

# The Hot Spot in Al-Rod Extrusion Investigated by FEM-analysis

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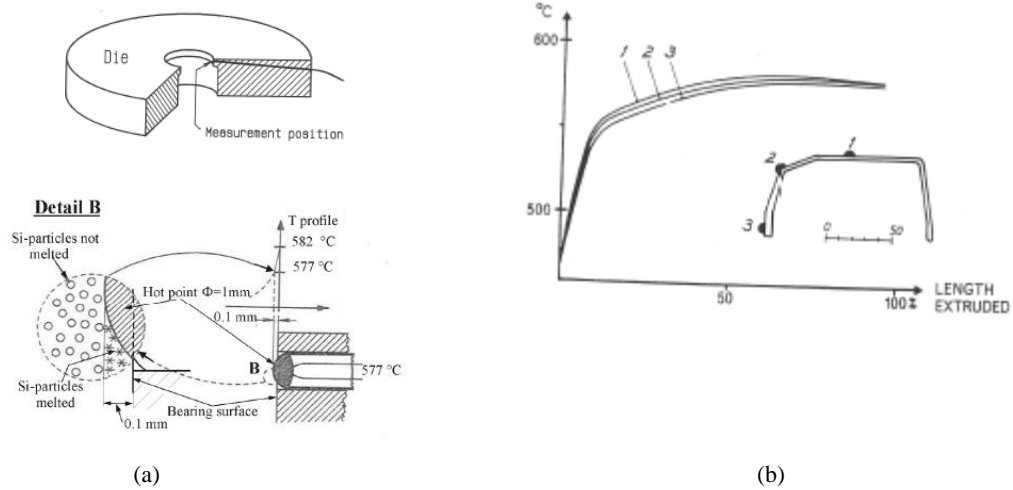
**Abstract.** FEM-analysis is applied to study thermo-mechanical conditions in an industrial Al-rod extrusion process using long billets as stock material. In the analysis, focus is on the conditions in the hot spot present inside the metal of the billet material near to the die edge during extrusion. Here the strain-rate and the temperature in the hot zone reaches critical conditions if the extrusion ram speed is set too high. When overcritical conditions exist here, speed cracking will occur in the metal. The Lagrangian version of the software DEFORM 3D is applied to model the process numerically, and it is investigated how the distribution of the temperature as state-variable is predicted in the hot spot and else how inside the billet, and how it depends on the extrusion conditions. Through the analysis, new information on this important issue is achieved.

## INTRODUCTION

Thermal conditions in metal extrusion is generally of great interest. One important reason for this is that the quality of the extruded product is closely connected to the maximum temperature in the extrusion metal flowing through the die orifice out into the resulting profile. If this temperature exceeds a certain critical level, an inferior quality is obtained<sup>1</sup> in the extruded product. This can either be because large recrystallized grains form in the outer surface layer of the extruded profile<sup>1</sup>, or due to cracking of the metal that forms this layer<sup>1</sup>, causing a dense pattern of unacceptable cracks on the surface of the profile.

Because of this, the thermal conditions in metal extrusion has been thoroughly investigated, and a vast amount of technical information exist on the topic. Different approaches have been applied in these studies; measurement of temperature by 1) an optical device placed behind the die<sup>1</sup>, by 2) thermocouples placed inside the billet prior to extrusion<sup>2</sup>, or by thermocouples placed 3) inside holes machined into the die<sup>3</sup>. Moreover, a thermocouple inserted through a hole machined through the die, so that it extends through the bearing surface and 4) drags against the extrusion metal which flows over the bearing has also been used<sup>4</sup>. Finally, an indirect metallurgical method has been developed, and used, in which 5) the thickness of the surface layer of the extrusion has been heated to a given temperature, or above, is determined<sup>4</sup>. This was done by using a billet material with a purpose-made microstructure, which transforms and forms a different microstructure as well as appearance above this temperature. Finally, it is common to study thermal conditions by means of 6) theoretical models of the extrusion process, and from the models to calculate temperatures at given locations in the material.

