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INVESTIGATION OF THIXOFORMING PROCESS TO ENHANCE MECHANICAL PROPERTIES FOR AUTOMOTIVE COMPONENTS PRODUCTION

(PEYIASATAN PROSES 'THIXOFORMING' UNTUK MENINGKATKAN SIFAT MEKANIKAL BAGI PENGHASILAN PRODUK AUTOMOTIF)

IR DR ASNUL HADI BIN AHMAD

PROF DR MAHADZIR BIN ISHAK@MUHAMMAD

IR DR MOHD RASHIDI BIN MAAROF

DR ZAKRI BIN GHAZALI

RESEARCH VOTES NO:

RDU 160311

FAKULTI KEJURUTERAAN MEKANIKAL

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ABSTRACT

This research presents the works on the behaviour of aluminium 6061 which processed via thixoforming route for automotive components. Thixoforming is a forming process which exploits metal rheological behaviour during solidus and liquidus range temperature. Many research works in thixoforming are currently focusing on the raw material used to produce superior mechanical properties and excellent formability components, especially in automotive industries. Furthermore, the thixoforming process also produced less casting defect components such as macrosegration, shrinkage and porosity. The direct thermal method is one of the methods to create a globular microstructure feedstock billet, which gives the material a thixotropic behaviour during semisolid metal processing. In this experimental work, a molten aluminium 6061 was poured into a cylindrical copper mould before quenched in water at room temperature. The effect of pouring temperature of 660°C and 700°C and holding time of 20s and 60s were observed from the microstructure formation. The result shows that the combination of a pouring temperature of 660°C with a 20s holding time produces a finer near globular microstructure. These fine near globular microstructures gives a thixotropic behaviour improvement in better fluidity for a better flow during shaping. The design and manufacturing dies and molds are very important and vital tools to make sure that semi-solid metal processing process can produce high-quality product. The part was designed by using computer-aided design and fabricated by using a CNC machine. The design and product specification are very important aspects in order to make sure that die manufacturing followed the predetermined criteria. The works also aim to manufacture a die for automotive exhaust valve which is one of the components in a car engine. This research objective also to investigate the parameters that involve in thixoforming operations using hydraulic press machine such as pouring temperature, injection pressure, packing time and die temperature.

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CHAPTER 1

INTRODUCTION

1.1 EXECUTIVE SUMMARY

The use of the lightweight material such as aluminium alloy becomes one of the most important engineering materials in automotive and aerospace industries. Most of the automotive components such as cylinder heads, pistons, intake manifolds and chassis application in automotive power trains are made from aluminium alloy, typically by using a conventional metal casting process. The rapid growth in automotive industries in Malaysia, make the foundry a vital technology to keep Malaysia automotive sector can a head of the competition. There are several potential drawbacks are associated with conventional casting process, for instance shrinkage porosity formation, gas entrapment and hot cracking which leads to product rejection. Nevertheless, some of these conventional casting process weaknesses can be overcome by applying a semisolid metal (SSM) processing technique.

The main objective of this research is to study the thixoforming operation in order to enhance the mechanical properties for automotive components production. This research also aims to design, develop a die for thixoforming operation and thixoformed the globular microstructure feedstock billet. In particular, the relationship between microstructure, formability and mechanical properties of the formed components will be also investigated.

The experimental design of this research will be divided into four main phases. The first, second and third phase of this work will involve with the design, develop a die for thixoforming and formed the component. The fourth phase of this research will be conducted by assessing the microstructure formation and mechanical properties of the thixoformed components.

The findings of this work will establish the processing conditions, metallurgical and mechanical properties behaviour information for automotive components production. The findings of this work will establish the processing conditions, metallurgical and mechanical properties behaviour information for automotive components production.

1.2 PROBLEM STATEMENT

There is interest to process wrought aluminium alloy within the semi-solid state due to the enhanced properties available from this alloy compared to its cast alloy alternatives. The properties of wrought aluminium alloy are superior to conventional cast alloy. Wrought aluminium alloy however is more difficult to process within the semi-solid state due to its narrow solidification range and a higher propensity for hot tearing. Although extensive research within the literature has been carried out on wrought aluminium alloy, less attention was given to detailed experimental on the production of automotive components. There is also currently a lack of detailed experimental investigation within the literature detail material behaviour information for semisolid metal wrought aluminium alloy components, metallurgical and mechanical characterization works which need this work to be conducted.

1.3 OBJECTIVES OF THE RESEARCH

a) To develop a die for thixoforming operation and form the components
b) To investigate the effective of processing parameters for thixoforming operation
c) To determine the thermal profile of the raw material such as liquidus and solidus temperature.
d) To evaluate the flowability of the wrought aluminium formed components.

1.4 HYPOTHESIS

An important metallurgical characteristic that has significant effect during SSM processing is a fraction solid. The fraction solid determines material flowability and influence microstructure and defect formation. The low viscosity (low fraction solid volume) component helps material to flow inside die cavity. Meanwhile, high fraction solid volume helps to prevent various defects, a finer internal structure and a high quality product. This fraction solid however is found highly depended on material processing parameters. Hence, in order to produce better quality component with the combination of excellent flowability and superior mechanical properties, the fraction solid volume during SSM processing need to be controlled. This can be achieved by executing adequate processing parameters during SSM processing.

CHAPTER 2

RELATED TECHNICAL PAPER 1

An Overview of Thixoforming Process

N.H. Husain[1], A.H. Ahmad[1,a)], and M. M. Rashidi[1,]

[1]*Manufacturing Focus Group, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia.*

[a)]*Corresponding author: asnul@ump.edu.my*

Abstract. Thixoforming is a forming process which exploits metal rheological behaviour during solidus and liquidus range temperature. Many research works in thixoforming are currently focusing on the raw material used to produce superior mechanical properties and excellent formability components, especially in automotive industries. Furthermore, the thixoforming process also produced less casting defect component such as macrosegration, shrinkage and porosity. These advantages are sufficient to attract more exploration works of thixoforming operation. However, the weakness of this process such as high production cost due to leftover billet which cannot be recycled, encourage researcher works to overcome thixoforming limitations by using various methods. The thixoforming methods that widely used are thixocasting, thixoforging, thixorolling, thixoextrusion and thixomoulding. Each method provides varieties of final product characteristics; hence offer the extensive possibility of component invention. On the other hand, new thixoforming method leads to exploration research such as microstructure evolution, heating and pouring temperature, die temperature, mechanical properties, viscosity and final product quality. This review paper presents findings in the rheological material behaviour of thixoforming, advantages and disadvantanges of thixoforming, parameters affecting the thixoforming operation, morphology of thixoforming and various methods which have been used in this research area.

1.0 Introduction

Semisolid metallic alloys were discovered by Spencer in 1972 at MIT while investigated viscosity of Sn-15%Pb and found out during the experiment, semisolid state without stirring produce dendritic while the continuously stirred material was spheroidal [1]. Since then, extensive research regarding semisolid metal processing (SSMP) leads to various processes development. SSMP were applied in the industry due to the final product has less defect such as porosity, shrinkage, gas entrapment and macrosegration [2]. SSMP can be categorized into two routes, namely rheocasting and thixoforming [3]. Rheocasting is a forming process start from liquid alloy, directly introduced into a die without any intermediate solidification step. The semisolid slurry in this route produced from an entirely liquid regular alloy. While thixoforming is a route consists of reheating and forming process. Thixoforming steps are feedstock billet with globular microstructure specially prepared, cut to length, reheated into solid-liquid temperature to achieve suitable solid fraction, then final product formed by various methods [4].

In the early years of SSMP research, scientists mainly focus on thixotopic material development because it was essential in both routes. The material in thixotropic condition was described as the ability of material to flow when shear force was given and it will thicken again when shear force was released [5]. Thixotropic condition happened due to globular microstructure in the material. Methods to gain fine globular microstructure such as Magnetohydrodynamic stirring, Strain Induced Melt Activated (SIMA), Mechanical stirring, Cooling slope and Direct Thermal Method are widely used either for scientific research or industry application [6].

