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Review Article

An Overview of Semisolid Processing of Aluminium Alloys

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Semisolid metal processing (SSM) or thixoforming is a new technology that offers several advantages over liquid processing and solid processing. This process utilizes semisolid behavior as well as reduces macrosegregation, porosity, and forming forces during shaping process. A lot of research work has been carried out by various researchers in order to exploit the potential of this process to produce different products especially for automotive industry. This paper will summarise the rheological behavior of aluminium alloys in semisolid slurries, thixoformability of modified aluminium alloys, the effect of feedstock production method on mechanical properties, and the importance of developing low-cost raw materials for semisolid processing.

1. Introduction

Thixoforming is a viable technology for forming alloys in semisolid state to near net-shaped products. Thixoforming basically consists of three phases, as shown in Figure 1; (a) producing a material with a globular microstructure, (b) heating the material to the forming temperature, and (c) forming the material in a die-casting press. The process relies on the thixotropic behavior of alloys with a spheroidal rather than a dendritic microstructure in semisolid state [1]. Flemings and his students were the first to discover accidentally this thixotropic behavior in the early 1970s while performing continuous hot tearing test of solidifying Sn-15% Pb [2].

In thixotropic condition, an alloy decreases in viscosity if it is sheared but it will thicken again if it is allowed to stand [3–6]. This process requires uniform heating and partial remelting of the alloy slug to obtain a homogeneous consistency throughout [7]. This technology promises some advantages such as prolonged die life due to less thermal shock and also provides more laminar cavity fill which could lead to reduced gas entrapment [8]. This process also can improve the usage of feedstock materials and it can contribute to the reduction of processing cost of thixoformed parts [9]. Viscous flow is improved in semisolid metal processing because this process can provide additional laminar cavity fill, which can reduce gas entrapment.

Aluminium alloys are among the most prominent and well-known materials used in the mechanical construction and automotive industries, as shown in Figure 2. According to Kenney et al. [10], the energy needed to heat aluminium alloys for casting is 35% greater than that required to heat the same aluminium alloy for the conditions needed for semisolid forming. Millions of aluminium alloy components are produced every year through thixoforming processing route. Most of the parts are made from conventional casting alloys such as A356 and A357, which provide high fluidity and good castability [11]. Nowadays, many vehicles used aluminium engine blocks instead of cast iron, so significant weight reduction is achieved. Aluminium castings are used in almost 100% of pistons, about 75% of engine cylinder heads, 85% of intake manifolds, and 40% of chassis applications in automotive power trains [12]. The minimum fracture elongation of 15% demanded by automotive industry in safety-critical parts is hard to be achieved by die casting [13]. Therefore, the automotive industry highly needs thixoforming because it can improve the elongation as well as the mechanical properties of the materials used in automobiles [14].

This paper is divided into four sections. The first section focuses on the rheological behavior of aluminium alloy which is a very important element in semisolid processing. The second section focuses on the thixoformability of new aluminium alloys tailored for semisolid processing. The third section discusses the effect of feedstock production method

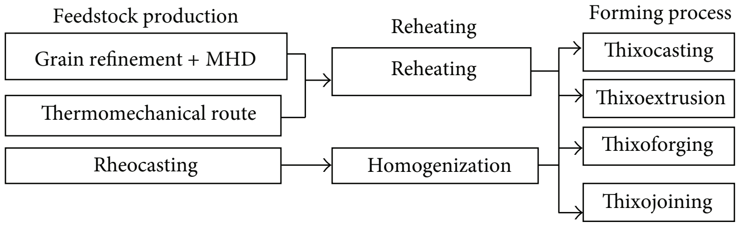

Figure 1: Semisolid metal processing routes.

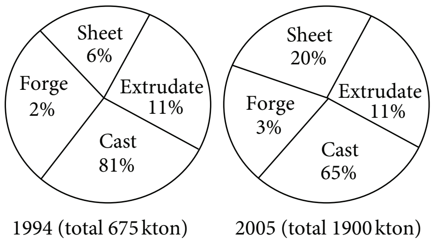

Figure 2: Development of aluminium consumption for automotive applications in Europe [12].

on the mechanical properties of thixoformed samples. The last section presents the importance of developing low-cost raw materials for semisolid processing.