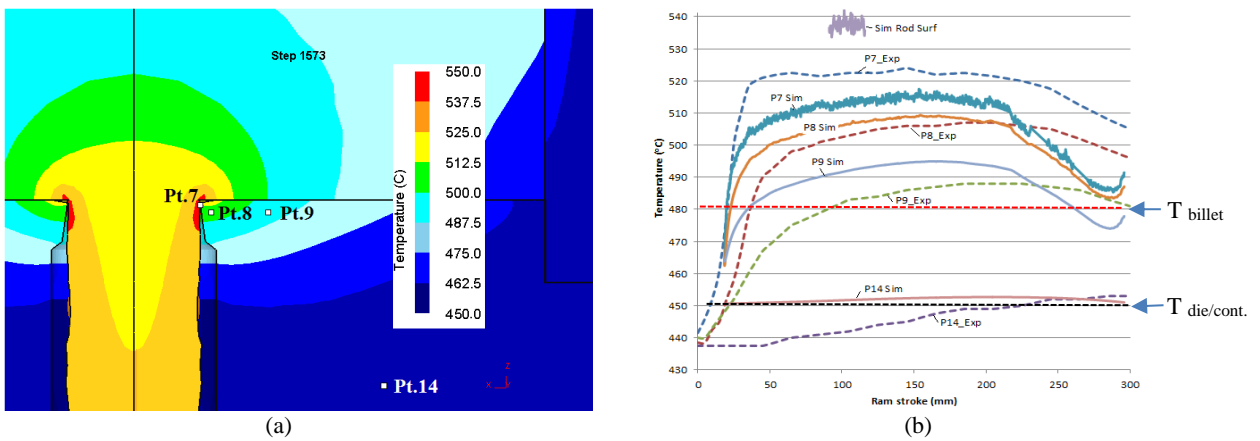
Fig 1 (a) shows possible placements of thermocouples in the die, and Fig.1 (b) typical graphical results obtained of measured temperature vs. extrudate length (or process time). Many similar graphs are available in the literature, and multiple behaviors are reported. After a steep increase, the temperature graph flattens out, and then remains flat during the stroke, or it may increase all the time, eventually drop down towards the end of the stroke, after having passed over a maximum value.



**FIGURE 1.** Temperature measurement<sup>4</sup> in aluminum profile extrusion: (a) Thermocouple inserted into die bore near to bearing (at the top), and dragging against the extrusion metal (at the bottom). (b) Typical measurement results in industrial extrusion.

As regards temperature determined by theory, already in 1956, Bishop<sup>5</sup> showed the presence of a hot spot in the extrusion metal at the entrance to/ in the die bearing, by calculation and drawing of iso-temperature lines on the longitudinal section of the billet. Numerical methods, as the finite-difference method, were later developed. Dahlheimer<sup>6</sup>, for instance, performed an early extensive analysis and confirmed the presence of a hot spot when extruding Pb and Al. Later, many theoretical investigations have been performed which shows the presence of the hot spot in extrusion, and the temperature levels reached here.

Earlier work performed by us<sup>7</sup> to map thermal conditions in Al-extrusion is now to be reviewed. With thermocouples placed inside the die and the punch head, information on the thermal conditions were collected in a laboratory extrusion process. In addition<sup>7</sup>, the process was simulated by FEM-modelling, to predict the same temperatures. The obtained temperature distribution in the billet and the die at a certain stage of extrusion is shown in Fig.2 a). In Fig.2 b), there is a comparison between experiment and simulation for various measurement positions in the die. There was confirmed fair agreement between the data sets from experiments and simulation, see Fig.2 b). The hot spot is clearly visible in Fig.2 a) as the red area in the extrusion material, near the edge of the sharp-edged die applied. The temperature, here, at the considered stage of extrusion, is predicted to exceed 540 °C, i.e., the temperature rise on the extrusion metal is  $\Delta T \approx 60$  °C, with an initial billet temperature of 480°C. The model, in this case, predicts a rather large jump in temperature of  $\Delta T \approx 20$  °C between the surface of the metal flowing through the die bearing and the corresponding temperature on the surface of the die.



**FIGURE 2.** Thermocouple vs. FEM-simulated die temperature in laboratory extrusion of rod; (a) FEM-computed temperature distribution plot with given location of measurement points, (b) Experimental readings vs. results from FEM-analysis.