Thixoforming particularly needs feedstock billet which prepared by special method because solidification step is essential compared to rheocasting. Thixoforming also described as near net shape forming due to billet reheated into solid-liquid temperature and partially melted non-dendritic slug into a metal die [7].

In industry application, thixoforming was considered high-cost manufacturing because of raw material was not supplied widely [4]. However, this method offers broader ranges of design option which attract people in this area improves it continuously [8].

This paper focused on thixoforming and divided into four sections. The first section highlights the rheological material behaviour, the second part emphases on advantages and disadvantages of thixoforming, the third section focuses on parameters affecting the thixoforming operation, the fourth division explained morphology of thixoforming and final section presents various methods have been used in this process.

2.0 Rheological material behaviour

Rheology is a term to describe deformation and flow behaviour of material. In SSMP, non-dendritic microstructures play the main role of semisolid state behaviour. Globular microstructure which gains from continuous stirring during cooling exhibits lower viscosity compared to a material with dendritic microstructures. Spheroid solid surround by the liquid matrix, is a requirement for semisolid processing and thixotropic condition. The thixotropic condition is explained as material decreases in viscosity if shear but stand still again if allowed [9].

Material or alloy in the semisolid state also referred as slurry, which can be divided into two categories: a liquid-like and a solid-like. Liquid-like named for slurry behaves like liquid under external shear due to dispersed solid particles. Meanwhile, solid-like slurry exhibits solid behaviour because of containing interconnected solid phase [6]. In thixoforming process, solid-like slurry is involved. Solid-like slurry with thixotropic condition has the ability to flow in laminar, which uniform flow during forming is possible.

Viscosity is the main parameter for rheology in semisolid processing. Viscosity indicates capabilities of semisolid material in filling mould, flow behaviour and required force for deformation [10]. The viscosity in semisolid metal was influenced by solid fraction, particle size, and particle distribution. Solid fraction was defined as the density of solid in the semisolid slurry. Solid component was generated by partial solidification of slurry [11]. For thixoforming processing, effective solid fraction is between 0.5 and 0.6. If the solid fraction is below 0.5, the slug cannot support its weight and consider as too soft. Whereas, if solid fraction is over 0.6, the slug will not be able to fill the die because too stiff to flow [12].

3.0 Advantages and disadvantages

Thixoforming process like any other operation, hold its own benefits and limitation. As for advantages, thixoformed parts reported have higher quality compared to conventional produce. Better quality products of thixoforming were gain due to globular microstructure. Spheroidal microstructure provides flow ability in billet during forming. Less shrinkage, gas entrapment and porosity parts were created from slug flow in laminar. Other than that, mechanical properties of final product were enhanced by fine and uniform microstructure. Due to fine and uniform structure, thixoforming operation able to create wide range of component shape with different wall thickness, sharp edged and radii edge [4-6, 8, 9, 11-15].

However, limitations of thixoforming process may cause less response in industry. The most well-known shortcoming of thixoforming was special requirement for feedstock billet may increase production cost. Besides, scrap from forming process cannot be recycled. Furthermore, to ensure final product quality, knowledgeable supervise were needed for each step. Moreover, crucial points in thixoforming operation were viscosity and solid fraction. Both were dependent on temperature control, therefore, high technical personnel were needed for accurate temperature control. Even though SSMP has taken places in research light for 40 years, continuous research in thixoforming is necessary to support development of new components [4-6, 11, 16].

Identifying leads and shortcomings of thixoforming will lead to deeper investigation, thus improve thixoforming in many aspect. Recently, researchers focus on thixoforming as changed from development of technique produce feedstock billet into improvement of cost saving thixoforming operation.

4.0 Parameters affecting thixoforming process

Since the expansion of thixoforming research takes place, many research appoint parameter affecting thixoforming based on critical criteria for thixoforming to be successful.

4.1 Solid fraction

Viscosity of material during thixoforming highly influence by solid fraction. In SSMP, suitable solid fraction usually in range of 30% - 70% [17, 18]. Low solid fraction indicates high viscosity, thus slurry flowing ability during forming will be lower.

Ahmad et al. conduct an experiment to find effect of cooling rates on thermal profiles aluminium alloy 7075. They pour molten metal into chamber with Kaowool blanket then, thermocouples were inserted at the centre and near cubicle wall. Temperature differences were plotted against time to determine dendritic coherency point. Through the experiment, they found that fraction solid were affected by cooling rates. From graph plotted, the different value of fraction solid for slow cooling rates and high cooling rates were at 0.7 fractions solid. This investigation exhibits the effect of cooling rate on solid temperature and liquid temperature which is crucial during reheat in thixoforming
process [17].

Earlier than Ahmad et al., Nafisi et al. investigate fraction solid during processing temperature with the same set up. Melts were prepared in silicon carbide crucible which later transferred into cooling stand and K-type thermocouple inserted at two locations. In this experiment, they processed data using computer aided cooling curve analysis (CA-CCA), computational thermodynamic and quantitative metallography. They concluded inefficient during quenching methods lead to more primary α-Al formation as the main reason for fraction solid differences in the experiment [19].

4.2 Particle size

Thru understanding of SSMP, smaller or finer particle size of material is expected to provide smooth filling movement and less viscose. However, through various experimental, particle sizes are much affected by temperature such as pouring temperature, tool temperature and cooling rate.

El-Mahallawi et al. investigated effects of pouring temperature and water cooling on semisolid microstructure of A319 aluminium cast alloy. This experiment started with A319 melted in electric furnace and allowed to cool down to specified pouring temperature before continuously poured on cooling slope. For each temperature, pouring was carried out with and without water cooling. They found that ingots with water cooling show lower bulk porosity and increasing pouring temperature slightly reducing bulk porosity. Other than that, they discovered ingot with water cooling exhibits lower shape factor and with increasing pouring temperature accumulate shape factor of α-Al grains. Furthermore, they also found that water cooled ingot shown lower average grain size and with increasing pouring temperature accumulate average size of primary grains [20].

5.0 Morphology of thixoforming

In investigation of thixoforming, microstructures were frequently used to analyse relationship between process and mechanical properties. Based on experiment by Tavakoli et al., cooling slope method and thixoforming were proven improved mechanical properties of A380 alloy, such as tensile strength, elongation and hardness [21].

Lee et al. has produced 6061 wrought aluminium alloy feedstock billet from thermo-mechanical method and thixoextruded it into automotive component. The research was concentrated on the possibility of thixoformed 6061 into steering knuckles. The grain size distribution of the steering knuckles from this research is presented in figure 1. This research finding showed that 6061 was able to be produced by thixofroming operation which ductility and strength were significantly increased after T6 heat treatment [22].

