ¹, M. RAUDENSKÝ¹, P. KOTRBÁČEK¹, B. ŠARLER²

¹Technical University of Brno, Czech Republic

²LFD, University of Ljubljana, Slovenia

Prejem rokopisa - received: 1998-11-25; sprejem za objavo - accepted for publication: 1998-12-07

The aim of the experiments was to measure the steel resistance to the tool indentation in mushy state (i.e. between the solidus and liquidus) in dependence on the tool position and to evaluate the influence of the temperature and that of the rate of loading on the history of forces acting on the tool.

Key words: steel, mushy state, resistance, forces on the tool

Namen predstavljenih poskusov je meriti odpor vdiranja orodja v kašasto stanje jekla (med solidus in likvidus temperaturo) v odvisnosti od položaja orodja in oceniti vpliv temperature in hitrosti obtežbe na časovni potek sil, ki delujejo na orodje.

Ključne besede: jeklo, kašasto stanje, odpor, sile na orodje

1 INTRODUCTION

In order to determine a constitutive model suitable for the simulation of the mushy state metal deformation, experimental testing providing material characteristics is required. In the temperature range of the semi-liquid area, the environment changes progress from a fully solid zone (solid curve) to a completely liquid zone (liquid curve). The changes in the composition of these two phases are followed by the changes in material rheology which results in the necessity to apply dynamically appropriate physical laws so that the material could be described in each instant. The behaviour of metals and other materials can be described using different mathematical-physical relations, however a thixotropic substance cannot be described by a single equation^{1,2}.

2 THEORY OF EXPERIMENT

The sum of equations used for the modelling of mushy state steel forming includes about 20 parameters that need to be determined or specified. Therefore, an experimental program was prepared verifying the influence of the following factors:

- influence of the penetration speed,
- influence of the percentage contents of solid and liquid phase on the penetration force.

The experiment was conducted for a series of constant temperatures between the temperature of solidus (T_s) and that of liquidus (T_L). The dependence of force on position at a constant temperature and velocity is the result of each measurement:

$$F = fce(x); v, T = \text{constant}$$

F - force

x - position

v - velocity

T - temperature

The series of measurements it repeated for the same temperatures, but different velocities of motion.

3 EXPERIMENTAL MATERIAL

Tool carbon steel was tested. It has a low content of additions (**Table 1**), which enables to study its parameters using the equilibrium metastable binary diagram Fe-C.

Table 1: Chemical composition of steel

Tabela 1: Kemična sestava jekel

ELEMENT	C (%)	Mn (%)	Si (%)
CONTENT	0.95-1.10	0.20-0.35	0.30

It is obvious from the diagram that the solidus temperature for the given steel is approximately 1346°C and

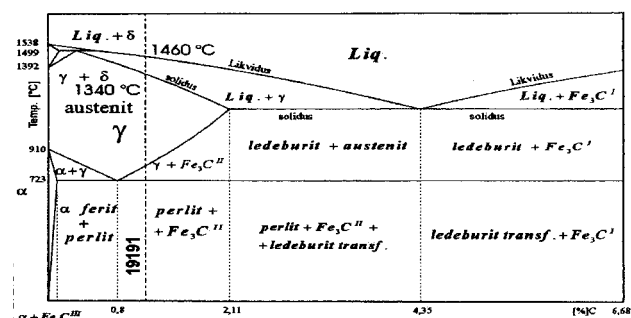


Diagram 1: Equilibrium metastable binary diagram Fe-C

Diagram 1: Ravnotežni metastabilni dvoestavinski diagram Fe-C

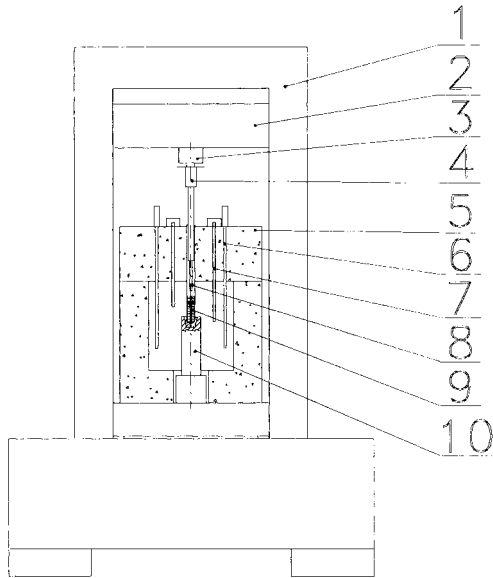


Figure 1: Principal scheme of the experimental apparatus: 1-load frame INSTRON, 2-load frame cross beam, 3-dynamometer, 4-tool chucking head, 5-furnace, 6-resistance heating elements, 7-thermocouple, 8-tool, 9-specimen - melted-down metal, 10-refractory concrete base