## FEM-MODEL OF THE EXTRUSION PROCESS

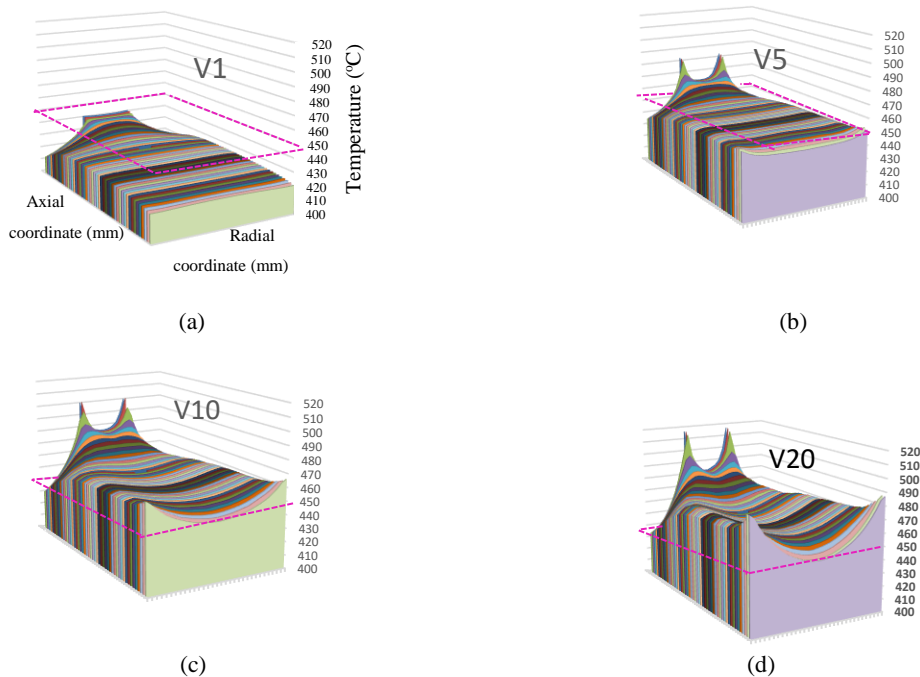
To model axisymmetric large-size billet extrusion (initial billet length 1000mm and diameter 280 mm) we used the Lagrangian version of the FEM-program DEFORM 3D. Extrusion was performed through a flat-faced die with die aperture diameter of 96.2 mm, i.e., the reduction ratio was  $R = 8.5$ . A number of else how identical simulations were run with the exception that the ram speed was changed stepwise in the simulations from low up to high speed. Initial settings of temperature in all simulations were  $T_{\text{billet}} = 450^{\circ}\text{C}$  /  $T_{\text{cont.}} = T_{\text{die}} = T_{\text{ram}} = 400^{\circ}\text{C}$ . Simulations were run for different ram speeds of: 1, 2, 3, 5, 10 and 20  $\text{mms}^{-1}$ .

The analysis was conducted to investigate ram speed effects on the temperature conditions. In the beginning of each simulation, some simulation steps were run with zero friction between billet and tooling, until the billet had been upset into the gap between the billet and the container. After full contact had been established between the billet and the container wall, the simulation was stopped. Full sticking friction was now specified between billet and tooling. An exception was the bearing channel of the die, where there was specified sliding friction, with a friction factor of 0.6 on the interface. The flow stress of the billet material was measured data for an AA7108 alloy. A finer FEM-mesh than elsewhere in the billet was used on the material in the back-end corner of the billet, in front of the die edge and in the bearing. More details about the simulation model and the extrusion process is given in a previous article<sup>8</sup>.

### RESULTS FROM THE MODEL

Computed thermal data collected from the simulations, are presented in Fig.3-Fig.5. It is advantageous to present the temperature distribution over the longitudinal section of the billet as a 3D-plot. Such plots collected for a partial stage of extrusion when half the billet material is extruded, are shown in Fig.3, for four different simulations.

The graphs in Fig.3 show how the temperatures varies with radial and axial position inside the longitudinal section of the billet, as a 3D-surface. Highest temperature are always predicted in the hot spot near the die edge while the lowest temperature is in the corner of the primary dead zone. In the figures, one plane is marked with pink broken lines, defining the initial temperature of the billet. The basal plane of the diagram represents the temperature of the tooling. By comparison, of the different 3D-surfaces in the figure, one can see that for the low ram speed ( $1\text{mms}^{-1}$ ) cooling effects is dominant over the billet section. However, in spite of this, there is in this case a hot zone with two hot spots in the material in front of, and in the die exit.



