Measured temperatures on die bearing surface in aluminium hot extrusion

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Abstract: The paper presents an improved technique of temperature measurement on the bearing surface of industrial die during hot extrusion of aluminium. The measurement was carried out by using a method of split die and three thermocouples (incorporation of the K type and welded at distances from 0.18 to 1.32 mm from the bearing surface) with high measuring accuracy. Extrusion exit speeds was increased to the extent that Mg_2Si, with a known melting point, started to melt on the extruded profile. This state was determined by the phenomenon of oscillations of the measured temperature of the nearest two thermocouples and by the phenomenon of visually remarked deterioration of surface finish of the extruded profile. The applied method of temperature measurements is good either from the point of economic effect of industrial technologies, i.e. for increased productivity and for looking for technological solutions to cool industrial dies locally (close to the bearing surface of die) more intensively, or from the point of more accurate numerical modelling and optimizing the process of hot extrusion.

Keywords: AA 6063, aluminium hot extrusion, die bearing surface, temperature measurement

Introduction

Aluminium hot extrusion (Figure 1a) is a forming process, whereby a billet material is forced by compression to flow through a suitably shaped opening in a die to obtain a profile of smaller, but of uniform cross section. In this way produced various profile shapes due to their small weight and good mechanical properties have found their application in electrical and automotive industries, aeronautics, household goods, etc. The process of hot extrusion occurs at a billet temperature between 450 °C to or slightly above 500 °C, and at a profile exit speed between 5 to 100 m/min. The die opening through which the extrudates pass gives the profile the desired shape and dimensions, and the tribological conditions on the bearing surface (beside its quality) in the opening influence the quality of the extrudate surface. The contact pressure on the bearing surface (on it occur the sticking-, the transition- and the slipping zone, Figure 1b) reaches values above 100 MPa, while locally the temperatures increase even above 600 °C, since much heat is generated as a result of friction with the extruding profile. The temperature on

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the bearing surface of the die (and/or of the extrudate surface) is of crucial importance, as it determines the maximum extrusion speed; should the temperature on the profile surface reach the melting temperature of the phase (particles) with the lowest melting point, it results in an increased surface roughness thus diminishing the aesthetic and utility value of the product[1-3].

Temperature is generally measured[4-7] by inserting a thermocouple on the bearing surface of the die using the principle of the so-called grounded thermocouples of chromel-alumel type, in which the wires are connected to the front top of the thermocouple making the "hot point" (ϕ=1mm) of the measurement system (Figure 2). Such a measurement system requires very accurate placing of the thermocouples with regard to the bearing surface of the die and very precise calibration before extrusion (usually at the melting point of Si particles (577 °C) in extruding Al-1.2%Si alloy, Figure 2). Furthermore on, there exists a danger of changing the thermocouple position with regard to the calibration state due to the presence of highly normal contact pressures between the die bearing surface and the extrudate. This factors together with the use of dimensionally over-massive thermocouples (hot point Φ=1 mm) with an excessively long reaction time (longer than 0.6 s) essentially decrease the accuracy of the results obtained. Some authors[5,7] report that it is not entirely clear what the thermocouple inserted in this way actually measures: whether the temperature on the bearing surface or the temperature on the surface layer of the extruded profile and/or the temperature under the profile surface.

For a more precise measurement of temperature on the tribologically loaded parts of a die during hot forming such as laboratory