Slika 1: Osnovna shema eksperimenta: 1-obtežilni okvir INSTRON, 2-prečni drog obtežilnega okvirja, 3-silomer, 4-prižemna glava orodja, 5-peč, 6-uporovni grelni elementi, 7-termočlen, 8-orodje, 9-vzorec - raztaljena kovina, 10-podstavek

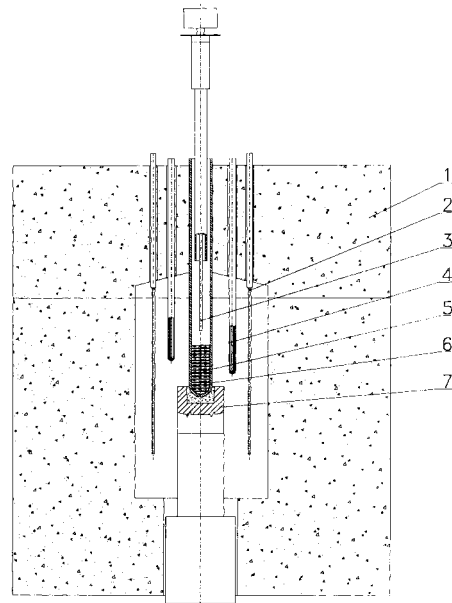


Figure 2: Resistance furnace scheme: 1-ceramic insulation CERACHEM, 2-resistance heating element SUPERKANTHAL, 3-tool (Al_2O_3), 4-thermocouple (Pt-PtRh13), 5-steel sample, 6-crucible (Al_2O_3), 7-refractory concrete base

Slika 2: Shema uporabne peči: 1-keramična izolacija CERACHEM, 2-uporovni grelni element SUPERKANTHAL, 3-orodje (Al_2O_3), 4-termočlen (Pt-PtRh13), 5-jeklen vzorec, 6-talilnik (Al_2O_3), 7-podstavek

the liquidus temperature $1465^{\circ}C$ (see **Diagram 1** Fe_3C). The difference between the temperatures is about $120^{\circ}C$. The theoretical contents of the solid and liquid phase were computed using the "lever rule".

By the tool diameter of 10 mm the ratio of the crucible diameter to that of the tool is $D_0 < 5$ in this case the forging becomes similar to the back extrusion³.

4 INDENTATION TEST

Indentation test procedure (see Figure 5)

- a sample is placed into the furnace and it is heated to a temperature corresponding to the melting-down

Description of the experimental apparatus for the indentation test

The basic part of the stand is formed by load frame INSTRON, (**Figure 1**) newly equipped with a position measuring device and a HOTTINGER dynamometer with a range up to 2000 N.

The inner structure of the furnace placed in the frame is shown in **Figure 2**. The furnace has a special design allowing to reach the mushy state of steels and to access the sample-area both from the top and the bottom side. The heated elements are made from SUPERKANTHAL. The control thermocouple is placed close to the sample of the material.

The measurement is carried out for two tool types of different diameters, 5 and 10 mm. The inside diameter of the crucible is $D_0 = 27$ mm. By the ratio $D_0/D > 5$ the forming becomes similar to the indentation into the half-space. The maximum length of the tool indented into the melted metal during the experiment is about 50 mm, (**Figure 3**).