2. Rheological Behavior of Aluminium Alloys in Semisolid Slurries

Rheology is a scientific term that refers to any material with a behavior between liquid and solid and which might be deformed if stress or load is applied on it. All types of materials with solidifications extending over a temperature range in the mushy zone are generally suitable for semisolid processing. A lot of research has already been done for the rheological characterization of the semisolid alloys [15–21]. Alloy deformations are exclusively dependent on viscosity which varies with metallurgical as well as process parameters [22]. Fraction solid in the primary phase, such as α-Al dendrites in Al-Si alloys, is one of the important parameters that affect the viscosity of the mush. Experiments show that an effective amount of fraction solid for thixoforming is between 0.5 and 0.6. When the fraction solid is below 0.5, the slug becomes too soft to support its own weight. When it is above 0.6, the slug will become too stiff to flow and will not fill in the die [23]. Semisolid slurries can be categorized into two groups; (a) liquid-like and (b) solid-like. Liquid-like slurries contain dispersed particles, and they demonstrate fluid behavior under external forces. By contrast, solid-like slurries have a solid phase, and they behave like solids that exhibit well-defined yield strength [7]. Semisolid slurries with less than 0.6 fraction solid have two different rheological properties; (a) pseudoplasticity and (b) thixotropy. Pseudoplasticity refers to the shear rates that are dependent of steady-state viscosity, while thixotropy describes the time dependence of transient state viscosity at a given shear rate [7]. Viscosity is inversely proportional with shear rate because it decreases with an increase in shear rate. This phenomenon occurs when agglomerated particles break down as shear rate increases. It also reduces the amount of entrapped liquid in the particles and effectively decreases particle size at low cooling rates.

A comprehensive study on the rheological phenomena in stirred SSM slurries was performed by Joly and Mehrabian in 1976. In their experiment, they found that vigorously agitated slurries exhibit thixotropic behavior, whereas their apparent viscosity depends on the structure which increases with an increase in volume fraction solid [24]. They have divided the rheological phenomena in stirred SSM slurries into three categories; that is, pseudoplastic, thixotropic, and continuous cooling behaviours. The first two behaviours are described above, while the last one can be described as the viscosity evolution during continuous cooling at constant cooling rate and shear rate. This phenomena plays an important role on the rheological behavior of semisolid slurries. In particular, it can give the first insight into the effects of solid fraction, shear rate, and cooling rate that is relevant in semisolid processing. Hirt et al. [25] stated that if semisolid slurries are allowed to stand, their viscosity will increase, whereas their globular particles will tend to agglomerate, as seen in Figure 3. It can be said that the parameters that influence the rheological behavior of semisolid slurries mentioned above are very crucial in semisolid metal processing.

Another experiment was conducted by Kattamis and Piccone [26] in various solid fractions. They found that the apparent viscosity of sheared semisolid Al-4.5% Cu-1.5% Mg alloy slurry increases with an increase in volume fraction solid (f_s) and cooling rate, and it decreases with an increase in shear rate, as shown in Figure 4. The higher cooling rate will lead to a greater volume of α-Al dendrites in the microstructure [27]. Kattamis and Piccone presented graphs on variations in apparent viscosity versus isothermal holding time at a constant shear rate and temperature purely related to various solid fractions, as shown in Figure 5. The decrease in apparent viscosity with time is caused by the breakdown of agglomerated particles with simultaneous coarsening and the decrease in specific particle surface area.

Yang et al. [28] investigated the relationship between apparent viscosity and shear rate during thixocasting in A356 aluminium alloys. They observed that when shear rate is less than $4 \times 10^3\ s^{-1}$, viscosity sharply decreases, and when the shear rate is over $4 \times 10^3\ s^{-1}$, viscosity slowly decreases and tends to approach a minimum value for apparent viscosity.