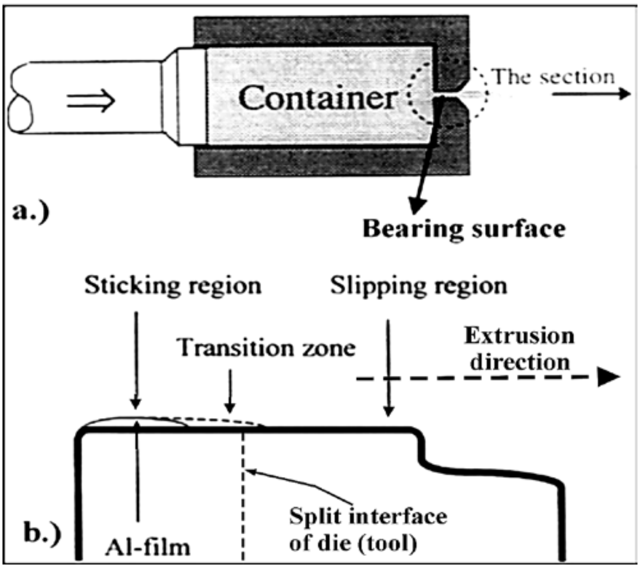

Figure 1. The principle of aluminium hot extrusion (a.) and a schematic depiction of occurring zones on the bearing surface of die with the marked division of die (b.).

hot rolling[8] and/or forging[9], investigators used thermocouples of type K. In the case of hot rolling Yoneyama et al.[8] welded and embedded the relatively thin wires of thermocouples (making channels) directly under the tribologically loaded surface by means of a special arbour ϕ=5 mm, which was then inserted in a roll, while Terčelj et al.[9] welded and embedded thin thermocouples close to the tribologically loaded surface by means of split die for hot forging in channels manufactured on the interface of the die. This kind of arrangement opens the option of more precise temperature measurements on the bearing surface of an industrial die applied for hot aluminium extrusion, a need expressed by several authors for some time[7, 10-11].

A knowledge of and control over the temperature on the bearing surface of the die and/or on the surface of the extruded profile is important from the viewpoint of the economy of the process (we want to work at as high speeds as possible), from the tribological aspect (higher temperature accelerates the wear of the bearing surface, the use of PVD coating), and from the point of view of the mechanical properties, structure and quality of the extrudate surface. Further, a precise knowledge of temperature is important for the improvement of the precision of FEM simulations (as a tool for the optimisation of the extruding process) and, along with it, a knowledge of the extrudate temperature on the basis of which the optimal extrusion speeds, etc. will be better determined (assessed)[6, 10-13].

The paper presents an improved method of temperature measurement on the bearing surface and/or at different distances from the bearing surface of an industrial die by means of the method of a split die and a thermocouple of type K with very short reaction time. This and a precise knowledge of the distance of the thermocouples from the tribologically loaded surface assured a more accurate assessment of the heat transfer coefficient.

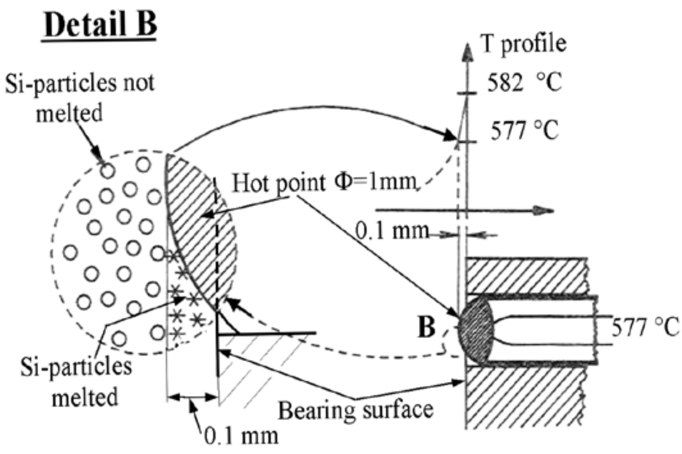

Figure 2. The basic principle of the previously way of temperature measurement on the bearing surface of die in aluminium hot extrusion[5].