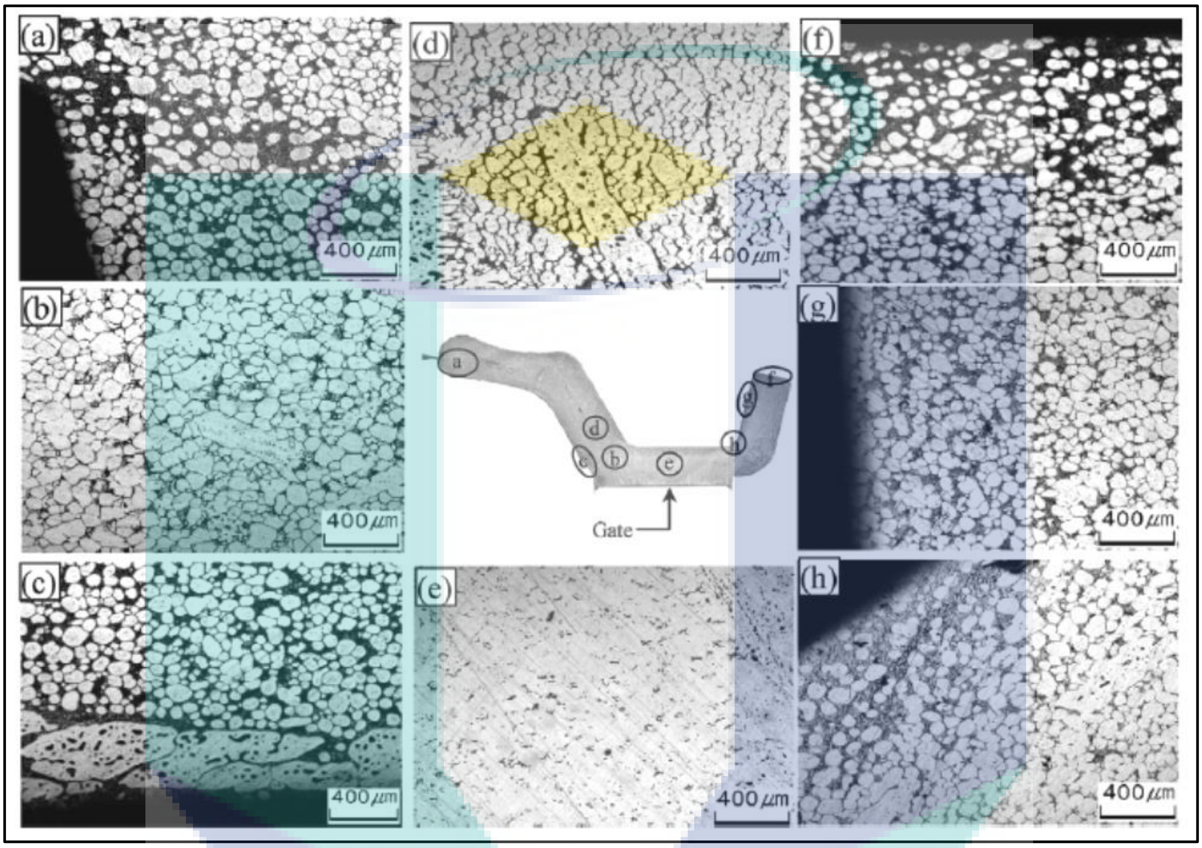

Figure 1. Microstructures of steering knuckles which shown fraction solid distribution at different area [22].

6.0 Various forming method

In the early years of SSMP, forming method mainly same as conventional, the difference is SSMP using globular microstructure feedstock billet. For thixoforming, after billet is reheated into semisolid temperature range, forming shortly takes place. Following are few of thixoforming methods.

6.1 Thixoforging

Thixoforging is a process similar to closed-die forging. Billet is placed between open die halves and pressed to form final product. In this process, billet with lower liquid fraction is significantly used. This method able to produce product with variable wall thickness, sharp radii and sharp edge thickness changed [16].

Jung et al. conducted an experiment to determine reheating process for cast and wrought aluminium alloy for thixoforging. They achieve optimal reheating by controlling holding time and relevant temperature for each step using induction heating. From this experiment, they find that suitable temperature for each step in thixofoging will lead to high quality product. Since fluidity of billet during forming have high influenced on final product, reheating holding time were take account. If the reheating holding time were too long, risk for grain coarsening will increase too [23].

Meanwhile, Cho et al. has done experiment on mechanical properties of thixoforging product. This experiment, researcher observing filling behavior during forming, investigates defects on product and final product mechanical properties. They used A356 and Al2024 (wrought) with different die temperature to find die temperature filling limitation. From the research, results shown that ultimate tensile strength and yield strength were increase at higher applied pressure. Other than that, highest hardness degree was shown at the center of area. This happened due to edge of the area have higher liquid distribution during forming [24].

As research of thixoforging using aluminium alloy expanding tremendously, Wang et al. investigated microstructural evolution and mechanical properties of 9Cr18 steel after thixoforging. Through this research, they found out optimal heat treatment for 9Cr18 steel thixoforging is at 550^{o} C for 2 hour. Strong hardening at the inner area was observed and compressive strength of 4680 MPa were achieve with compressive strain of 53.3% [25].

6.2 Thixocasting

In thixocasting, billet is shot into a closed-die by piston to form and usually used billet with liquid fraction in range of 40% - 60%. During forming in thixocasting, laminar flow of slug is critical aspect in ensure high quality product[6]. Shown in figure 2 is difference process for thixoforging and thixocasting method.

In order to understand filling or flow in thixocasting, scientists develop software to calculate and have better picture of product forming using thixocasting method. Modigell et al. investigate tin lead alloy (Sn-15%Pb) rheology by changing shear rate under isothermal conditions. Data from experimentation later compared to model develop by using commercial CFD software. Results from this experiment exhibit filling velocity give high impact on product quality [26].

Another experiment on rheology behavior for thixocasting is conducted by Yang et al.. Aluminium alloys (A356) were thixocasted and compared to model. From their calculation, it is proven rheological behavior of semisolid metal during thixocasting is pseudoplasticity of non-Newtonian. Their calculation has open to better understanding of filling flow during thixocasting and provide improvement in producing higher quality product using thixocasting method [27].

While, Kim et al. used thixocasting method to produce possible high strength Mg-Cu-Y alloy. Magnesium alloy is an attractive material for aeronautic transportation application industry because of its light weight properties and excellent damping capacity [28, 29]. However, magnesium alloy were limitedly found in industry is cause by its poor corrosion resistance. Thru thixocasting, Mg_{90} Cu_5 Y_5 alloy exhibits high tensile strength compared to conventional magnesium. Researchers explained that globular magnesium as primary particles were surrounded by liquid quenched (partly amorphized) with later transform into hard amorphous. This microstructure has improved Mg-Cu-Y alloy strength[29].

Other than using slug, researchers also extend their interest towards powder thixocasting. Chen et al. investigation shown powder thixocasted Al-Si powder provide good formability with satisfied strength and uniform distribution of Si particles [30].

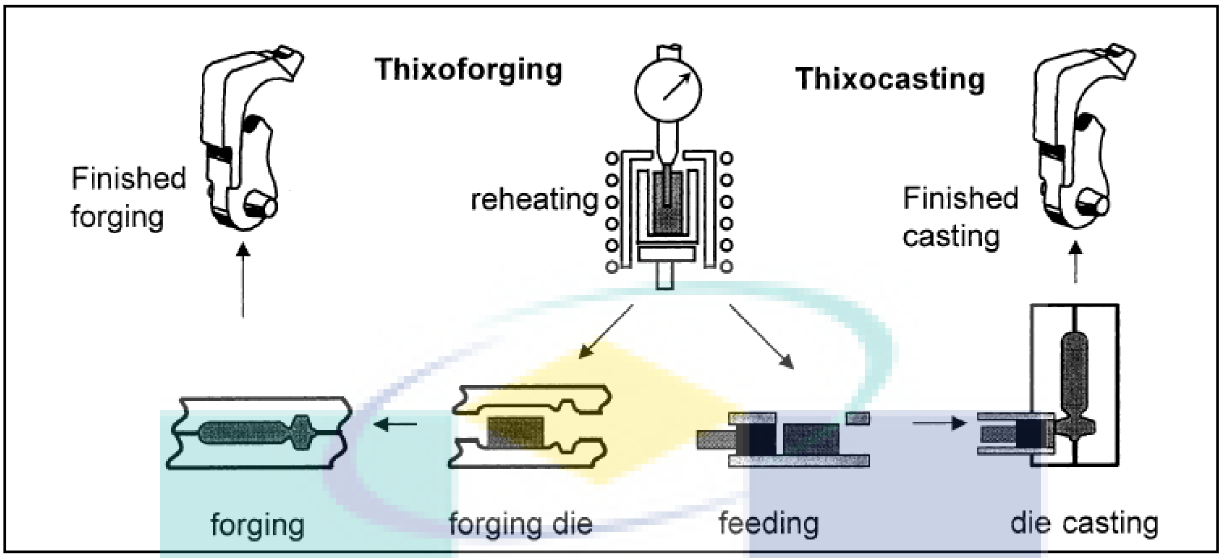

Figure 2. Illustration of thixoforging and thixocasting process[6].