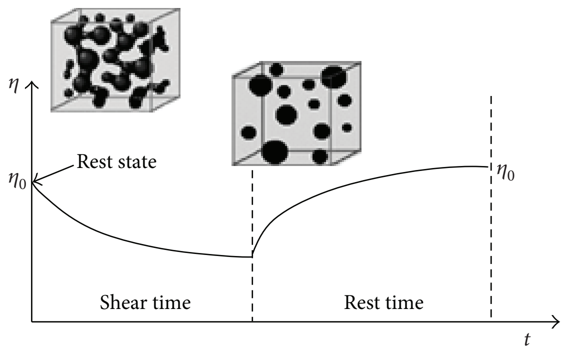

Figure 3: Time-dependent thixotropic behavior [25].

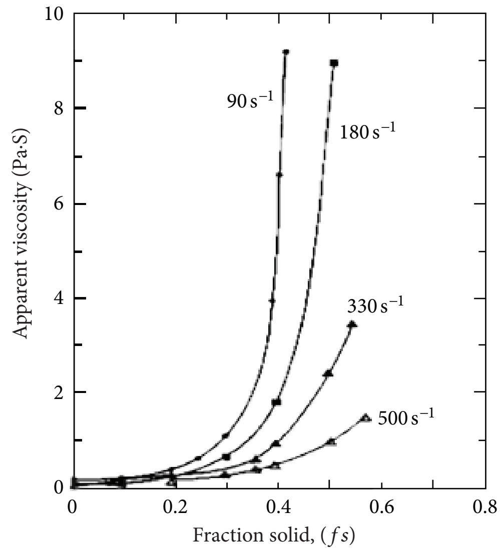

Figure 4: Apparent viscosity versus solid fraction of Al-4.5%Cu-1.5%Mg continuously sheared during cooling at 0.33 K min^{-1} at different shear rates [26].

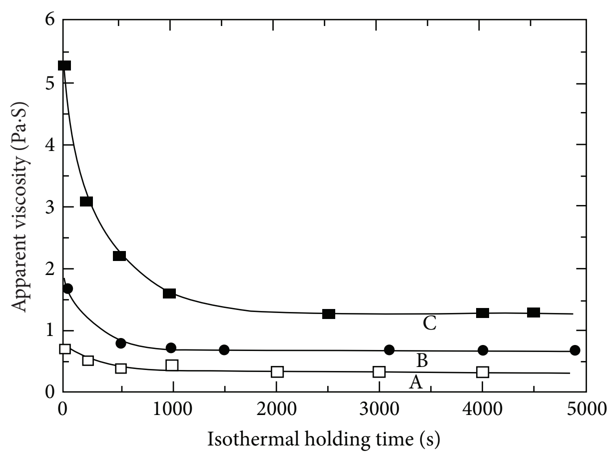

Figure 5: Apparent viscosity versus isothermal holding time at a constant shear rate of 200 s^{-1} and constant temperatures corresponding to $f_s = 0.3$ (A), 0.4 (B), and 0.5 (C) [26].

This phenomenon is attributed to thixocasting, which it can easily break the solid groups into pieces and then recompose them to reduce internal fraction. Thixocasting may increase the inner energy and the temperature by enhancing internal fraction function; viscosity is then reduced. However, a low shear rate produces the opposite result. When viscosity does depend upon velocity of flow, the fluids are called non-Newtonian. The relationship between shear rate and apparent viscosity, which is based on Poiseuille's equation, proves that the rheological behavior of semisolids during thixocasting of A356 alloys is characterized by pseudoplasticity of non-Newtonian fluids [28]. Viscosity can be estimated from Poiseuille's equation (1):

$$\Delta p = \frac{8Q\mu L}{\pi R^4}, \quad (1)$$

where Δp is the pressure difference, Q is the volume flow rate, μ is the viscosity, L is the Length, and R is the pipe radius. Although A356 is used widely in SSM processing, it may not be fully utilized because it is purposely designed for casting. Therefore, efforts should be made to modify this alloy for use in SSM processing. New modified alloys will be discussed in Section 3.