Characteristics of applied measurement and materials

Temperature assessment of the contact of the extrudate with the die was carried out by measurement of the temperature close to the bearing surface (Table 1) of an industrial die made from AISI H11 during the hot extrusion of billets of AA 6063 with dimensions ϕ=210 mm x 800 mm in round rod ϕ=30 mm. The diameter of the container was ϕ=236 mm, which means that the extrusion ratio was ER=61.9. Figure 3 gives a schematic picture of the process of hot extrusion of aluminium, the assembly of die and backer with the spot of nitrogen cooling marked in the ϕ=60 mm circularly formed channel and 132.2 mm from the die bearing surface. Applied press equipment can extrude at the maximum extruding force 28 MN, and the maximum ram speed 15 mm/s. The applied initial temperatures of the front (this part entered the container first) and back part of individual billets are given in Table 2. The back parts of the billets had a deliberately lower temperature since during extrusion this part was additionally heated due to heat generation during extruding. Table 2 also presents the ram speed, profile exit speed and die cooling.

On the sectioned surface (contact interface) of the first part of the split die (Figure 1b, Figure 4 - Detail A) electroerosion was used to make very narrow channels (1 mm wide and 2 mm deep), which ended in the shape of a sectioned wedge at different distances directly below the die bearing surface (Figure 4, Detail A). Four thermocouples of NiCr-Ni type K with 0.2 mm wire diameter and up to 10.000 °C/s response time were applied to assure a precise measurement even in cases of rapid temperature changes, i.e. in cases of a change of friction on the bearing surface. The thermocouples mentioned above were welded at a distance of 0.18 to 1.32 mm (Table 1) from the bearing surface. The method used allowed a very precise reading of the distance of the welded thermocouple from the bearing surface using lower magnification of an optical microscope (Figure 4, Detail A**)**. The small distance of

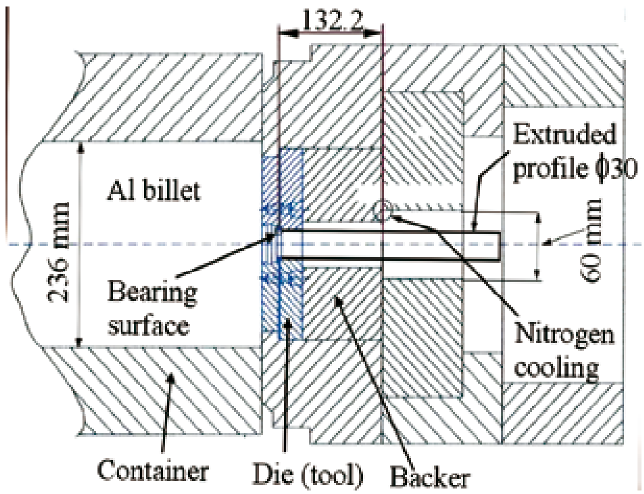

Figure 3. Schematic depiction of die assembly with the main dimensions and cooling spot

Table 1. Measured thermocouple (TC) distance from die bearing surface.

TC no.	1	2	3	4
Distance [mm]	0.18	0.30	0.55	1.32

Table 2. Cooling, temperature of billets (back/front), ram and profile exit speed.

Billet No.		1	2	3	4
Die cooling, N_2		No	Yes	No	Yes
Temp. [°C]	Back	470	459	461	457
	Front	459	466	459	458
Ram speed [mm/s]		5.7 8.8	8.8	13.6	13.6
Profil exit speed [m/ min]		21.2 32.7	32.7	50.5	50.5

the welded thermocouples from the bearing surface provided an additional guarantee of the possibility of an even more precise measurement of the least change of temperature on its surface or observation of when the surface of the extruded profile began to melt (e.g. of an Mg_2Si (Figure 5) particles (eutectic phase) with a known melting point (591 °C)[14-15]), resulting in a temperature oscillation at mixed friction (slipping and hydrodynamic). The wires were welded in the middle of the 6 mm long bearing surface, and the distance between the welded wires (NiCr-Ni) was 0.8 mm. For comparison the temperature measurement on the roll surface during hot aluminium rolling carried out by

