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# Extrusion Analyses by FEM and by Traditional Methods for 7075 Materials

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## Abstract

The extrusion of several Al alloys and composites have been modeled by an axisymmetric finite element method (FEM, DEFORM$^{tm}$ ) to determine the force-stroke curves and the temperature rise. With use of the FEM results as if valid experiments, the traditional methods are analyzed to clarify the approximations that are needed to bring those estimates into similarity with the FEM results. This exercise is carried out for a 7075 alloy and composites 7075/10v%$Al_2O_3$ and 7075/15v%$Al_2O_3$ for which the constitutive constants were derived by hot torsion tests.

## 1. Introduction

Extrusion of 7075 alloy and composites with 10 and 15% $Al_2O_3$ were analyzed by two techniques. The finite element method (FEM, DEFORM$^{tm}$) used data established by torsion testing and validated by comparison to other materials [1-10]. The method depends on reiterative calculation of strain $\varepsilon$, strain rate $\dot{\varepsilon}$, temperature T and stress $\sigma$ at each point on a mesh, as the ram moves to extrude the billet. The dependence of maximum total force $F_{TM}$ on billet temperature $T_B$ is shown in Figure 1 for 7075 alloy, being similar for the composites [3-6]. The traditional technique considers ideal and redundant work as well as friction with the chamber wall and uses average temperature and strain rate [11-20]. Clarification of the inter-relation of FEM and traditional techniques help make the highly detailed FEM results more acceptable to industrial users with long experience. Through comparison to results from 6061 materials [7,8], the estimates are extended to a higher ratio R=64 (from 31) by means of linear extrapolation at average slope for each material [27,28].

## 2. Method of Calculation, FEM

The general geometry of direct extrusion considers a billet of area $A_B$, diameter $D_B$ (178mm) and length $L_B$ (305mm) being extruded with a flat die with exit cross section $A_E$. The extrusion ratios R =($A_B$/$A_E$) were selected as 31 or 64 to match some actual press conditions. The ram speed $V_R$ was set at 2.6 or 5.1 mm/s. The billet temperature $T_B$ considered was in the range 350$^o$C to 500 $^o$C at 50 $^o$C intervals. The FEM calculations for an axisymmetric extrusion with a flat die were conducted for a slice from center line to chamber wall with two dimensional DEFORM$^{tm}$ software.

The model of calculation has been explained fully elsewhere [3-10]. The metal flow stress $\sigma_P$ (Figure 2) is calculated from sinh-Arrhenius constitutive equations derived from torsion testing [1,2]. The stress $\sigma_P$ is the maximum in the flow curve which is close to being a plateau, notably above 400 $^oC$. At 300 $^oC$ strength increases rapidly with rising $Al_2O_3$ content but declines with it at 500 $^oC$. The material is considered as a rigid-plastic solid; the tooling is considered as rigid [3-9].