3. Thixoformability of Modified Aluminium Alloys

SSM processing technology has achieved considerable advancements since its discovery in 1973. Only a few materials have been selected for SSM processing to produce commercial products mainly in the automotive sector. However, there is a demand to widen the existing aluminium alloys for this process. Kapranos et al. [29] performed thixoforming experiment of an automotive part using A390 Al-Si alloy as starting material. They modified the chemical composition of A390 by adding 1% nickel and 4% nickel to the aluminium alloy. The results showed that the A390 with 1% nickel addition has better strength compared with the starting material and the A390 with 4% nickel, as shown in Table 1. Addition of up to 4% nickel affects the rheological behavior of this alloy and spheroidicity of the microstructure was also decreased. These happen when inappropriate structures (coarse intermetallic phases, coarse aluminium phase) exist in the aluminium system. Furthermore, it is reported that 4% nickel leads to cracking problems. These effects would reduce the strength of the modified alloy compared with the original A390 aluminium alloy.

Paes and Zoqui [30] performed an experiment on a new Al-Si-Mg alloy which varies in silicon and magnesium, as shown in Table 2. The alloys were produced from three master alloys (A356, 90 Mg-10 Al, and pure aluminium). Silicon had three different compositions (1%, 4%, and 7%) and magnesium had two different compositions (0.5% and 1.0%) as used in the experiment. Paes and Zoqui employed rheocast quality index (RQI) approach to examine the thixoformability of the modified aluminium alloys. A high RQI value means good thixoformability of the modified alloys. This value is related to the low silicon content of the aluminium system.

Table 1: Examples of mechanical properties of thixoformed samples for modified aluminium alloys.

Process	Starting alloy	Modified alloys	Feedstock production method	Heat treatment	UTS (Mpa)	YS (Mpa)	Elongation (%)
Thixoforming (Kapranos et al.) [29]	A390	A390 + 1 wt% Ni	Continuous casting	T6	411	NA	0.10
		A390 + 4 wt% Ni	Continuous casting	T6	354	NA	0.25
Rheodie casting (RDC) (Patel et al.) [34]	A356	Al-6Si-2Mg-0.5Fe	Ultrarefining technique	T4	270	164	8.0
				T5	360	323	1.2
				T6	342	312	1.6
Thixoforming (Shabestari and Parshizfard) [35]	A380	A380 + 0.7 wt% Fe	Partial melting	NA	176.35	163.14	1.62
		A380 + 1.5 wt% Fe		NA	178.02	166.71	1.45
		A380 + 3 wt% Fe		NA	181.11	169.02	1.44

Table 2: Examples of the rheocast quality index for modified A356 aluminium alloys.

Process	Starting alloy	Modified alloys	Feedstock production method	Grain size (μm)	Rheocast quality index
Thixoforming (Paes and Zoqui) [30]	A356, Mg-10Al, and Al pure	Al-7Si-0.5Mg	Ultrarefining technique	137 ± 18	0.35
		Al-4Si-0.5Mg		106 ± 34	0.43
		Al-1Si-0.5Mg		74 ± 9	0.61
		Al-7Si-1.0Mg		237 ± 58	0.08
		Al-4Si-1.0Mg		157 ± 32	0.12
		Al-1Si-1.0Mg		74 ± 7	0.61

However, low silicon content leads to high viscosity values and is usually not suitable for good thixotropic behavior in semisolid processing. Therefore, RQI itself is not enough to understand the characteristics of modified alloys, and further investigation is needed to verify the behavior of these alloys in semisolid condition.

Birol [31] investigated the effects of adding silicon (4% Si to 12% Si) to molten A380 alloy using low superheat casting (LSC), as shown in Table 3. This process started with melting the alloys, followed by cooling them down to within 5°C to 15°C of their liquidus temperature before they were poured into a permanent mold to produce nondendritic feedstock for thixoforming. The obtained slugs from the LSC ingots were thixoformed after they were heated in situ in a semisolid range from 568°C to 573°C. The hardness of the thixoformed parts, which ranged from 84 HB to 96 HB, increased to 121 HB to 131 HB after T6 heat treatment.