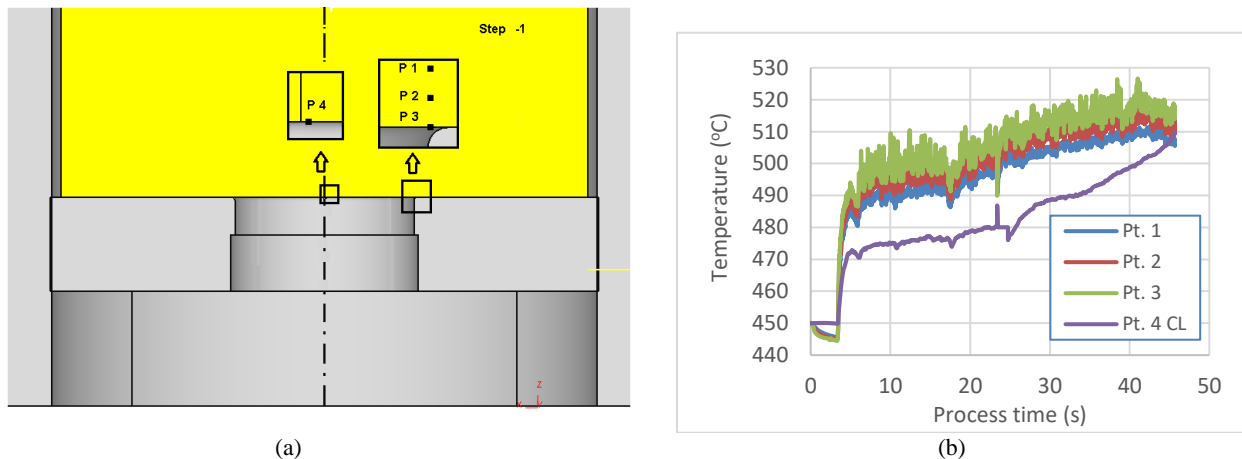
**FIGURE 3.** Temperature distributions inside longitudinal section of the workpiece for different ram speeds.

As regards the temperature distribution in extrusion, for the other cases of simulation there is predicted more heating than cooling over the major part of the billet, moreover, the part of the section which is cooled is decreasing with increasing extrusion speed. The temperature distribution is now characterized by the presence of a high ridge extending from inside the billet and toward the die edge; creating two hot zones, with the temperature in the rod in the center of the bearing being lower. Hence, in this distribution, there are two temperature peaks in the material, i.e., hot spots, located with symmetry on each side of the edge of the die bearing.

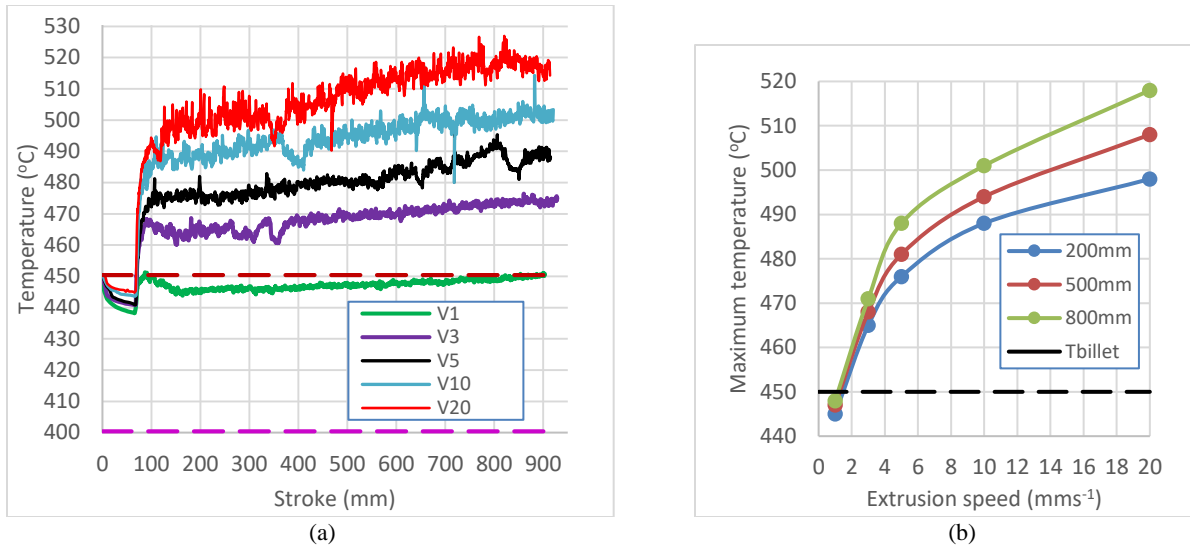
As regards the two simulations run with the high speeds of 10 and 20  $\text{mms}^{-1}$ , respectively, there is so much internal heating inside the whole billet volume, that the temperature increases all over the longitudinal section of the billet. However, there are two exceptions, one is in the primary dead zone in the corner of the billet between the container and the die, the other is in the secondary dead zone, in the middle rear end of the billet. Here, the material is still being cooled. For the high-speed extrusion simulations, significant heating is predicted along the shear zone extending backwards along the billet towards the ram at the rear end of the billet. Besides, as compared to the simulations run at lower speed, the temperature in the hot spot is strongly raised, concurrently, there is a larger temperature difference between the high peak temperature and the low temperature in the center of the bearing.