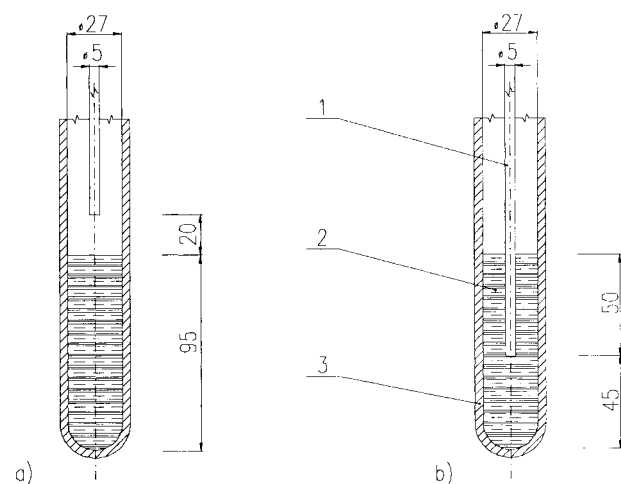


Figure 3: The initial and final position of the needle during the experiment: a) initial position, b) final position; 1-tool, 2-semi-liquid metal, 3-crucible

Slika 3: Začetni in končni položaj igle pri eksperimentu: a) začetni položaj, b) končni položaj; 1-orodje, 2-kovina v kašastem stanju, 3-talilnik

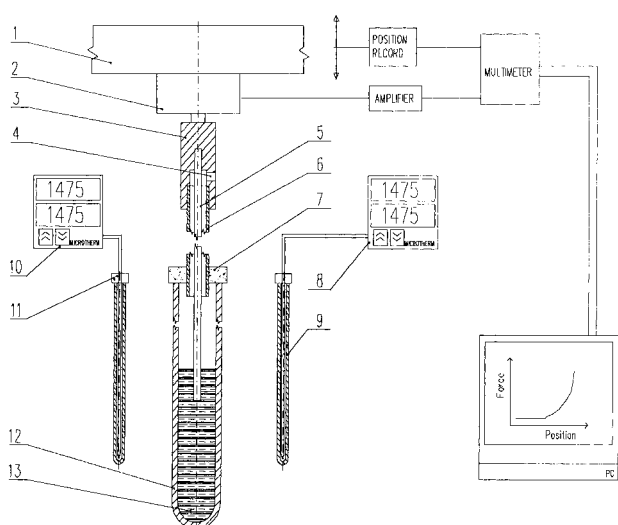


Figure 4: Experiment diagram: 1-load frame cross beam, 2-dynamometer HOTTINGER, 3-tool chucking heat, 4-argon inlet, 5-tool (Al_2O_3), 6-projective tube, 7-ceramic seal, 8-secondary programmable controller MICROTHERM, 9-secondary thermocouple (Pt-PtRh13), 10-primary programmable controller MICROTHERM, 11-primary thermocouple (Pt-PtRh13), 12-ceramic crucible (Al_2O_3), 13-specimen

Slika 4: Diagram eksperimenta: 1-prečni drog obtežilnega okvirja, 2-silomer HOTTINGER, 3-prižemna glava orodja, 4-vstop argona, 5-orodje (Al_2O_3), 6-usmerilna cev, 7-keramično tesnilo, 8-sekundarni programirni nadzor, 9-sekundarni termočlen (Pt-PtRh13), 10-primarni programirni nadzor, 11-primarni termočlen (Pt-PtRh13), 12-keramični talilnik (Al_2O_3), 13-vzorec

- the temperature in the furnace is decreased to a value prescribed for the experiment
- the needle is indented into the sample with a selected speed of motion and data describing the instant position of the needle and the instant force acting on the needle are monitored (the upper part of the furnace with low voltage wiring and the projecting part of the tool)
- the sample is heated to a temperature where the liquid state is reached
- now, the motion is reversed and the needle is moved into the starting position. (Position of the needle during the experiment can be seen in **Figure 3**).

Example of obtained results

A steel with a solidus temperature of 1340°C and a liquidus temperature of 1460°C was selected as experimental material.

Two examples of experimental force recordings were selected in: the material temperatures range from 1450°C down to 1410°C . The percentage of the solid fraction varies from 10% to 65% and it is described in detail in the appendixes. Resistance values were measured for velocities of loading 5 and 50 cm/min. for a tool with a diameter of $\phi D = 5$ mm and then for two velocities of

loading 5 and 50 cm/min. for a tool with a diameter of $\phi D = 10$ mm (see the appendixes A, B).