Zoqui and Naldi [32] conducted an experiment on the thixoformability of Al-9.5 wt%Si-2.5 wt%Cu aluminium alloy. The results indicated that the semisolid behavior of this alloy at 572°C was similar to A356 alloy (Al-7Si-0.5Mg) at 580°C, which is commonly used in thixoforming to produce automotive parts. From the experiment (morphological evolution and compression test), A332 can possibly be used as a raw material for thixoforming.

Shabestari and Ghanbari [33] performed an experiment to form Al-8%Si-3%Cu-4%Fe-2%Mn, and the results show the ability of the alloy to be thixoformed as the liquid volume fraction is changed from about 30% to 50% between 570°C and 580°C. Microstructural investigation indicated that the material produced α-Al spheroid after it is reheated in semisolid temperature. The mean diameter of iron-manganese bearing intermetallic was reduced from 26 μm to 43 μm in the as-cast condition to 9 μm to 11 μm in the thixoformed samples. Reductions were also recorded in the aspect ratio from 1.7 in the as-cast condition to 1.2 in the thixoformed samples. These results show that the alloy can potentially improve tensile strength and elongation to fracture.

Patel et al. [34] modified A356 and A357 aluminium alloys using ultrarefining technique, as shown in Table 1. T5 heat treatment resulted in the highest value for ultimate tensile strength and yield strength. Their analysis showed that Al-6Si-2 Mg-0.5 Fe can potentially be used in semisolid metal processing.

Table 4 [44–46] shows an example of the mechanical properties of thixoformed samples with different feedstock production methods. For A356 aluminium alloys, MHD produces the highest ultimate strength and yield strength compared with CS and LSC. This is due to the fine and uniformly globular size of the primary phase in the alloy that produced by MHD method [47]. For A357, MHD can produce a tensile strength of up to 346 MPa as shown in Table 4. The slurry is free from gas entrapment; hence, contamination is reduced to a minimum. Although MHD can produce an ideal feedstock for thixoforming, the processing cost for the feedstock production is very high. Therefore, other potential manufacturers started to investigate the other routes to reduce the material cost. The latest potential route is an NRC which offers the capacity to recycle scrap in-house

Table 3: Examples of hardness for modified A380 aluminium alloys.

Process	Starting alloy	Modified alloys	Feedstock production method	Heat treatment	Hardness (HB)
Thixoforming (Birol) [31]	A380	A380 + 12 wt% Si	Low superheat casting	T6	121.7 ± 0.6
		A380 + 15 wt% Si		T6	130.3 ± 0.6
		A380 + 20 wt% Si		T6	130.7 ± 1.2

Table 4: Examples of Mechanical properties of thixoformed samples.

Process	Alloy	Feedstock production method	Heat treatment	UTS (Mpa)	YS (Mpa)	Elongation (%)
Thixoforging (Cho and Kang) [44]	A356	Magnetohydrodynamic stirring (MHD)	T6	298	253	5.4
Thixoforming (Haga and Kapranos) [45]	A356	Cooling slope (CS)	T6	293	234	15
Thixoforming (Haga and Kapranos) [45]	A356	Low superheat casting (LSC)	T6	291	232	12
Thixoforming (Lee and Oh) [46]	A357	Magnetohydrodynamic stirring (MHD)	T6	346	280	4

and reduce the processing cost [48]. The importance of low-cost raw material for SSM processing will be discussed in the Section 5.

Shabestari and Parshizfard [35] explained that modified A380 (addition of iron and manganese) aluminium alloys can be thixoformed, and temperature suitable for thixoforming is at the range of 577°C to 579°C at 30–50% liquid volume fraction. They modified A380 via recrystallization and partial melting (RAP) route as shown in Table 1. Thixoforming formed very fine and well-distributed α-$Al_{15}(FeMn_3)_3Si_2$ compounds in the aluminium matrix. The proper distribution of intermetallic compounds in the alloy is very important in improving mechanical properties. The yield strength of the thixoformed samples increased, whereas elongation and ultimate strength decreased with the addition of up to 3 wt% Fe. Microstructural evaluation showed that the average particle size decreased with an increase in iron content in the thixoformed samples. Increasing in iron content leads to increasing in segregation factor (SF). Segregation factor can be defined as the volume fraction of intermetallic in the final structure: SF = wt% Fe + 2 wt% Mn. Figure 6 shows the variation of intermetallic volume fraction versus SF for the investigated alloys. It is noted that increasing segregation factor or increasing iron content will produce smaller intermetallic compound which is beneficial for thixoformability of A380 aluminium alloy. In thixoforming process, the diameter of the intermetallic compounds decreased around 39% and 59% when the segregation factor was 2.23 and 5.37, respectively. It can be said that addition of iron content in A380 aluminium alloy produces smaller intermetallic and beneficial for semisolid processing.