The software can also perform point tracking, i.e., a material point inside the workpiece can be selected (either as a moving or a fixed point) and the software calculates the variation of any state variable in the point during the course of the forming operation. Such tracking was performed by us on four fixed points located in the billet as shown in Fig.4 a). Pt.4 is in the middle of the billet at the entrance to the die aperture, while the other points Pt.1 – Pt. 3 are placed in the hot spot right above the die edge. Pt.3 was closest to the die edge, the two other points short distances above this point. Fig.4 b) shows temperature data for the selected points traced vs. time, for the model with ram speed 20  $\text{mms}^{-1}$ . The maximum temperature in the hot spot (i.e., Pt.3) increases as shown approximately linearly throughout the course of extrusion by  $\approx 20\text{ }^{\circ}\text{C}$  from  $\approx 490$  to  $\approx 510\text{ }^{\circ}\text{C}$ . Throughout the largest part of the stroke, the temperature in the center of the die exit lies  $\approx 15\text{-}20\text{ }^{\circ}\text{C}$  below that of the temperature in the hot spot. Towards the end of extrusion, there is a shift in behavior. At this instant, the billet length becomes so short that only a disc of material remains in the container. The ram now starts to push out the cold material from the primary dead zone into the surface of the extrusion, and the deformations in the center becomes intensified, so the temperature in the center of the material rises strongly.

Fig.5 (a) shows recordings of the maximum temperature in the hot spot (Pt.3) vs. stroke length for all simulations. For the high ram speed levels 5, 10 and 20  $\text{mms}^{-1}$  the graphs show the same trends as already described for the temperature vs. time curve in Fig.4b). Note that the steep temperature rise at the end of extrusion that is visible in Fig.4b) has been cut away in Fig.5a) for the reason to avoid considering the end stage of the process. In Fig.5a) the temperature gets higher with increasing ram speed, and, in addition, the slope of the curve increases with increasing ram speed.



**FIGURE 4.** Point tracking of temperature in fixed material points on the billet material at the entrance to the die exit (a) Locations of points, b) Temperature-time history of points for extrusion speed of  $20\text{mms}^{-1}$ .

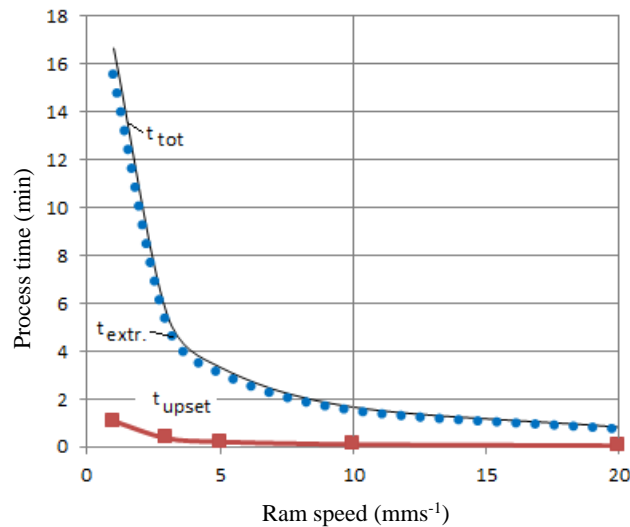


**FIGURE 5.** Maximum temperature in the hot spot in aluminum extrusion as collected from the simulations; (a) vs. stroke length for different ram speeds and (b) vs. ram speed at different stroke lengths.

