A Review on Extrusion Process of Alloys in Semisolid State

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Abstract – The extrusion in semisolid state is a developing technique in present days for the production of military, critical automotive and aerospace components. The importance of the semisolid extrusion technique relies primarily on the distinct rheological behaviour of the alloys during solidification under deformation. It is noticed that, the extrusion in semisolid state depends on various process parameters like shear rate, slurry temperature, cooling rate, length of contact, die angle etc. Hence, theoretical models of semisolid rheology need proper implementation for successful implication of the semisolid extrusion technique. In the present study, the author presented an overview of various theoretical models on semisolid extrusion of alloy slurry based on existing literature and their own work.

Index Terms – Semisolid forming, Extrusion, Rheology, Apparent viscosity, Extrusion power.

1. INTRODUCTION

In recent years, the development of new production technologies has become a challenge to the researchers from quality as well as cost aspect. In this connection, semisolid forming (SSF) is a developing technique for producing critical automotive, military and aerospace components. Especially the metals that are difficult to process with conventional technologies can be easily processed with SSF technologies. It is found that the alloys in semisolid state have good fluidity and low flow stress [1, 2, 3, 4). Hence, SSF reduces energy consumption, saves production stages and increases productivity. In SSF, liquid metal is stirred mechanically or electromagnetically during solidification. Hence, the dendrites are fragmented at solid-liquid interface and transported into liquid. The suspended solid particles form semisolid slurry. In the slurry, the fragmented dendrites become globular particles, surrounded by nearly eutectic liquid, after coarsening. The semisolid slurry shows low viscosity even at high solid fraction, which implies low forming efforts and smooth laminar flow in the die during filling. Hence, SSF reduces the porosity and redistributed the macrosegregation during forming, and results high mechanical properties of the products.

In this connection, few literatures are reviewed. Atkinson [5] and Fan [6] reported the effect of process parameters like shear rate, cooling rate and microstructures on rheological behaviour of semisolid slurries, and few related models of slurry rheology are presented. Burgos et al. [7] presented the kinetics of agglomeration as well as de-agglomeration of the suspended particles in the slurry using a structural parameter which mainly depends on shear rate and shear stress. Alexandrou [8] presented the non-Newtonian behaviour of slurry using the Herschel-Bulkey model where shear stress is represented by multiplying the yield strength of the slurry with the structural parameter. Simlandi et al. [9] developed a model to predict the rheological behaviour of A356 in semisolid state where the alloy is sheared between two parallel plates during continuous cooling. They also represented the non-Newtonian behaviour of the semisolid slurry considering the shear stress based on the Herschel–Bulkley model. However, the theoretical model of the slurry behaviour during solidification under shear is rarely found in literature. Barman and Dutta [10] investigated the rheological behaviour of semisolid aluminium alloy (A356) slurry under high cooling rate (30 to 50°C/min) and high shear rate (650 to 1500s^{-1}). They predicted that the slurry viscosity increases with increasing fraction of solid and increasing cooling rate, and it decreases with increasing shear rate.

From the above literatures, it is seen that the essence of the SSF technique relies primarily on the distinct rheological behaviour of the alloys during solidification under shear. It is also noticed that, the success of SSF technique depends on process parameters like slurry temperature, shear rate, cooling rate, and length of contact, die angle etc. For successful implication of the SSF technique, theoretical models of semisolid rheology need proper implementation during forming.

Thus, in the present work, the author presented an overview of various theoretical models of semisolid extrusion technique of alloy slurry based on existing literature and their own work.

1.1. Model on forward extrusion process of alloys in semisolid state

Since, forward extrusion process is one of the most demanded forming technologies in industry; the present study considers the extrusion process of A356 alloy in semisolid state. In this regards some related literature are reviewed. Sadough et al. [12] presented the backward extrusion process experimentally where the influence of temperature on flow behaviour of an A356 alloy in the semi-solid state is presented. Rattanochaikul et al. [13] developed a new semi-solid extrusion process using semisolid slurry at low solid fractions. They used a laboratory extrusion system to fabricate aluminum rods of 12 mm diameter. Jafari et al. [14] simulated forward extrusion process of an aluminium alloy using finite volume method at semisolid state and reported that the temperature and die angle influence the process significantly. Form the above literatures it is found that the extrusion process in semisolid state depends on many parameters such as temperature of the alloy, die-angle, length of contact etc, which demands a systematic study. However, the theoretical model needs proper implementation of the semisolid rheology during processing.