The new development of aluminium alloys is ongoing [36]. This effort, to modify aluminium alloys based on commercial alloys (e.g., A356 and A319), should proceed in order to ensure that the thixoforming of aluminium alloys can survive in the future. The effects of feedstock production method on the mechanical properties of thixoformed alloys will be discussed in Section 4.

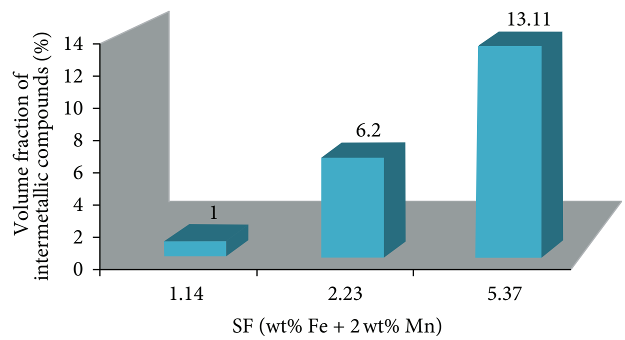

Figure 6: Intermetallic volume fraction versus segregation factor [35].

4. Effect of Feedstock Production Method on the Mechanical Properties of Thixoformed Samples

Several commercial aluminium alloys such as A356, A357, and A390 were used as thixoforming materials. These alloys provide high fluidity and good castability and usually used in fabrication automobile components. Forming an alloy in the semisolid state condition requires a roughly spherical fine grain microstructure uniformly dispersed in a liquid matrix when it enters the forming die [37, 38]. When this microstructure is reheated, the grain boundaries start to melt and a new secondary phase also takes place. The reduction in internal energy will change the structure into a globular morphology that benefits semisolid processing [39].

Table 5: Parts produced by Stampal S.p.A for various automotive manufacturers [23].

Alloys	Commercial product	Processing routes	Commercial products
A356	Front suspension arm (L&R) for TRW	MHD	
A357	Engine suspension mounts	MHD	
A357	Steering Knuckle	MHD	
A357	Rear Axle for Volkswagen	MHD	

Alloys with the ability to be globular at high temperatures and to maintain a lubricant behavior during thixoforming are promising candidates for semisolid processing. Many feedstock production methods offer globular microstructure feedstock; examples of these methods are cooling slope (CS), low superheat casting (LSC), and magnetohydrodynamic stirring, (MHD). Among these techniques, MHD stirring is the most popular feedstock production method [40], because it can produce a very fine grain feedstock as well as increase mechanical properties of the thixoformed products [41].

According to Zoqui et al. [42] the structure that presents minor grain size, minor shape factor (roundness), and the most homogenous and globular size of the primary phase has the best behavior in semisolid forming as well as the best mechanical final properties. This statement is supported by Bünck et al. [43] that specified that the shape factor must be below 2 in order to have good mold filling behavior. The equation of shape factor (F) is given below:

$$F = \frac{U}{4\pi A}, \qquad (2)$$

where U is the circumference and A the area of a grain. In their simulation using heat flux rate and seed density, the shape factor equal to 1 representing all grains is circular and for shape factor above 1, the grains exhibit an increasingly complex shape. Therefore, for good castability, it is suggested that the shape factor should less than 2.