The diagram of the force-position dependence obtained by the indentation test can be divided into two sections.

In the first section, the force is constant until the instant of the tool touching the melted metal. For the second section, an exponential growth of the force is characteristic (see appendixes A, B).

In the experiments with other temperature or loading rate, the second part of the curve is shifted to higher or lower force values. Still, the character of the loading history is preserved.

5 HOT UPSETTING TEST

The experimental apparatus was additionally equipped to enable the hot upsetting test of a steel cylinder at very high temperatures corresponding to the melting of the specimen (see **Figure 8**). The first approach - the indentation of a thin tool into steel in semi-solid state, can be used at higher temperatures, i.e. also for a larger liquid phase in the specimen. The stress in the thin tool increases quickly with the increasing content of the solid phase, and may cause its failure. On the contrary, the temperature, at which the liquid content reaches a value where the tested cylinder cannot keep its original shape and gets destroyed due to the gravity, limits the second test. These two methods enable to study the steel

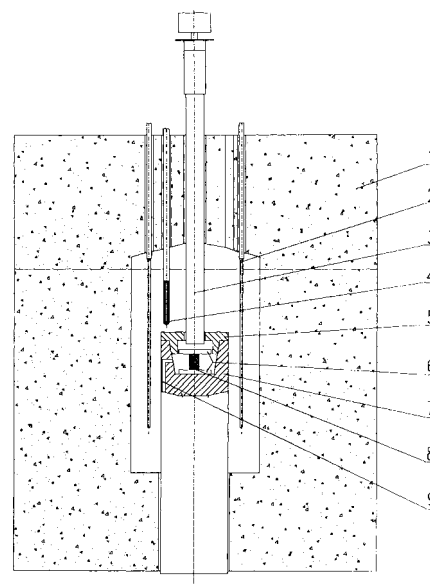


Figure 5: Resistance furnace scheme for the hot upsetting test: 1-ceramic insulation CERACHEM, 2-resistance heating elements, 3-refractory concrete tool, 4-thermocouple (Pt-PtRh13), 5-refractory concrete cover, 6-ground ceramic discs (Al_2O_3), 7-refractory concrete base, 8-tested cylinder, 9-inert atmosphere inlet

Slika 5: Shema uporovne peči pri: 1-keramična izolacija, 2-uporovni grelni element, 3-orodje, 4-termočlen (Pt-PtRh13), 5-pokrov podstavka, 6-keramična diska (Al_2O_3), 7-podstavka, 8-valjni preizkušane, 9-vstop interne atmosfere

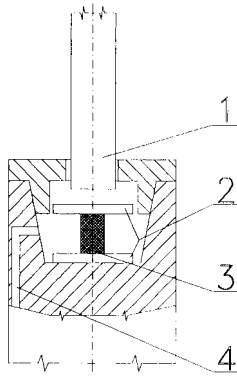


Figure 6: Hot upsetting test in detail: 1-refractory concrete tool, 2-ground ceramic discs (Al_2O_3), 3-tested cylinder, 4-inert atmosphere inlet

Slika 6: Podrobnost testiranja vročega posedanja: 1-podstavek, 2-podložna keramična diska, 3-valjni preizkušavec, 4-vstop inertne atmosfere

behaviour within the whole temperature range between the liquidus and solidus curves.

Description of the experimental apparatus for the hot upsetting test

The furnace was adapted for the hot upsetting test. The detail of experimental specimen used for the hot upsetting test is presented in **Figure 6**. The steel sample is cylindrical and the ratio sample diameter over height is $d_0/v = 1,6$. The sample diameter is then 15 mm and its height is 24 mm. The tested steel sample is placed on a corundum fine-grained ceramic disc with a ground surface. The massive support under the specimen is made of refractory concrete. Protective atmosphere is led through the refractory concrete directly to the steel sample. The tool diameter is 29 mm and it is made of refractory concrete. The steel sample is loaded through a second corundum disc by the tool (see **Figure 6**). Three hot upsetting tests were conducted for a temperature of 1369°C (10% of the liquid phase), 1388°C (20% of the liquid phase), 1405°C (30% of the liquid phase) and 1418°C (40% of the liquid phase).