6.3 Thixomoulding

Thixomoulding is a process to produce near net shaped component from magnesium alloy. This process took place in a single integrated machine as shown in figure 3. Magnesium alloy chips in range size of 2-5 mm feed into machine and heated until partial melted. Partial melted alloys transform into semisolid slurry. Huge and high speed screw later injects slurry into mould for final product forming. As magnesium alloy would oxidize when heated, an argon atmosphere was maintained at in-feed. Thixomoulding is an effective process of thixoforming because involved only one step process [6, 31, 32]. However, thixomoulding only available for magnesium alloy production because other alloy such as aluminium alloy would likely attack the barrel and screw while in semisolid state [5].

To evaluate capabilities of thixomoulding system in processing magnesium alloy, Czerwinski operate an experiment using a Husky's prototype system named TXM500-M70. The researcher used mechanically chipped magnesium alloy as material. In this experiment, major operating parameters are cylinder barrel temperature, screw rotation speed, injection velocity, injection pressure and mould temperature. Thru this experiment, Czerwinski conclude that temperature along injection mould is the key factor in controlling process. While, solid fraction and injection velocity were influenced flow behaviour of magnesium alloy slurry during mould filling [33].

Furthermore, thixomoulding is seen as potential near-net shape method which could provide effective energy usage and less pollution. Thus, Patel et al. conduct an experiment focusing on evaluating thixomoulded AZ91D and AM60B due to its flexibility in fabrication, high strength-to-weight ratio besides increasing usage in automotive industry. from this experiment, for fracture characteristic, AZ91D exhibited cleavage like fracture with secondary crack while AM60B shown dimple like features due to formation and coalescence microvoids. Ultimate tensile strength for both were shown equivalent within experimental scatter. AZ91D alloys displayed higher yield strength and lower ductility compared to AM60B. Characteristics of both alloys revealed in this experiment were lead to deeper understanding of their production through thixomoulding method [34].

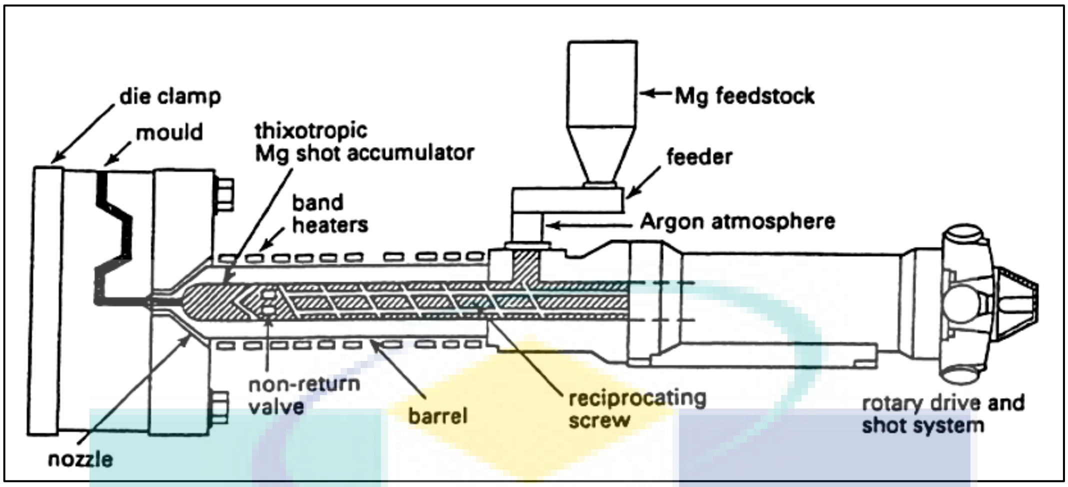

Figure 3. Diagram of a thixomoulding machine [6].

6.4 Thixorolling

Rolling is a process where materials were undergoes two rollers which produce flat like metal [35]. In thixorolling, slug or reheated billet with globular microstructure were flowed through two roller and produce alloy strip. Semisolid Powder Rolling (SSPR) is said possible for industrial application and its product possible to be used in aerospace application [36].

Liu et al. investigated microstructural evolution of 7050 aluminium alloy during SSPR. Researchers used gas atomized 7050 aluminium alloy powder which, reheated to semisolid temperature and inserted into inert atmosphere with different period. They observe that the most suitable liquid fraction for SSPR is 45 – 65 %. Alloy strips can be produce with nearly full density and high micro-hardness. They highlight three important mechanisms in this technique which are filling and flowing of liquid, solidification by rolling and recrystallization [37].

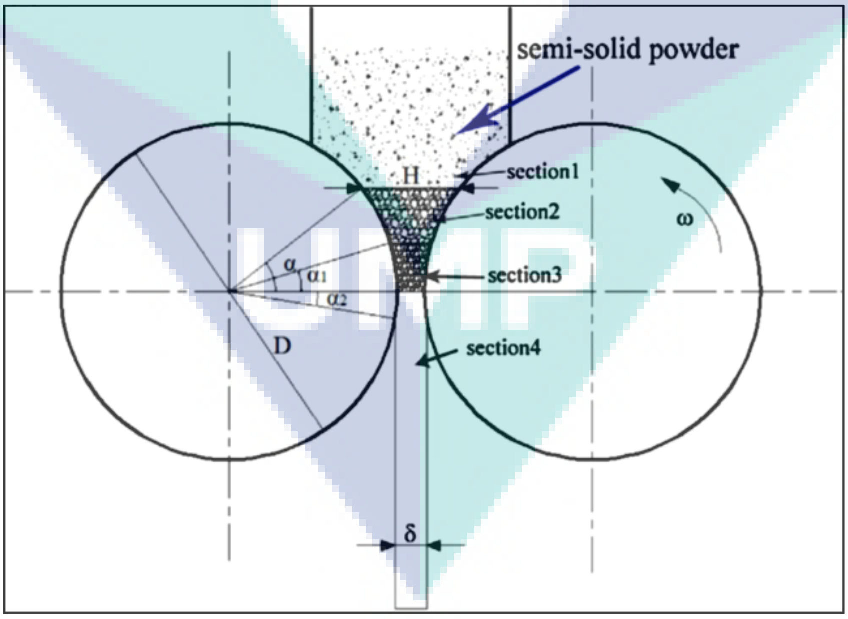

Figure 4. Schematic picture of semisolid powder rolling [37].

6.5 Thixoextrusion

In thixoextrusion, reheated billet with globular microstructure were squeezed into an already closed die [38-40]. Like any other thixoforming method, thixoextrusion offer several advantages compared to conventional extrusion such as higher material fluidity, lower pressure and longer tools life. Thixoextrusion also offer production of hard-to-form aluminium alloys for automotive industry [38].

Rovira et al. has done experiment thixoforming of Al-Cu alloys by using thixoforging and thixoextrusion. They compared thixoforming method with conventional processing, proved thixoextrusion produce final product with fine and equi-axial structure besides lower energy use [41].

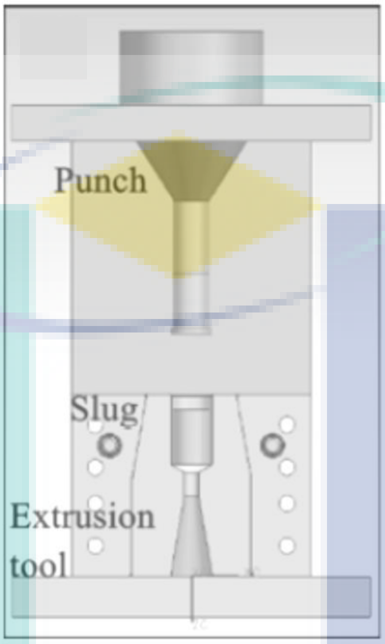

Figure 5. Example outline of extrusion tool by Forn et al. [38].

Conclusion

This overview shows thixoforming process for component forming by using semisolid principle. These methods were applied in several industries worldwide such as automotive and aerospace. This review appoints that effective route for thixoforming development is understanding rheology behaviour of material during process. Likewise, highlighted identified benefit and limitation of thixoforming gives deeper comprehension of this operation. Although thixoforming operation was applied in industry, continuous study on material aspect for this process still needed as an effort to accommodate future industry requirement. Nevertheless, thixoforming is still providing wider possibility production of high quality components compared to conventional.