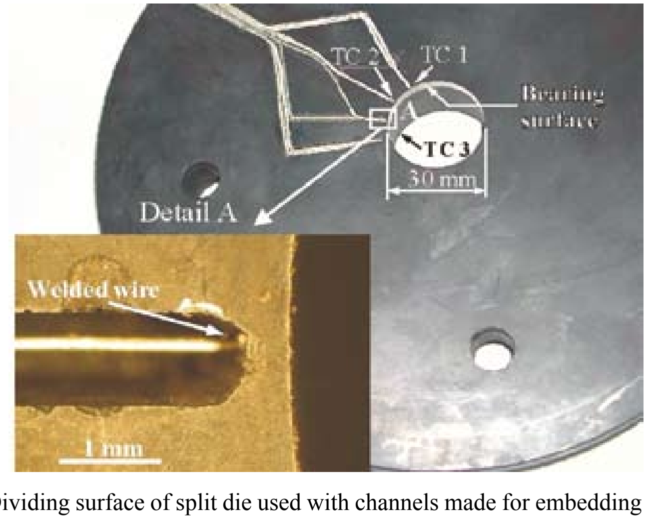

Figure 4. Dividing surface of split die used with channels made for embedding and welding

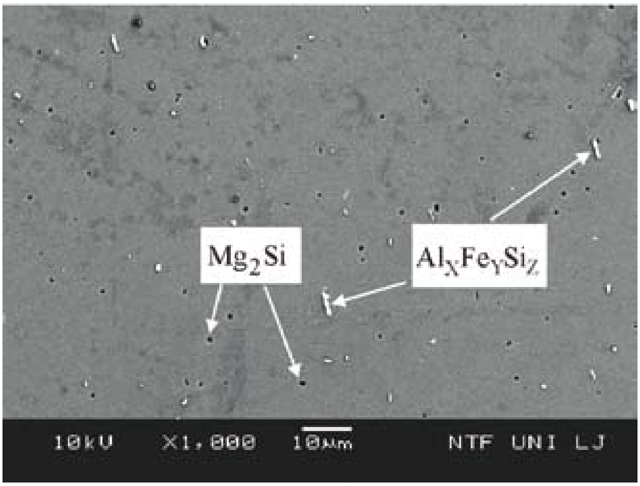

Figure 5. BEC image of homogenized initial billet microstructure; distribution of Mg_2Si and AlFeSi particles across the cross-section of the billet visible.

Yoneyama at al.[8] should be mentioned; namely they welded the thermocouples (type K) at a distance of 0.15 and 0.25 mm from the surface, and on the basis of results obtained in this way, determined the heat transfer coefficient in the hot rolling of aluminium. On the first die already mentioned above only one industrial measurement was carried out due to damage to the wires of thermocouple at the end of the extrusion process, but on the second die the remaining six measurements were carried out without any difficulties. During measurement of temperature the speed of the ram was varied both in the case of nitrogen cooling of die and in the case of non-cooling of the die (Table 2).

Results of measurements

The response of measured temperatures to the modified speed was selective enough and recorded both non-cooling and additional nitrogen cooling of the die. Each observation of an individually extrusion recorded the temperature resulting to all technological phases (billet bearing contact with the die bearing surface) of extrusion process (Figure 6), i.e. insertion and filling of container with extrudate, backward movement of the ram, extrusion phase and its completion. After entering the container and the movement of the ram forward, the billet filled the space (Stage 1) since its diameter (210 mm) was by 26 mm smaller than that of the container (236 mm). The temperatures measured of all three thermocouples increased distinctively, but the contact between the extrudate and the extrusion surface was still unstable so that it came to strong oscillations of the temperatures measured. This was followed by the drop of temperature (Stage 2) due to a temporary recurrent moving away of the ram in order to remove the air (burbcycle). During the extrusion process the temperature increased (Stage 3), towards the end of the extrusion a steady state was established when the supplied heat (slipping and aluminium forming generated heat) equalled the removal of heat in the interior of the die. Temperature (ca. 328 °C) on the bearing surface of the die before the beginning of extrusion process was a great deal lower than the expected temperature of the die at the placing in the extrusion equipment (450 °C) according to the criteria of industrial technology. During the extrusion of the billet No. 1 (no cooling, ram speed 5.7 mm/s) the temperature measured on the bearing surface increased all the time but it increased distinctively at the change of ram speed to 8.8 mm/s. Maximum temperature measured on TC 1 was 550 °C, on the second thermocouple (TC 2) it was ca. 543 °C and on the third thermocouple (TC 3) it was ca. 531 °C (Table 3). Towards the end of the extrusion phase a steady state was established in which the equation for heat transfer and conduction are easier to solve (Chapter 4). A slight temperature oscillation was noticed on the thermocouple TC 1, which may be the result of less stable friction conditions, especially in the transition zone (Figure 1b)[3] on the bearing surface of the die. By the end of the process (Stage 4) the temperatures measured displayed a distinctive drop.