For the simulation run with the lowest speed of 1 mms<sup>-1</sup> there is almost no heating in what else how makes up the hot spot, instead cooling effects from the colder tooling dominates, see Fig.5 a).

However, for the rest of the simulations the maximum temperature rises above that of the initial billet temperature of 450 °C. For the simulations with speeds 1 and 3 mms<sup>-1</sup> there is just a small change in temperature in the hottest spot throughout the stroke, such that conditions remains rather isothermal in these cases. Finally, towards the end of the stroke it starts to rise strongly again, i.e., when only a short disc of metal remains un-extruded in front of the die, but this is not shown in the graphs presented here.

In addition, the maximum simulation temperature in the hot spot (Pt.3) was collected at three different partial levels of extrusion for each simulation. The resulting data plotted vs. ram speed for all the simulations is shown in Fig.5 b). When maximum temperature is depicted this way, it can be seen that each of the graphs has approximately linear appearance at low speeds, up to a velocity of  $\approx 3$  mms<sup>-1</sup>, then there is a turning point at  $\approx 5$  mms<sup>-1</sup>. From this instant and onwards, up to 20 mms<sup>-1</sup>, the rise in temperature vs. ram speed is less.



**FIGURE 6.** Duration of the upsetting and the extrusion stage for different extrusion ram speeds.

It is straightforward to calculate process times of extrusion (eventually collect them from the simulations), both for the upsetting and the extrusion stage of the process. Such data are shown in Fig.6 for the different ram speeds in the chosen velocity range, used in the simulations. As the figure shows, the upsetting time is very short in relation to the time used during the following extrusion process. While total process time is more than 16 min for a ram speed of  $1 \text{ mms}^{-1}$ , it is 5 min for a ram speed of  $5 \text{ mms}^{-1}$  and less than 1 min for a ram speed of  $20 \text{ mms}^{-1}$ . Thus, as extrusion speed increases the time for heat transfer from billet to tooling strongly decreases. Concurrently, the amount of cooling on the billet from surrounding colder tools drops off strongly.

## DISCUSSION

The presentation of the FEM-calculated temperature distribution over the longitudinal section in terms of three-dimensional distribution diagrams, in which hatched lines marks the initial set temperature of the billet and the tooling, shows in a very illustrative way, where the billet material cools down and where it heats up during the extrusion process. From these diagrams it is easy to interpret the thermal effects on the material as the extrusion ram speed is increased. These diagrams show that cooling overrules heating effects when the extrusion speed is sufficient low (in the range  $1 - 2 \text{ mms}^{-1}$ ). At an extrusion speeds of  $5 \text{ mms}^{-1}$ , however, the heating effects due to shearing of the billet material against the container wall, will cancel out the cooling effects from the colder tooling. Finally, at high extrusion ram speeds in the range  $10-20 \text{ mms}^{-1}$  the extrusion process time becomes short and heating effects on the billet due to shearing of it against the container wall, overrule cooling effects on the billet from the colder container. Due to this, the temperature in the hot spot for high ram speeds rises significantly, from the beginning to the end of the extrusion stroke.

## CONCLUDING REMARKS

The FEM-analysis of the extrusion process provides fundamental information about the thermal conditions in large size billet industrial extrusion. For axisymmetric extrusion of the investigated alloy, such information is presented graphically in three different kinds of diagrams presented in the article. The diagrams visualize clearly how extrusion speed affects the thermal conditions inside the billet, and particularly the variation of the maximum temperature of the metal in the hot spot ahead of the die edge, throughout the course of the extrusion process. The diagrams which describes these thermal conditions are 1) 3D-distribution diagrams for each ram speed used in simulation, showing the predicted variation of temperature over the longitudinal section of the billet. In addition to this, there is; 2) a diagram showing the variation of the maximum temperature in the hot spot vs. stroke length, and finally; 3) same as 2) but with the maximum temperature in the hot spot plotted graphically vs. ram speed at different partial extrusion levels.

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