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CHAPTER 3

RELATED TECHNICAL PAPER 2

Direct thermal method pouring temperature and holding time effect on aluminium alloy 6061 microstructure

Benjunior B.[1,2], A. H. Ahmad[1,2], M. M. Rashidi[1,2]

[1]*Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Pekan, 26600, Pahang, Malaysia*
[2]*Manufacturing Focus Group, Universiti Malaysia Pahang*

ABSTRACT

The microstructure variances of aluminium 6061 billet produce via direct thermal method with different pouring temperature and holding time are presented in this paper. The direct thermal method is one of the methods to create globular microstructure feedstock billet, which gives the material a thixotropic behaviour during semisolid metal processing. In this experimental work, a molten aluminium 6061 was poured into cylindrical copper mould before quenched in water at room temperature. The effect of pouring temperature of 660°C and 700°C and holding time of 20s and 60s were observed from the microstructure formation. The result shows that the combination of a pouring temperature of 660°C with a 20s holding time produces a finer near globular microstructure. These fine near globular microstructures gives a thixotropic behaviour improvement in better fluidity for a better flow during shaping. The pouring temperature just slightly above the liquidus temperature provides slower cooling rates from above to below the liquidus temperature. This process causes less superheat to be extracted by the cylindrical copper mould and gives a slow cooling rate action during the solidification stage that promotes the formation of further nuclei, which results in smaller grain size. The result also shows the combination of the lowest pouring temperature of 660°C with the lowest holding time of 20s produced the smallest grain size measured in area. However, the circularity and aspect ratio that indicates globular shape grain has a slight change in result which indicates that every feedstock billet has a near globular grain size. In conclusion, this work has shown that specific combination of pouring temperature and holding time has an effect on the microstructure formation of the feedstock billet produced by using direct thermal method.

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Keywords: Direct Thermal Method; Pouring Temperature; Holding Time; Microstructure; Aluminium Alloy 6061

Introduction

Semi Solid Metal Processing (SSMP) is a method to process metals and alloys, which takes place between solidus and liquidus temperatures [1-5]. The SSMP is subjected to the material microstructure behaviour in the semi-solid state condition. These materials microstructure behaviours are characterized by a solid-like behaviour at rest and a liquid-like flow when submitted to shear. The microstructures flow when subjected to shear but thickening again when it is allowed to stand requires the microstructure to be made of globular or spheroids of solid surrounded by a liquid matrix [6]. SSMP has the advantage of low shrinkage porosity defect over conventional processes [2, 7, 8].

SSMP technologies group into two categories based on the initial material state which is rheo-routes and thixo-routes. Rheo-route consist of preparation of SSMP slurry with globular grain from a liquid state solidified into semi-solid state and injects directly into the die for component shaping without an intermediate solidification stage. Rheo-route process generates the shear needed to obtain a globular microstructure by using mechanical stirring to stir the liquid metal. The slurry obtained is either directly use in die filling for component shaping or made as a feedstock production material with a thixotropic microstructure where globular and fine primary phases were homogeneously dispersed in a matrix of lower melting point. Thixo-route consists of the molten metal has an intermediate solidification stage, which the material was treated in such a way that it has a non-dendritic microstructure which is made as raw feedstock material. When it is heated in the semi-solid state, it is then injected into a die for component forming [9-11].

Direct Thermal Method (DTM) was developed by Brabazon and coworkers in 1997 as an alternative method to produce thixotropic feedstock by University College Dublin in 2002 [12-16]. DTM involves using a thin-walled cylindrical mould whose thermal conductivity is high but low in thermal mass commonly is made of copper to hold a low superheat liquid alloy. Rapid cooling action occurs during the first interaction between the molten metal and the mould wall result in the formation of multiple nucleations. The cooling action then continues to reach thermal equilibrium at a very low rate. Isothermal arrests state has resulted from heat matches between the mould and the alloy. This results in a low heat convection transfer by way of small thermal gradient [16]. Basically, the spherodization mechanism of this method starts with nucleation at several locations during the first contact and slower cooling rate to prevent the growth of dendrite arms [12]. Quenching is done in order to freeze the formation of globular microstructure [17]. Previous research has remarked that certain parameter has an effect on a more spherical structure and need to be controlled, which were the pouring temperature, holding time before quenching or forming, and size of cooling mold. Lower pouring temperature and shorter holding periods give a result in more spherical structures [13]. This gives results in increasing the material fluidity for better flow during shaping. Pouring temperature closer to the liquidus temperature provides higher cooling rates from above to below the liquidus which causes less superheat to be extracted by the cylindrical copper mould. Hence, it gives a slow cooling rate action during the solidification stage that promotes the formation of more nuclei, which in turn results in a smaller grain size [13].

Aluminium alloys is an ideal material to be used for automotive, aerospace and transportation components with casting alloy such as A356 due to their fluidity behaviour. However, while the cast series of aluminium alloys has the excellent fluidity properties advantage, it has relatively poor mechanical properties compared to wrought aluminium alloys. Wrought aluminium alloys provide significant advantages in terms of the higher ultimate tensile strength (UTS) and yield strength. Wrought aluminium alloy 6061 is among the wrought alloy series that known to have various benefits of medium strength, formability, weldability low cost and also corrosion resistance [18].

Fraction solid is an important aspect to be considered during the process of SSMP due to its impact on the material mechanical properties. Fraction solid is a comparison between the amounts of solid-phase when compared to the liquid phase within the semisolid microstructure of the alloy. Previous research stated that for a fixed cooling rate and shear rate, viscosity has increased parallelly with solid fraction. The process slowly occurs at low solid fraction and sharply at high solid fraction [4]. In SSMP, to obtain a low viscosity at a high fraction solid is important. Low viscosity will allow the material to flow easily within the mould and high fraction solid helps to prevent major defects, better globular microstructure, and high-quality feedstock.

Pouring temperature plays a significant role in the formation of the globular microstructure of the feedstock billet. The proper combination of the pouring and holding time will greatly affect the formation of a globular microstructure within the billets. Previous research shows that smaller primary and secondary phases within the microstructure were formed for lower pouring temperature which approaching the semisolid temperature [19].

Holding time affects the formation of the globular microstructure of the feedstock billet. The purpose of holding time was to ensure a sufficient fraction solid before quenching. Previous work shows that longer holding time for a set pouring temperature resulted in larger primary phase grains formation[20]. Therefore, a proper combination of pouring temperature and holding time should be considered as it will greatly affect the billet spherodization mechanism.

Experimental Method

Aluminium 6061 was used in this work and Table 1 presents Chemical compositions of aluminium 6061 determined by using Optical Emisson Spectrometer.

Table 1 Chemical Composition of The Aluminium Alloy 6061.

Composition	Al	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ni	Ti
Wt (%)	97.400	1.00	0.290	0.030	0.530	0.570	0.009	0.011	0.019	0.020

In this work, 1kg aluminium 6061 was placed inside a graphite crucible and was melted by using a resistance heated Carbolite 1600 box furnace at a temperature of 800°C. After the aluminium completely melt, the graphite crucible contained molten aluminium 6061 was taken out of the furnace and the temperature was measured using k-type thermocouple connected to a data logger. After achieved the desired temperature for pouring temperature, the molten aluminium was then poured into a copper mould of 1mm of wall thickness, 25mm diameter, and 100mm in height hold by retort stand and clamp. The pouring temperature was set to 660°C and 700°C. Once the copper mould was completely filled with the molten aluminium, holding time was counted by using a stopwatch. The copper mould was then dropped into the water tank for quenching after the holding time was achieved. The holding time before quench was set to 20s and 60s for every pouring temperature. The schematic diagram of DTM was present in Figure 1 as follows:

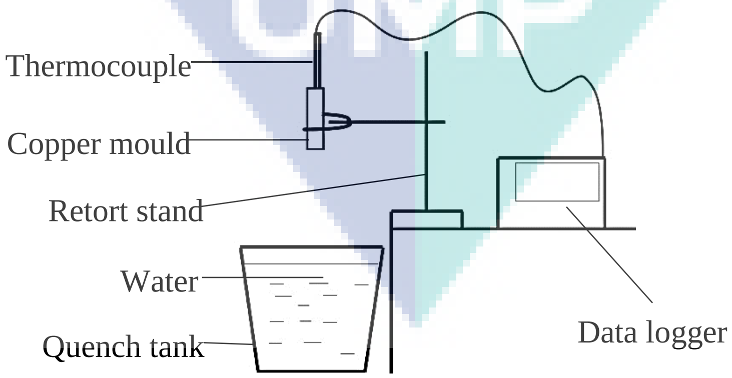

Figure 1 Schematic Diagram of Experiment Rig for DTM.