Hot upsetting test procedure

- The tested cylinder is placed in the furnace and it is heated up to the required temperature in inert atmosphere.
- The tool is set into the starting position (10 mm above the specimen) (**Figure 7a**).
- The temperature in the furnace is homogenised (homogenisation time is 30 min.).
- The velocity of the tool is set (hot upsetting rate $v = 0.5$ cm/min.).
- The tested cylinder is upset using the pre-set rate and data on the instantaneous position of the tool and the instantaneous force acting on the tool are recorded (see **Figure 7b**). The mentioned system of force and position scanning enables a simultaneous transmission of data into the computer.
- The specimen is deformed to a 1/3 of its original length and after stopping the motion of the tool, the relaxation of the tested cylinder is measured (**Figure 7c**).
- The motion is reversed and the tool is moved back to the initial position.
- The measurement is repeated for a different upsetting temperature.

The dependence force-position (see **Figure 8**) is characteristic of the initial increase in force. In the following section, the material relaxation and the force reduction can be observed. In the final section, the force grows exponentially up to the maxim value. The force grows with the increasing diameter of the upset cylinder. After releasing the motion, the force decreases instantly and the material in mushy state relaxes.

ACKNOWLEDGEMENTS

The experiments presented here were supported by the project COPERNICUS, contract number OK 380290/2110/3422: "Computer aided process simulation of iron mushy state forming", with contribution of the

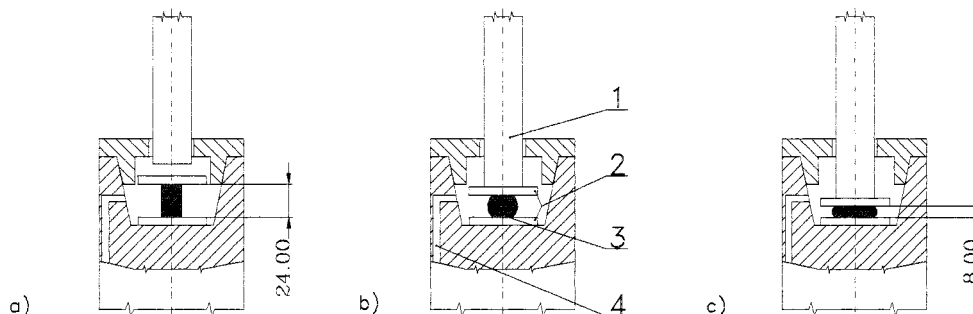


Figure 7: Hot upsetting test: 1-refractory concrete tool, 2-ceramic discs, 3-tested cylinder, 4-inert atmosphere inlet

- a) initial position of the tool - ($T=const.;v=0$)
- b) hot upsetting of the tested cylinder - ($T=const.;v=0,5$ cm/min.)
- c) final position of the tool - ($T=const.; v=0$)

Slika 7: Testiranje vročega posedanja: a) začetni položaj orodja, b) posedanje, c) končni položaj orodja; 1-podstavek, 2-keramični ploščici, 3-valjni preizkušavec, 4-vstop inertne atmosfere

Czech-Slovene cooperation project ME 380266/2110/3422.

Appendix B

Appendix A

Influence of temperature (of the solid friction) on the history of forces acting on the tool with a diameter of 5 mm. The experiments are carried out for three rates of loading 5 and 50 cm/min, (for detailed description see the diagrams and their captions below).

Diagrams showing the influence of temperature (of the solid fraction) on the history of forcing acting on the tool with a diameter of 10 mm. Measured for two rates of loading 5 and 50 cm/min, (for detailed description see the diagrams and their captions below).