5. Low-Cost Material for SSM Processing

Cost per component produced is an important factor in the commercial viability of a thixoforming process [49]. Table 5 lists automotive parts that use MHD processing route. Examples include engine suspension mounts for Fiat, steering knuckle for Alfa Romeo, and rear axle for Volkswagen [23]. A356 and A357 aluminium alloys are normally used to fabricate these products. Although semisolid processing has advantages compared with other processing methods, however, automotive manufacturers are constrained from using it because the prices of needed raw materials and various electromagnetic systems are high [50]. Figure 7 shows a cost comparison of manufacturing a brake drum with different materials and processes. The figure shows the higher cost of the thixoroute compared with the conventional processing route [29].

According to Zoqui and Naldi [32], semisolid raw materials which are more expensive than the raw material usually used in conventional processes typically cost 150% more

Table 6: Comparison of cost elements and relative bottom line component cost: 1 = lowest cost; 3 = highest cost [7].

Cost	SSM forming	Die casting	Squeeze casting	Permanent mould casting
Material	2.5	1	1.25	1.25
Tooling	1	2	3	1.5
Capital	1.2	1	1.2	1
Labor	1.2	1	1.3	1
Heat treating	1	NA	3	3
Machining	1	1	1.2	2
Finishing	1	1.5	1	2
Bottom line casting	2	1	2.2	3

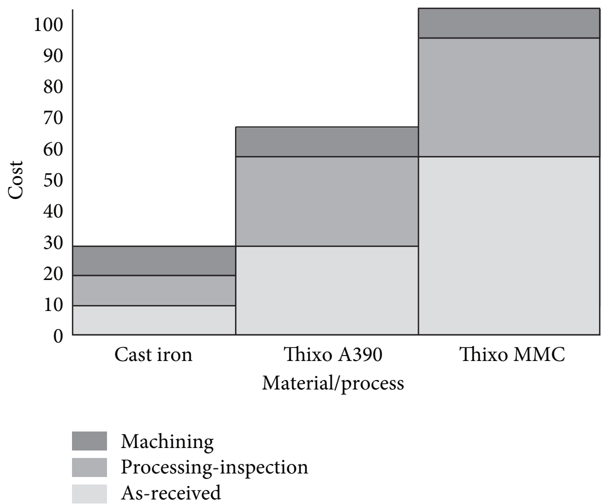

Figure 7: Brake drum: cost comparison for different materials/ processes [29].

than die casting materials and 125% more than squeeze casting, or permanent molding materials. Table 6 presents a comparison of the cost components produced in SSM forming, die casting, squeeze casting and permanent mold casting in 2002 [7]. The table shows that the cost of material for SSM forming is the highest. Comparison of the overall cost of tooling, capital, labor, heat treatment, machining, and finishing indicates that the bottom line castings cost is about 100% higher than that of die casting, 10% lower than that of squeeze casting and 50% lower than that of permanent molding [32]. Alloys that take full advantage of thixoforming are not yet available [51]. Therefore, developing new low-cost materials and new processing systems that decrease overall costs is important. Potential alloy candidates discussed in the Section 3 can be used as feedstock for thixoforming. Researchers and manufacturers should focus on the development of new alloys and processing methods to reduce the costs of semisolid processing products. For this purpose, thermodynamic modelling can be used for predicting alloy compositions suitable for semisolid processing hence avoiding any unnecessary experimental work that are both time-consuming and costly [52].

6. Concluding Remarks

This paper describes semisolid processing of aluminium alloys particularly modified aluminium alloys. Understanding the rheological behavior of aluminium alloy is important before a particular alloy is chosen as a material for semisolid processing. Alloys with high viscosity are usually not suitable for semisolid processing. The development of new alloys for SSM is needed because no aluminium alloys are specially designed for semisolid processing. Studies are still on going to modify alloy composition and to characterize processing variables for successful SSM processing. The thixoformability of aluminium alloys tailored for semisolid processing has also been discussed in this paper. MHD stirring remains widely accepted feedstock technique because it can increase tensile and yield strengths, which are desired qualities in the production of engine parts in automotive applications. This technique has advantages compared with other processes, but it is costly. Therefore, research should focus on how its cost can be reduced. The development of semisolid low-cost raw materials for thixoforming has been explained and cost comparison among processes has also been presented. The authors believe that semisolid metal processing will be an important manufacturing method in many sectors especially in the automotive and aerospace industries.

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