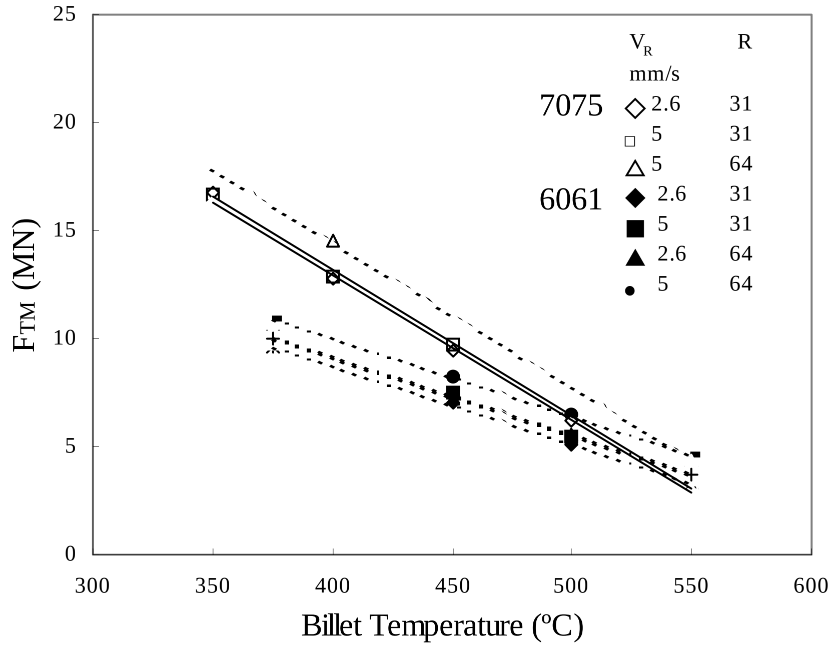



Figure 1: The dependence at $V_R$=2.6 or 5.1 mm/s of maximum force $F_{TM}$ on billet temperature for a) 7075 alloy (6061 for comparison). The FEM results for R=31 are shown as solid lines and the estimated ones for R=64 are dot-dashed. The result for 6061 are shown at 450 and 500 $^oC$ while the points at 375 and 550$^oC$ are calculated for the best fit lines with average slope.

### 3. Method of Calculation, Traditional

The work $W_T$ of direct extrusion has been traditionally divided into three quantities: ideal deformation $W_{id}$, redundant deformation $W_{rd}$ and chamber wall friction $W_f$ [11-13]. These can be converted into forces F by dividing each by the distance increment traversed, thus:

$$F_T = F_{id} + F_{rd} + F_f \qquad (1)$$

Because of the difficulty in estimating $F_{rd}$, the first two terms can be combined by using an efficiency factor $\eta$ which is unity if here is no redundant work [11-20].

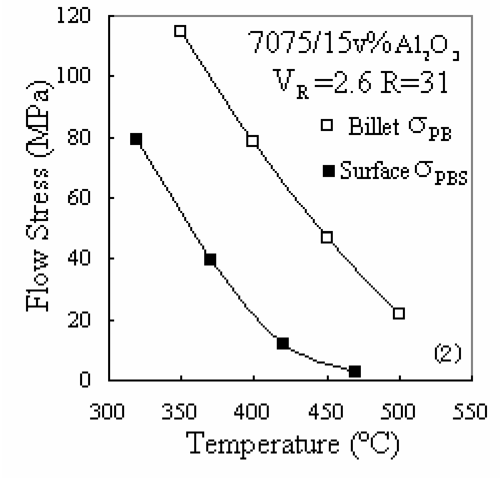
$$F_T = (1/\eta)F_{id} + F_f \qquad (2)$$

The maximum force $F_{TM}$ is attained when the deformation zone has spread across the entire billet section causing emergence of a nose just reaching the full profile [21-23]:

$$F_{TM} = (1/\eta)(A_B \sigma_{PB} \varepsilon_{id}) + \pi D_B L_B \mu_f \sigma_{PBS} \qquad (3)$$

The ideal strain is $\varepsilon_{id} = \ln R$. The initial flow stress $\sigma_{PB}$ is evaluated at the billet temperature $T_B$ and $\dot{\varepsilon}_{AV}$ (Figure 2). The average strain rate $\dot{\varepsilon}_{AV}$ is evaluated from the time it takes to fill the deformation zone when the billet is moving at ram speed $V_R$ [11-20].

The deformation zone is an ellipsoid with half length $3D_B/2$ in the axial direction; this gives an $\dot{\varepsilon}_{AV} = (2V_R \ln R)/D_B$ for volume $\pi D_B^3/8$. This shape is estimated from flow patterns in sectioned billet macrographs [21-23] or distortions of grids embedded before extrusion [11-13,24]. The friction force was calculated (Figure 3) with the coefficient of friction $\mu_f = 0.577$ for sticking conditions, i.e. the metal shearing internally. The strain rate $\dot{\varepsilon}_{AS}$ at the surface is estimated as less than $\dot{\varepsilon}_{AV}$ by a factor of 1000. Moreover, the chamber wall ($T_S$) was cooler than $T_B$; $T_B$ - $T_S$ was estimated as 30 $^oC$. The $\sigma_{PBS}$ calculated is given in Figure 2 and the friction force in Figure 3. With $F_{TM}$ from FEM analysis, the estimated $\eta$ for all 3 materials appear in Figure 4.