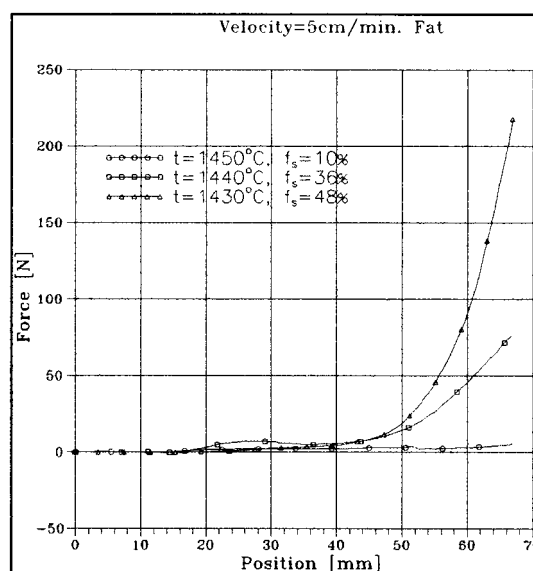
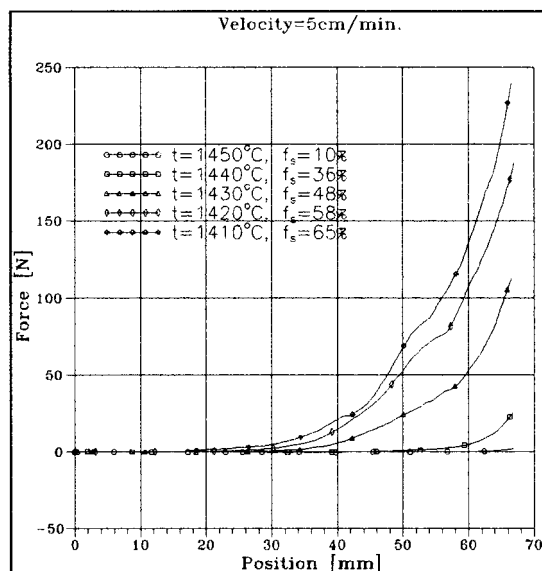


Diagram (Appendix A): Distribution of forces required for the indentation of tool of a diameter of 5 mm and rate of loading 5 cm/min.

Diagram (Appendix B): Distribution of forces required for the indentation of tool of a diameter of 50 mm and rate of loading 5 cm/min.

Diagram (Priloga A): Porazdelitev sil potrebnih za vtis orodja premera 5 mm s hitrostjo obtežbe 5 cm/min

Diagram (Priloga B): Porazdelitev sil potrebnih za vtis orodja premera 50 mm s hitrostjo obtežbe 5 cm/min

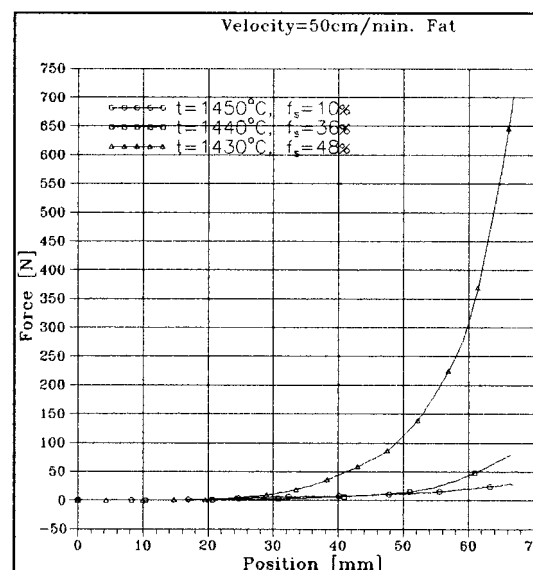
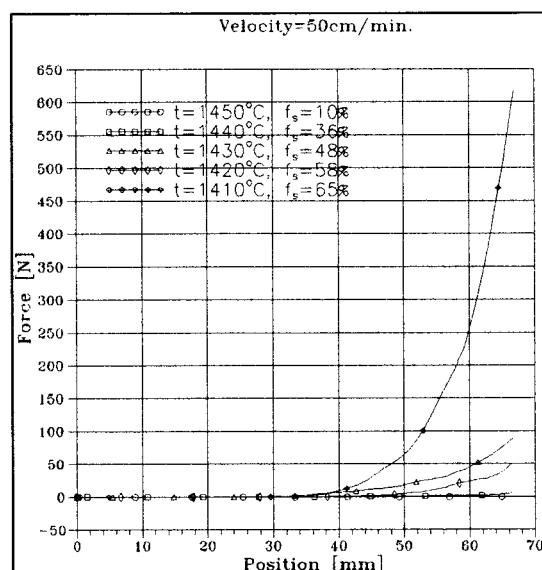


Diagram (Appendix A): Distribution of forces required for the indentation of tool of a diameter of 5 mm and rate of loading 50 cm/min.