The microscopic samples were then taken at the center of solidified feedstock billet. The sample was then mounted by using SimpliMet 1000 Automatic Mounting press mounting machine and grind by using Metkon Forcipol 2V grinding machine with rotation of 240-300rpm and grit specification P600, P800 and P1200 of abrasive paper respectively. The sample was polished and etched with Keller solution and microstructure image of the sample was taken. The microstructure image was analyzed with ImageJ software in order to obtain grain size area, circularity and aspect ratio. The circularity and aspect ratio were calculated with Equation (1) and Equation (2) where P and A are representing a perimeter and an area of the particle respectively:

$$C = \frac{4\pi A}{P^2} \tag{1}$$

$$AR = \frac{major\ axis}{minor\ axis} \tag{2}$$

Effect of Pouring Temperature and Holding Time on Microstructure

Direct Thermal Method (DTM) was used to produce thixotropic feedstock billet with pouring temperature was set to 660°C and 700°C. The holding time before quench was set to 20s, and 60s for each pouring temperature. Figure 2 shows the aluminum alloy 6061 feedstock billet. The microstructure formation indicates that different pouring temperature and holding time affect the microstructure.

Figure 2 Aluminium Alloy 6061 Feedstock Billet.

Figure 3 (a) shows the combination of pouring temperature of 660°C with a 20s holding time produces a fine near globular microstructure. These fine near globular grain gives a better fluidity for better flow during shaping. The pouring temperature just slightly above the liquidus temperature provides slower cooling rates from above to below the liquidus temperature. This process causes less superheat to be extracted by the cylindrical copper mould. Hence, it gives a slow cooling rate action during the solidification stage that promotes the formation of more nuclei, which turn to results in smaller grain size.

Figure 3 (b) shows the combination of pouring temperature of 660°C with a 60s holding time still produce near globular microstructure. However, the grain size has increased because of the longer holding time has allowed the grain to join with the nearby nuclei when the secondary phase starts to solidify. The holding time before quenching was obviously crucial as a mechanism that will instantly freeze the small grain size formed and to ensure a sufficient fraction solid before quenching.

Figure 3 (c) shows the combination of a pouring temperature of 700°C with a 20s holding time still produces a little near globular microstructure. However, the grain size was not uniform and bigger in size with the presence of a dendritic mixture. Pouring temperature higher than the liquidus causes more superheat to be extracted by the cylindrical copper mould. Hence, it will not have a slow cooling action effect during solidification stage. The short holding time before quenching has instantly frozen the microstructure before the microstructure reaches a uniform grain size.

Figure 3 (d) shows the combination of pouring temperature of 700°C with a 60s holding time still produces a near globular microstructure. The result shows with holding time increase, the grain size starts to develop into uniform structure. However, because of the high pouring temperature, the grain size is bigger due to the fast cooling rate action during solidification stage.

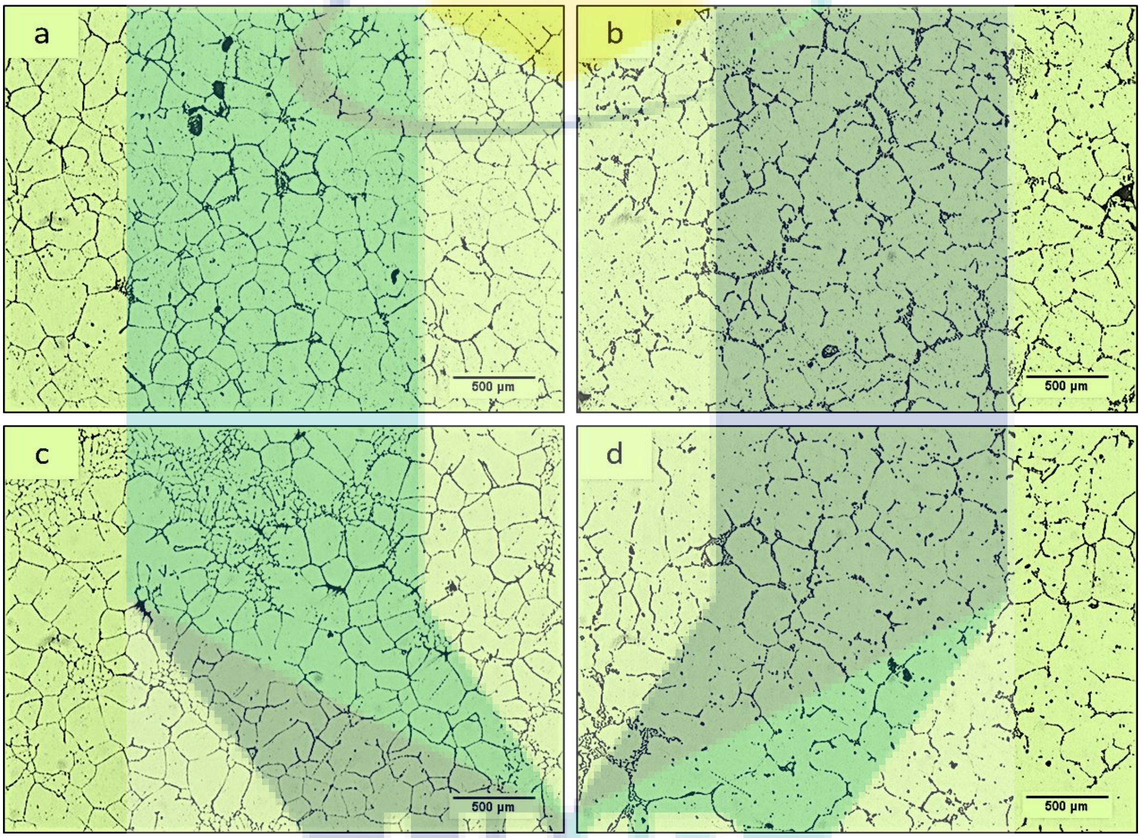

Figure 3 Microstructure of Aluminium Alloy 6061 DTM Feedstock Billet With Different Combination of Pouring Temperature and Holding Time (a) 660°C and 20s (b) 660°C and 60s (c) 700°C and 20s (d) 700°C and 60s.

Table 2 presents the average grain size measurement for aluminium alloys feedstock billet produced by using direct thermal method. The result shows obvious and significant changes which are the combination of the lowest pouring temperature of 660°C with the lowest holding time of 20s produced the smallest grain size measured in area. The circularity and aspect ratio that indicates globular shape grain has a slight change in result which expresses that every feedstock billet produces a near globular grain size.

Table 2 Microstructure Average Grain Size Measurement of Feedstock Billet With Different Combination of Pouring temperature and Holding Time.

	Area (μm²)	Circularity	Aspect Ratio
660°C 20s	27965.14	0.78	1.51
660°C 60s	34629.64	0.78	1.51
700°C 20s	38903.35	0.77	1.39
700°C 60s	43029.93	0.75	1.61

Conclusion

In conclusion, the result obtained from this work has shown that a specific combination of pouring temperature and holding time produced a globular microstructure of the feedstock billet. The pouring temperature and holding time has an effect on microstructure of aluminium 6061 feedstock billet. The specific combination of pouring temperature and holding time will produce a finer and globular microstructure of the feedstock billet. Lower pouring temperature at 660°C with holding time of 20s produced a finer globular and uniform microstructure compare to other processing parameter combinations. This characteristic gives results in increasing the material fluidity for better flow during shaping. The lower pouring temperature delivers a slower cooling rates effect from above to below the liquidus temperature, which in turn causes less superheat to be extracted by the copper mould. Hence, the slow cooling rate condition during the solidification stage promotes the formation of more nuclei, which turn to results in smaller and uniform grain size.