Accordingly, the authors developed an appropriate rheological model for forward extrusion process of semisolid A356 alloy in the work Simlandi et al. [15]. The semisolid alloy is forced through a plunger with the help of a Ram. Subsequently, the alloy is deformed while it passes through the die and reduces to a diameter of the final product. During processing, the total force applied to the ram is divided into two parts: one that requires displacing the alloy without deforming it in the section of length L and the second part that requires deforming the alloy in the die. Accordingly, the total extrusion force is calculated as

$$F = \frac{\pi}{4} d_i^2 \sigma_{xx} + \pi d_i L \tau_0 \tag{10}$$

Corresponding extrusion power is calculated as $P = F \times V_B$. Where V_B is the speed of ram, d_i is the billet diameter, and τ_0 is the shear stress. The normal stress σ_{xx} is represented as

$$\sigma_{xx} = 2\mu_a \frac{\partial u}{\partial R} \tag{11}$$

The flow field is represented by the following conservation equations in cylindrical coordinates as

Conservation of Mass:

$$\frac{1}{r}\frac{\partial}{\partial r}(ru) = 0 \tag{12}$$

Conservation of Momentum:

$$\rho u \frac{\partial u}{\partial r} = -\frac{\partial p}{\partial r} + \mu_a \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{1}{r^2}\frac{\partial^2 u}{\partial \theta^2} - \frac{u}{r^2}\right) \tag{13}$$

$$-\frac{\partial p}{\partial \theta} + \frac{2}{r^2}\mu_a \frac{\partial u}{\partial \theta} = 0 \tag{14}$$

The non-Newtonian behaviour of the semisolid slurry is incorporated considering the Herschel–Bulkley model.

$$\tau = \left[\frac{\tau_0(\lambda)}{\dot{\gamma}} + K\dot{\gamma}^{n-1}\right]\dot{\gamma} \tag{15}$$

The rate of strain in Eq. (15) is calculated as

$$\dot{\gamma} = \frac{\partial u}{\partial R} \tag{16}$$

The corresponding evolution of the structural parameter (λ) is considered as [9, 11, 15, and 16]

$$\frac{d\lambda}{dt} = \alpha_0(1-\lambda) - \alpha_1 \lambda \dot{\gamma} \exp(\alpha_2 \dot{\gamma}) \tag{17}$$

Finally, the *Homotopy Perturbation Method* is used to solve the constitutive equations analytically and the corresponding velocity profile is obtained as

$$\begin{aligned} V(Y) = {} & 1 - Y^2 - \alpha\left[\frac{1}{30}\mathrm{Re}Y^6 - \frac{1}{6}(2\alpha+\mathrm{Re})Y^4\right] - \left(\frac{2}{15}\alpha\,\mathrm{Re} + \frac{1}{3}\alpha^2\right)Y^2 \\ & -\alpha^2\left[\begin{aligned} & \frac{1}{1350}\mathrm{Re}^2 Y^2 - \left(\frac{1}{70}\alpha\,\mathrm{Re} + \frac{1}{170}\mathrm{Re}^2\right)Y^8 + \left(\frac{3}{40}\mathrm{Re}^2 + \frac{1}{4}\alpha\,\mathrm{Re} + \frac{1}{6}\alpha^2\right)Y^6 \\ & -\left(\frac{1}{12}\mathrm{Re}^2 + \frac{3}{8}\alpha\,\mathrm{Re} + \frac{5}{12}\alpha^2\right)Y^4 \end{aligned}\right] \\ & -\left(\frac{163}{18900}\alpha^2\mathrm{Re}^2 + \frac{1}{21}\alpha^3\mathrm{Re} + \frac{1}{15}\alpha^4\right)Y^2 \end{aligned} \tag{18}$$

Then, the assumed apparent viscosity (μ_a) is updated as

$$\mu_a = \left[\frac{\lambda\tau_0}{\dot{\gamma}} + K\dot{\gamma}^{n-1}\right] \tag{19}$$

First, the authors presented velocity distribution of the alloy during deformation in the die. Subsequently, the extrusion power is calculated. It is found that the extrusion power of the semisolid A356 alloy depends on process parameters. The main process parameters are alloy temperature and cone angle of the die. Accordingly, variation of the extrusion power at different alloy temperatures and cone angles of the die is predicted.