Diagram (Appendix B): Distribution of forces required for the indentation of tool of a diameter of 50 mm and rate of loading 50 cm/min.

Diagram (Priloga A): Porazdelitev sil potrebnih za vtis orodja premera 5 mm s hitrostjo obtežbe 50 cm/min

Diagram (Priloga B): Porazdelitev sil potrebnih za vtis orodja premera 50 mm s hitrostjo obtežbe 50 cm/min

Appendix C

The results of the measurements are presented in the following **Figures 8 and 9**.

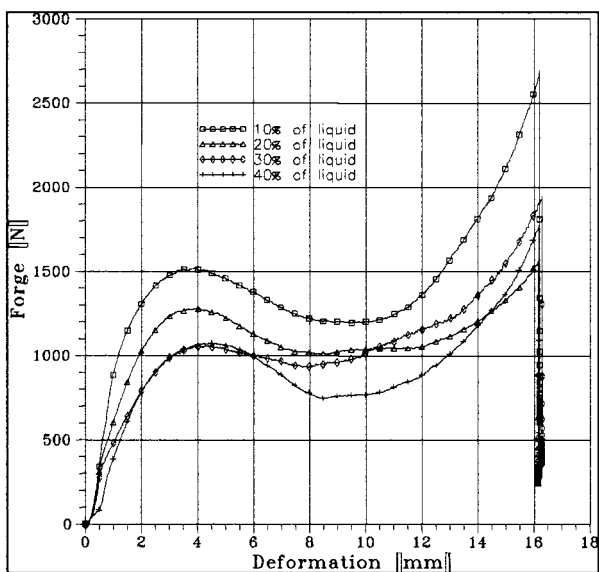


Figure 8: Dependence of the load force on the deformation of the tested cylinder during the hot upsetting test for a content of the liquid phase 10%, 20%, 30% and 40%

Slika 8: Vpliv utežne sile na deformacijo valjnega preizkušanca pri poskusu vročega posedanja za vsebnost kapljevine faze 10%, 20%, 30% in 40%

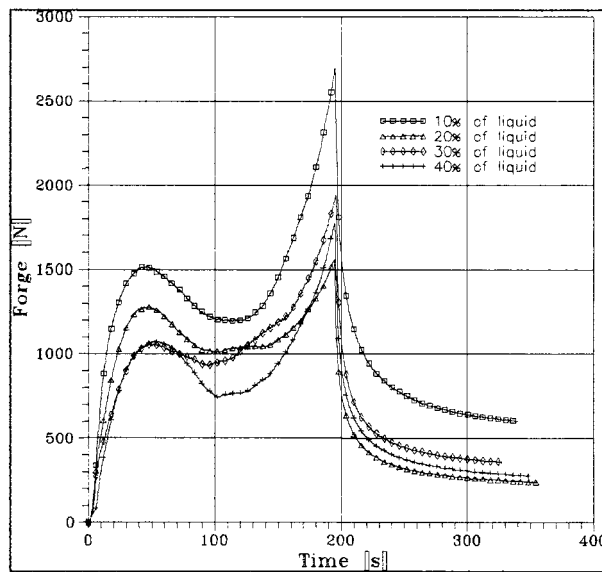


Figure 9: Time history of the load force during the hot upsetting test for a content of the liquid phase of 10%, 20%, 30% and 40%

Slika 9: Časovni potek utežne sile za vsebnost kapljevine faze 10%, 20%, 30% in 40%

6 REFERENCES

¹ V. Laxmanan, M. C. Flemings: Deformation of semi-solid Sn-15%Pb alloy, *Metallurgical Transaction A*, 11A (1980) dec

² M. Kiuchi, S. Sugizama: A New Process to Manufacture Semi-Solid Metals, *Proceedings of the Second Int. Conf.*, Eds Brown and Flemings, 1992, 47-56

³ M. Forejt: Teorie tvareni, Vysoke učeni technicke v Brne, Nakladatelstvi Vysokeho učeni technickeho v Brne, 1992