Acknowledgments

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CHAPTER 3

RELATED TECHNICAL PAPER 3

Design and development of forming die for wrought aluminium thixoforming operations

N.H. Husain [1,2], A. H. Ahmad[1,2], M. M. Rashidi[1,2]

[1]*Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Pekan, 26600, Pahang, Malaysia*
[2]*Manufacturing Focus Group, Universiti Malaysia Pahang*

ABSTRACT

Semi-solid metal processing has been the subject and topic of discussion for manufacture near-net shape for a modern day now. There are still largely unaware that advantage offered by semi-solid metal processing. The design and manufacturing dies and molds are very important and vital tool to make sure that semi-solid metal processing process can produced high quality product. This process gives a lot of advantages in manufacturing industry especially in automotive sector. This paper presented the works on design and development of forming die and thixoforming operations. The part was designed by using computer-aided design and fabricated by using CNC machine. The design and product specification are very important aspect in order to make sure that die manufacturing followed the predetermined criteria. The works in this paper also aims to manufacture a die for automotive exhaust valve which is one of the components in car engine. The works also aims to investigate the parameters that involve in thixoforming operations using hydraulic press machine such as pouring temperature, injection pressure, packing time and die temperature.

***Keywords**: Direct Thermal Method; Pouring Temperature; Holding Time; Microstructure; Aluminium Alloy 6061*

Introduction

Semisolid Metal (SSM) processing or thixoforming is new technology in this era for metal forming. Thixoforming is shaping of metal components in the semi-solid state. This process is an alternative way or other option to manufactured components extremely in the lightweight parts because it can reduce cost and short process required. Thus, it saves time. This process happens when alloy have reach appreciable melting range and microstructure must consist of solid metal spheroids in a liquid matrix. Semi-solid state is thixotropic which if it is sheared the viscosity falls and it flows like a liquid but if allowed to stand it thickens again. A slug of alloy, heated into semi-solid state can be cut with knife and spread like butter provides the microstructure is non-dendritic(P. Kapranos, Ward, Atkinson, & Kirkwood, 2000). When it behaves as “Thixotropic” slurry, the viscosity decreases with increasing shear rate and at constant shear rate the viscosity decreases with increasing time. In the process thixoforming, alloy slurries flow in a laminar manner, which it gives advantage in uniform die filling(Chayong, Atkinson, & Kapranos, 2005). Semi-solid metal processing or thixoforming is manufacture final product by loading the materials at a temperature in semisolid state between the liquidus and the solidus(C. G. Kang & Jung, 2001). The liquidus is when the substances completely complete into liquid state while the solidus is when the substances complete into solid state. This thixotropic behaviour in semisolid alloy slurries was first observed by Flemings and his co-workers' in early 1970 in MIT(Merton C. Flemings, 1991). This process has been studied and used for over 30 years.

Thixoforming or Semi-solid metal processing gives an engineer broadly option to design component and fabricate. There are many advantages using this process. First of all, it is capable to manufacturing near-net shape complex part; Energy efficiency; it can reduce solidification shrinkage thus the dimensions are closer to near-net dimensions; it can reduce cost; and most important the gas in the laminar flow due to entrapment can be decreased. In term of thermodynamic, the thermal die loading can be reduced. Thixoforming process give freedom to an engineer to fabricate towards thicker cross-section and wall thickness changed. Thixoforming process can produced the high mechanical, geometric and surface quality of components without need additional production process such as machining steps.

The process more enthusiasms to components that subject to high pressure; brake cylinder, Thick-walled components subject to high loading; suspension part and Thin-walled structural components. The advantage using aluminium in process semi-solid metal processing is high yield strength, better fracture toughness, and the stiffness of the component is better(G Hirt, Cremer, Witulski, & Tinius, 1997).

However, every process manufacturing has their limitation and disadvantage. As well as Thixoforming process, due to the inevitable factor. For instance, the high cost of raw materials and low number of its suppliers, the higher die development costs than for conventional forming technologies because of the lack of available process experience and design rules and Viscosity and solid fraction depends on temperature so, temperature control is important. Other than that, non-uniform heating can result in non-uniform composition in the component thus it causes liquid segregation.

Thixoforming or semi-solid metal processing is relatively new process that is shaping of metal components in the semi-solid state. Flemings and co-workers had studied the flow behavior of metals in a semi-solid state in early 1970s(Merton C Flemings, 1974). This process had manufactured much type of component and part of automotive car. For example, exhaust valve, brake cylinder and so on. Since aluminium is lightweight material, so these journals discovered using aluminium or other metal in thixoforming process and the microstructure during the semi-solid state.

In order to investigate thixoformability of a high-performance aluminium alloy, the heat-treated condition for the feedstock is 505 MPa and 11% elongation commercially extruded from 7075 aluminium alloys (extrusion ratio 16:1). This process used to create objects of a fixed cross-sectional profile. A material is pushed through a die of the desired cross-section. The microstructures in the semi-solid state consist of fine spheroidal solid grains surrounded by liquid. The results of one step, two-step and three-step induction heating regimes for thixoforming are presented. Thixoforming processes have a typical defect that often occurs in thixoformed material such as Liquid segregation, impedance of flow by unrecrystallised grains and porosity. This defect shown alongside successful thixoformed material that is in temperature between 615 and 618◦C. The result also shown that 478 MPa is the highest yield strength and 6.9% are the elongation for the material that thixoformed into simple graphite die. For thixoforming at 615◦C. into a tool steel die heated to 250◦C, the highest yield strength and elongation obtained are 474 MPa and 4.7% (ram velocity 2000mm/s). These values particularly strength for approaching those of 7075 in the wrought(Chayong et al., 2005).

Other than that, in order to investigate thixoformability of a high-performance alloy at high solid fraction ($0.5<fs<1$) another method thixoforming is used that is thixoforging. This process is where it involving the shaping of metal using localized compressive forces. 7075 aluminium alloys have been used as a feedstock for this process. The characteristic of higher solid fraction of 7075 aluminium alloy is less sensitive to drop in temperature, avoids metal splash at high speed and it allows laminar flow at high speed. The thermal exchanges can be decreased by using hot tool to slow down the solidification rate of the high solid fraction metal. To determine the best parameters to achieve maximum mechanical properties in Thixoforging of 7075 aluminium alloy, we need to consider the impact of some parameters such as tool temperature, shear rate. Extrusion tests with constant speed were used where these parameters are known. The result of this study is that each parameter has its level of impact on the Thixoforging: the temperature of the tool and the deformation rate shouldn't be high to avoid cracks. Thermal exchanges between the material flow and the tool have to be reduced to avoid high solidification rate(Vaneetveld, Rassili, Pierret, & Lecomte-Beckers, 2008).

Furthermore, SSM processing produces commercial products mainly in the automotive sector. However, a few selected materials that suitable for SSM processing. So, existing aluminium alloy has been tested and used for this thixoforming process. An experiment has been performed on automotive part using A390 Al-Si alloy as starting material. They added 1% nickel and 4% nickel to aluminium alloy. The result showed that A390 with 1% nickel addition has better strength compared starting material while addition 4% nickel will reduce the strength modified alloys because it leads to cracking problem(P Kapranos et al., 2003).

Experiment Method

The die material was chosen from a high heat resistant material because it needs to process the feedstock billets in the range of temperature between 600 to 620 °C. The H13 tool steel was chosen for the die material as it has the favourable characteristics. Properties of the material also required a high deformation resistant when heat is applied. This is to make sure the plunger movement is smooth when entering the forming die. The hydraulic press machine also needs to able to apply a sufficient pressure in order to inject the feedstock billet into a die cavity. There are a few parameters setting that have been investigated for forming die to accomplished the Thixoforming Operations. First of all, compression force or Pressure, die temperature, packing time which it is the moment when plunger have reached the maximum force and pressure and it hold with the manipulated time that the machine set. Other than that, the pouring temperature also an important factor for Thixoforming operations. Good or better final product of Thixoforming operations is depending on microstructure of the billet when it reaches the semi-solid temperature. Two ways to get better shape of exhaust valve when it goes through thixoforming operations, either increase the pressure or increase the temperature. Some facts that stated that higher pouring temperature will be provide larger amount of secondary phase which give greater fluidity of semi-solid material. It will cause the forming operations will give better flow semi-solid material in the cavity. But greater amount of secondary phase will lead to lowest strength and hardness properties.