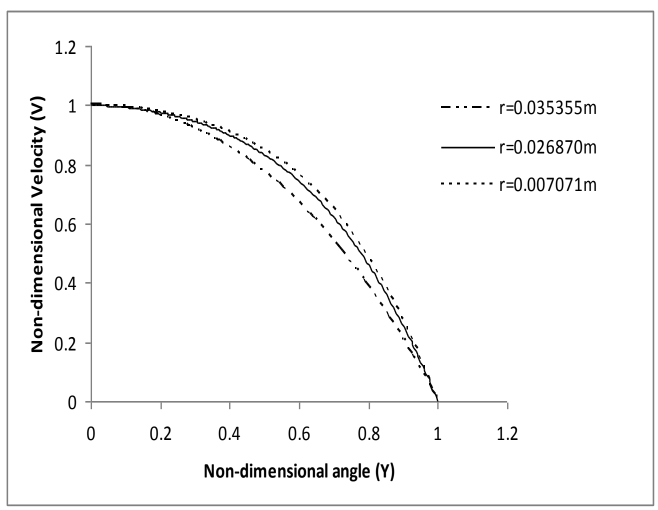

Figure 1 Variation of non-dimensional velocity at different die sections [15].

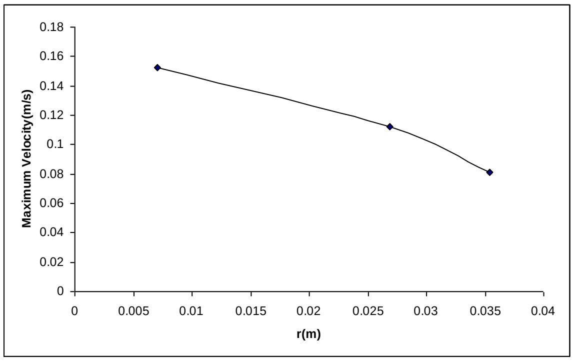

Figure 2 Variation of maximum velocity along die axis [15].

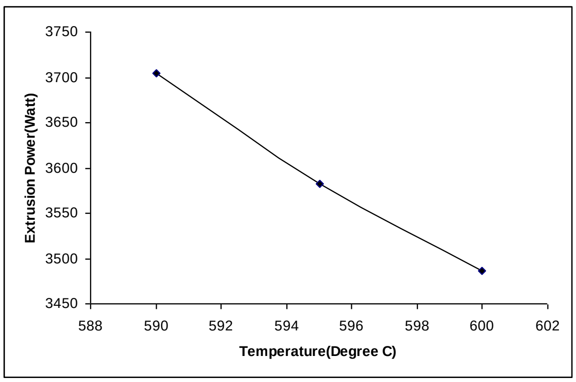

Figure 3 Variation of extrusion power with alloy temperature [15].

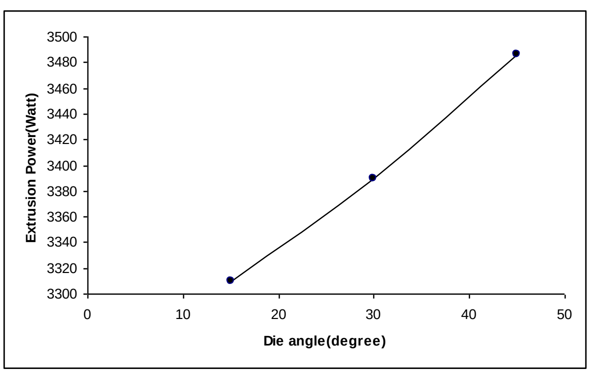

Figure 4 Variation of extrusion power with die angle [15].

2. CONCLUSION

In the present study, the author reported an overview of theoretical models of extrusion technique of alloy in semisolid state based on their own work. Hence, the authors first presented modelling of the forward extrusion process and bar drawing process of semisolid A356 alloy. In forward extrusion, it is predicted that the extrusion power decreases with increasing alloy temperature and increases with increasing die angle. The work also predicted the energy requirement for extrusion of semisolid A356 and solid aluminium separately. It is seen that about 50% of energy is saved in case of semisolid extrusion process at alloy temperature of 595°C.

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