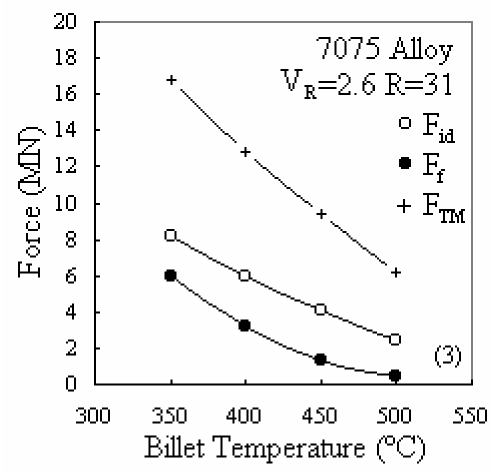




Figure 2 Flow stresses of 7075/15v%$Al_2O_3$ for use in Eq.(3): $\sigma_{PB}$ for average strain rate $\dot{\varepsilon}_{AV}$ (ellipsoidal deformation zone) and for surface shear at $\dot{\varepsilon}_{AS} = \dot{\varepsilon}_{AV}$/1000 and $T_S$=$T_B$-30.

Figure 3: Forces in extrusion of 7075 for total force $F_{TM}$, for ideal deformation $F_{id}$ and for friction $F_f$ from Eq.(3); the total is the result of the FEM analysis.

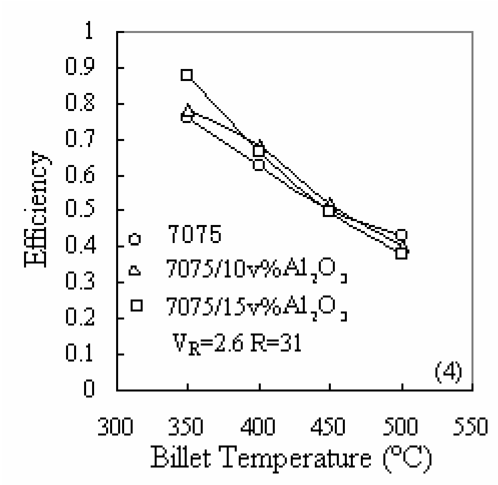
## 4. Calculation: Approximations, Results, Discussions

The efficiencies for 7075, 7075/10v%$Al_2O_3$ and 7075/15v%$Al_2O_3$ from Equation (2), $\eta$=0.8 to 0.4, diminish with rising $T_B$. Similar efficiency values were obtained for the 6061 materials that are shown in Figure 1, although the $F_{TM}$ values have a much different variation with T [7,8]. The value of $\eta$ in the literature has been determined by carrying the extrusion to near completion where the force starts to rise due to extreme friction in the short butt (Figure 5) [11]. With the assumption that $F_f$ (chamber wall friction) is almost zero at that stage, it was determined that $\eta$=0.2 to 0.3 for Al. However, it is possible that $\eta$ decreases across the extrusion stroke to the measured values [11] before the rapid rise in $F_T$ at the end. Additional support for this comes from some extrusion experiments on an Al-Si-Cu-Ni alloy [25] in which the friction was estimated from the initial pressures required to extrude different billet lengths; the values of $\eta$ were estimated to be in the presently determined range [26,27].