FEM simulations of the temperature on the surface of a profile (CHANDA[16]) on modification of the extrusion speed do not display such an expressed growth (or fall) of temperature, which implies that the heat transfer coefficient adopted in FEM simulations was not correct (probably too low). The same conclusion can be drawn on the basis of the rapid growth of temperature immediately below the bearing surface of the die at the beginning of compression of the billet.

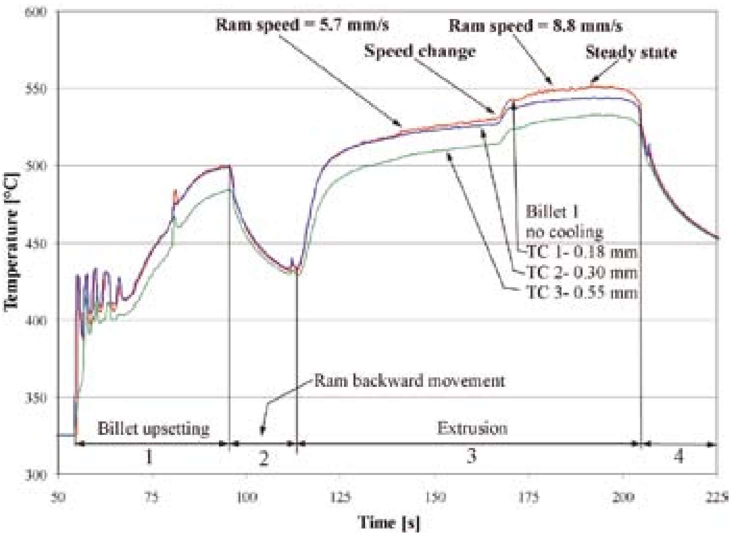

Figure 6. Time course of measured values of temperature in the die for different distances from the bearing surface, billet No. 1, ram speed=5.7 and 8.8 mm/s, no cooling.

During the extrusion of the second billet (Figure 7) the die was intensively nitrogen cooled, and the ram speed was kept constant all the extrusion time at 8.8 mm/s (the same as the maximum speed of billet No. 1). The final temperature measured on TC 1 was ca. 1 °C higher than for billet 1.

At billet 3 (no cooling of die, Figure 8) the ram speed was increased to 13.6 mm/s, which resulted in an additional temperature oscillation in the first two thirds of billet extrusion due to unstable friction conditions in the transition zone (Figure 1b**)**. Towards the end of billet extrusion (in the last quarter – establishment of steady state) the already visible beginning of melting of the present eutectic particle Mg_2Si occurred on the surface of the extruded profile. This was also reflected as an accentuated oscillation of temperatures measured and can be noticed at TC 1 and TC 2, which are welded the closest to the bearing surface, and to a lesser extent at TC 3. An accentuated oscillation of surface temperatures mentioned above can be attributed to the interchanging occurrence of slipping and hydrodynamic friction, which resulted in the oscillation of temperature on the surface of extruded profile due to their different friction coefficients and the heat consequently produced. The maximum temperature of thermocouple TC 1 measured was ca. 580 °C. The fact that TC 2 on the reaching of melting point of Mg_2Si showed approximately the same values as TC 1 (it is welded closer to the bearing surface) may be similarly explained by differently produced frictional heat due to uneven distribution of particles of the phase of the eutectic Mg_2Si phase across the cross-section of the billet, and consequently, on the surface of the extruded round profile. In the case of a lesser concentration of particles in Mg_2Si phase on the spot under TC 2, slipping friction was present to a greater extent, thus increasing the temperature on this part of bearing surface (before reaching the melting