Instead of questioning the reported efficiency, one could doubt the FEM analysis; however, there are the following factors that do not support such a contention. The Deform$^{tm}$ FEM analysis gave distributions of the internal parameters [3-10] that agree with distributions derived from both other modeling [24] and macroscopic analysis of sectioned billet [21-24]; the grid distortion was similar to the change in shape of embedded marker lines [11,24].

The value of $F_T$ is calculated by integrating the stress at every point; even when the distribution is right, one could imagine that the magnitudes are wrong. However the forces for extruding the 7075 alloy compared satisfactorily with those calculated by empirical formulas from extrusion trials (Figure 5) [19]. Finally the $F_{TM}$ calculated for 6061+10%$Al_2O_3$ was very close to that measured in an extrusion trial [5-8].

The increase in $\eta$ as T falls can be related to the inherent strength of the material since it also increases at fixed temperature as the material considered becomes harder (Figure 6). This would infer that for material of high flow stress, the deformation is more streamlined thus incurring less redundant strain. One could argue that the higher strain hardening rate results in a larger deformation zone which provide more gradual transition from the sliding billet to the dead zone. If the deformation zone was systematically shortened as $T_B$ increased, then the efficiency might be made almost independent of T.



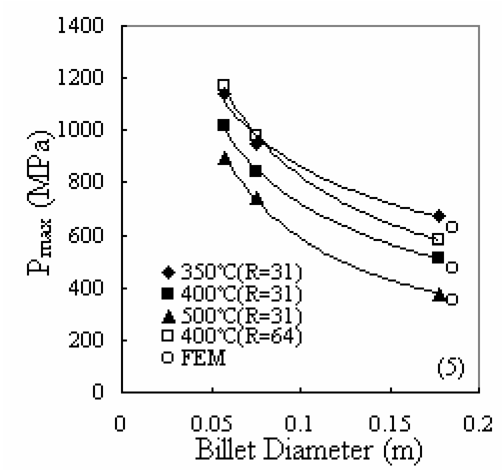




Figure 4: The efficiency calculated from Eq.(3) for 7075 alloy ( $\eta_{AV}$ = 0.580 ) , for 7075/10v%$Al_2O_3$ ( $\eta_{AV}$ = 0.597 ), and 7075/15v% $Al_2O_3$ ( $\eta_{AV}$ = 0.606 ); ( $\eta_{AV}$ = 0.594 ) for all 3 materials.

Figure 5: The maximum pressure is calculated for 7075 alloy at various billet diameters according to empirical formulae for several conditions of R and $T_B$ [19]; $P_{max}$ declines with billet diameter (the present 0.185m); for this the FEM calculated values are entered just to the right of the empirical calculations (represented by small circles lower for higher T at R=31).

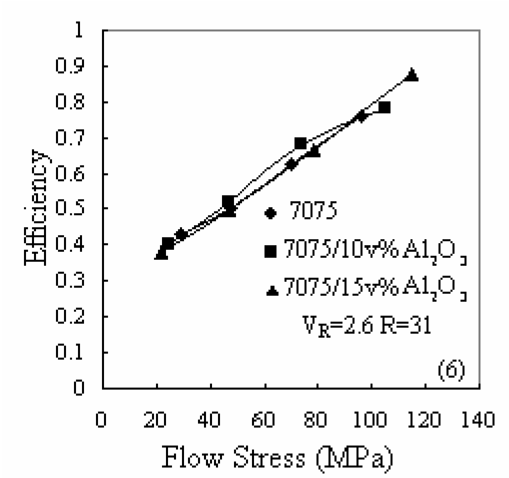
## 5. Temperature Rise in Hot Zone; Initial Drop in Force

The rise in temperature from the FEM calculations is simply ($\Delta T_{FEM} = T_{max} - T_B$). The rise in temperature $\Delta T_{gen}$ is calculated traditionally from the work done in the hot zone:

$$\Delta T_{gen} = (\dot{\varepsilon}_{AV}\sigma_{PB}) \text{ (time to reach 10mm stroke)/(heat capacity /unit weight)} \qquad (4)$$