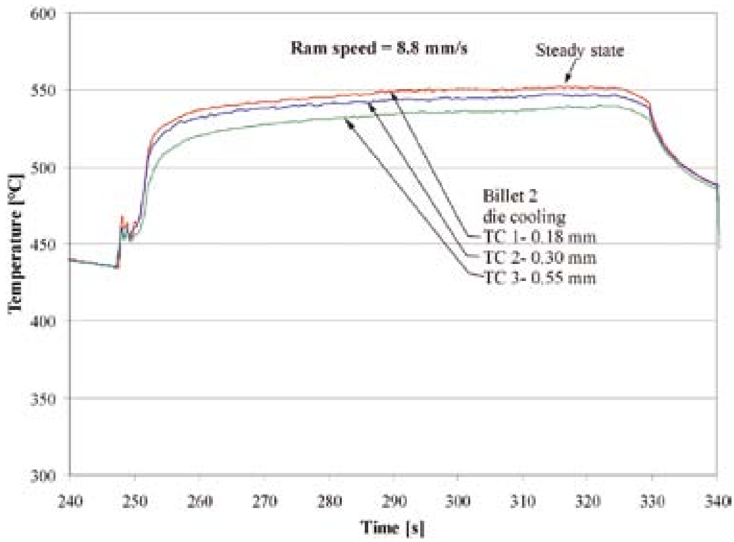

Figure 7. Time course of measured values of temperature in the die for different distances from the bearing surface, billet No. 2, ram speed=8.8 mm/s, die cooling (N_2).

point of the Mg_2Si phase in billet 3 and in the extrusion of all previously applied billets TC 2 always showed lower values than TC 1). The third thermocouple (TC 3) at a distance of 0.55 mm from the bearing surface scarcely recorded the attainment of melting point temperature of the Mg_2Si phase, which means that thermocouples at greater distances from the bearing surface are not suitable for a more precise measurement of its temperature changes. As already known, when the melting point temperature of the phase (Mg_2Si) reaches 591 °C[14-15], this causes a deterioration of extruded profile surface quality.

After casting the billets were slowly cooled and later they were reheated (2.1 hours) to the temperature of homogenisation (575 °C) for 2.5 hours, followed by a renewed slow cooling (350 °C/h), thus assuring the formation of eutectic Mg_2Si (Fig. 5) with a known melting point temperature. The eutectic thus serves as a calibrating value of the temperature on the extruding profile surface (oscillation of temperature on the bearing surface of the nearest thermocouples) in the determination of the heat transfer coefficient between the bearing surface of the die and the surface of the extruded profile.

In our opinion, measurement of temperature on the surface of the extruded profile using a pyrometer, especially due to difficulties in determination of the emission coefficient which depends on many factors such as, for example roughness of the surface, measurement angle, etc.[17], would not be more precise than our approach since we were able to perceive the change of friction using a sensitive thermocouple. We could observe very sensitively the local occurrence of hydrodynamic friction when the melting point of Mg_2Si was reached.