To take account of the rapid rise in both T and $\dot{\varepsilon}$ near the die exit, a much shorter conical hot zone with length $D_B$/4 was used so that $\dot{\varepsilon}_{AVH} = 4\dot{\varepsilon}_{AV}$, still only a small fraction of $\dot{\varepsilon}_{max}$ from FEM [3-10]. The use of a smaller hot zone than the deformation zone calculation of $\eta$ seems warranted from the manner in which the heat accumulated in an advancing slice of billet with very little loss due to conduction backwards into the billet because of its rising velocity.

In the later stage of a direct extrusion, there is a continuous decrease in $F_T$ as $F_f$ declines when the billet shortens. Just after the peak, there is an initial drop in $F_T$ which is much faster than the above. This drop to $F_{TAD}$ is considered to be related to the formation of a hot zone. From the FEM analysis of T distributions, $T_{max}$ is reached at the die land after about a 10 mm advance (~$0.03L_B$) [3-10], $F_{TAD}$ is evaluated from the load stroke curves at 10 mm. The ideal force is evaluated for deformation under the new conditions of the hot zone with $\sigma_{PH}$ calculated from Eq.(1) at $T_{max}$ and $\dot{\varepsilon}_{AVH}$. The total force $F_{THZ}$ after the hot zone is established is then evaluated from Eq.(3) with use of the same friction as previously but with $\sigma_{PHZ}$ and a value of $\eta$ derived from Figure 4 at $T_{max}$ instead of $T_B$. The value of $F_{THZ}$ is compared to $F_{TAD}$ in Figure 7. These calculations confirm that the initial drop in the force is related to the establishment of the hot zone [14,15,20-23]. This approximation is consistent with the traditional method and with the work being averaged over the hot deformation zone for $\Delta T_{gen}$.



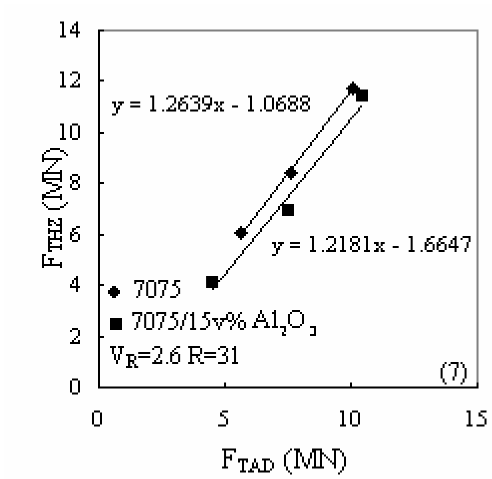




Figure 6: The efficiency is almost independent of the material but a function of $\sigma_{PB}$ at R=31, $V_R$ =2.6 mm/s

Figure 7: Graph of total force $F_{THZ}$ calculated by traditional formula Eq.(3), from same hot deformation zone compared to the force $F_{TAD}$ from the force-stroke curve at 10 mm stroke where $T_{max}$ is attained, for (a) 7075, (b) 7075/10v% $Al_2O_3$. With the slope of 1.2168, offset 1.5405 for 7075/10v%$Al_2O_3$, the average slope for three materials is 1.2329 and average offset is 1.4247.

## 6. Conclusions

In fitting the traditional analyses to FEM results, the use of the most common approximations did not yield reasonable values of the efficiency relating ideal and redundant work; the approximation had to be pushed to the feasible extremes to succeed. The efficiency in the early stages is estimated to be about 0.8 and agrees with values based on extrusion trials with varying billet lengths. It thus appear that the efficiency falls to about 0.3 as the extrusion is completed because the redundant work has become much greater in the short butt of the billet. With some altered approximations for analyzing the developed deformation hot zone, it was found possible to calculate the temperature rise and also the initial rapid decrease in the pressure caused by this rise.

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