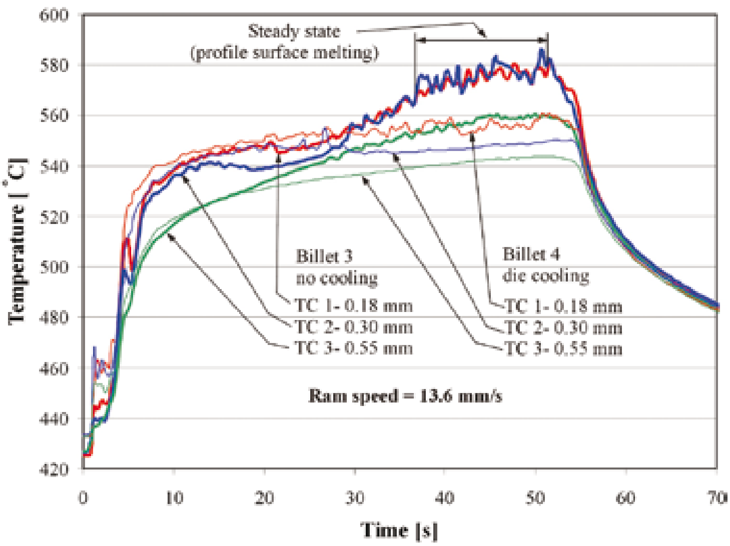

Figure 8. Comparison between the measured temperatures on the die bearing surface during extruding of the billet No. 3 and of the billet No. 4.

Table 3. Average temperatures and their relative errors in thermocouples obtained in measurements after the stationary state was established.

	TC 1 (r=15.18)	TC 2 (r=15.30)	TC 3 (r=15.55)
Billet 1	550.0 (1 ± 0.002) °C	543.3 (1 ± 0.002) °C	530.6 (1 ± 0.002) °C
Billet 2	550.8 (1 ± 0.002) °C	545.7 (1 ± 0.002) °C	535.3 (1 ± 0.003) °C
Billet 3	575.6 (1 ± 0.010) °C	574.7 (1 ± 0.010) °C	557.6 (1 ± 0.005) °C
Billet 4	556.5 (1 ± 0.004) °C	548.0 (1 ± 0.002) °C	542.0 (1 ± 0.002) °C

LEFSTAD AND REISO[15] reported two limiting temperatures (591 °C and 612 °C) on the surface of an extruded profile in extrusion of AA 6063. Which of those two temperatures would be limiting depends above all on the preliminary (previous) billet heat treatment (speed, cooling after casting, temperature of homogenisation, etc.) or the presence or absence of eutectic Mg_2Si[18-19].

Billet No. 4 was extruded at the same speed as billet No. 3; however, the die was nitrogen cooled. On the surface of the extruded round profile the beginning of melting was not observed since the maximum temperatures of the thermocouple at TC 1 were approximately 19 °C lower than for billet No. 3 (Figure 8). A slight temperature oscillation was noticed only in TC 1 and TC 2, which is connected with the already mentioned unstable friction conditions in the transition zone of the bearing surface.

All the measured values (Figures 6-8) the and their relative errors after the stationary state was established are given in Table 3.

CONCLUSIONS

In industrial hot extrusion of aluminium we used the improved method of temperature measurement on the bearing surface of die. The applied split die allows the making of channels for embedding of thermocouples on split interface of the first part of die and their welding on the top (end) of the channel just below the die bearing surface. The measurements of temperature field were carried out using four thermocouples, which were welded at different distances from bearing surface. The ram speed at the extrusion of each further billet was increased until the melting point temperature of Mg_2Si eutectic phase on the profile was reached.

The temperature was measured in the conditions of cooling of die (132 mm from bearing surface) as well as in cases of non-cooling of die. In spite of a relatively great distance of cooling from bearing surface it had an impact on its considerable decrease. This fact have lead us to the possibility of applying of a more locally cooled die (as near to the bearing surface as possible), which would help to remove the heat generated as a result of friction (slipping) between the extruded profile and die bearing surface, billet plastic deformations, etc. more intensively. Consequently, the extrusion speed could be increased even more relevantly and consequently the economy of this process.

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