Table 1: Parameter that Involve in Thixoforming

Sample No	Pouring Temperature (◦C)	Holding Time (s)	Pressure (Bar)	Packing Time (s)
1	700	20s	155 Bar	15s
2	700	20s	155 Bar	15s
3	660	20s	155 Bar	15s
4	660	20s	155 Bar	15s
5	660	20s	155 Bar	15s

Figure 1 shows the operation of hydraulic press for forming process but using open die. The type of die will be using for this semi-solid state is closed die. The specification that there should be in the lower mold is Ejector Housings that provides more rigid support for moulds and die cast dies. It equipped with riser which it functions is raising the height and compatible with hydraulic press. The hydraulic press has a limit for the Top mold to go down further. Thus, it helps the Forming process be smooth. Refer the figure below for Design in solid work. The riser also has Socket Head Cap Screws. It function is to tighten with plate above the riser. The screws have many type of design such as Socket head stripper bolt and flat head screws.

Figure 1: Actual Exhaust Valve

The component wants to fabricate is the exhaust valve or poppet valve. The dimension for exhaust valve is small in range 100-110 mm. The shape of exhaust valve is hollow, like in Figure 1, so the decision for create cavities for this part is using two block dies and we assemble the block as in Figure 2. The concept for plastic injection molding Mold between the internal risers is ejection plates, but in this design, it replaces with two die block containing cavities of exhaust valve

The in-gate design is like direct gate. The design gate is like that because to compress the billet and force it into the cavities to form exhaust valve shape. The in-gate is like 85mm and diameter 29 mm to hold the billet before thixoforming operations occur. The end of the cavities is containing hole to allow the billet of the semi-solid state to overflow when it already fill the cavity. The ejector block functions as eject the forming die when forming operations completed.

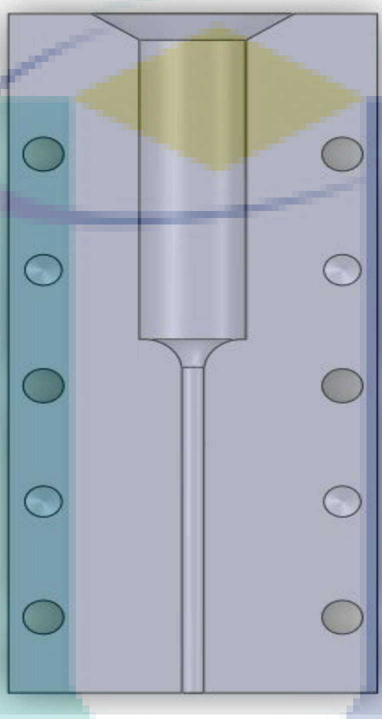

Figure 2: Die cavity design for exhaust valve.

Results and Discussion

Before run the thixoforming operations with sample, it tests with another testing billet or wasted billet to get the practically correct way to run the operations. When reheat billet must through the appropriate ways and procedure because the billet cannot reach the semi-solid temperature otherwise the billet can melt or it become solid before the operations. The semi-solid temperature is around 582°C and 652°C. Thus, set the temperature furnace higher than liquidus temperature which 750°C, when it reaches the temperature, drop the setting temperature to 660°C and let it constant. Then, insert the billet and reheat until 15-20 min. after that, bring the billet at the outside furnace get the temperature billet at that time with thermocouples and data logger. The results show suitable semi-solid temperature is 610°C which it reheats until 15 minutes. It becomes the benchmark to reheat the billet into semi-solid temperature. The formed part within the die cavity is shown in Figure 3 as follows.

Table 2: Results for formed part

Sample No	Reheating Time (Minutes)	Reheating Temperature (°C)	Pressure (Bar)	Height Billet before compressed (mm)	Height Billet after compressed (mm)	Overall length filled the cavities (mm)
1	15	650-760	155 Bar	22mm ±	13mm	48mm
2	13	650-660	155 Bar	20mm ±	14mm	11mm
3	17	650-670	155 Bar	21mm ±	14mm	45mm
4	13	660-670	155 Bar	21mm ±	16.5mm	13mm
5	15	650-660	155 Bar	20mm ±	15mm	10mm

Figure 3: Example of the formed part within die cavity.

The sample No 1 is formed after thixoforming operations occur. These parameter for example, pressure, reheating time, reheating temperature and transfer time is analyse to get optimum parameter setting for forming die to fabricate the exhaust valve. The wrought aluminium of 6061 is compressed in the forming die using hydraulic press which it capabilities maximum is 155Bar equivalent with 48.15 Ton-force or 480 kn. Length of the wrought aluminium is filled in the cavities is 9mm which billet before compressed is 22mm and after compressed it become 13mm. Visual inspection part formed shows the billet produce porosity and liquid segregation at the stem of part formed. The end of part formed contains higher liquid ratio and when it compressed it attracts with the gravity to flow below. These defects because the inner part of billet contains higher liquid fraction content thus produce liquid segregation when compressed because liquid flows quickly rather than solid phase. Liquid segregation means the liquid rejects to solidify during freezing because solid has less solubility compare to the liquid.

Figure 4: Sample No 2 aluminium 6061.

The Sample No 2 as shown in Figure 4 is analysed with the parameters reheating time is shortening which it is 13 minutes with the same. However, when it transfers to forming die, it become more to solid but it still in condition of semi-solid temperature. The thixoforming operations runs and it compressed the billet into the cavity as much as 6mm. The transfer times is important because it influence the cooling rate of billet when it transfer to the forming die before compressed. Furthermore, it reheats until 13 minutes only which it is not contain more liquid fraction and it contains more solid fraction.

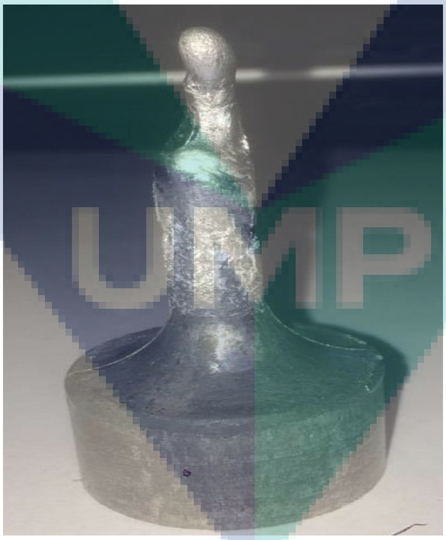

Figure 5: Sample No 3 aluminium 6061

The sample No 3 as shown in Figure 5 is reheat until 17 minutes because to get better semi-solid temperature. However, when it transfers to forming die it looks semi-solid aluminium which it looks like reddish metal and it compressed in the forming die. When it reaches room temperature, the result shows that end part formed like a drop of liquid because it contains too much liquid fraction in the inner of billet. The billet length that fills in the cavities is 7mm. The stem part formed shows the liquid segregation which it means it flow like liquid rather than flow like semi-solid temperature when it compressed. The part formed also produce porosity. Porosity means open space when it compressed or trapped air during compressed.

Conclusion

Thixoforming or semi-solid metal processing taking into accounts such as Pouring temperature, Pressure injection, Reheating temperature, Reheating time and Die temperature to get better flowability of aluminium 6061 semi-solid temperature. Higher reheating time will influence the billet contains more liquid thus liquid segregation occur when it compressed into the die. Low reheating time will cause the billet contains higher fraction solid and it cause when transfer into the die it solidified too quickly and hard to compress to form shape needed. Higher pouring temperature capture more liquid particles while lower pouring temperature capture more solid particles when it quenching. Transfer times is important to reduce cooling rate the billet to solidified quickly and heat loss excessively because when thixoforming operations occur the billet must be in semi-solid state. Die forming must be heat until it exceeds the 100°C to prevent the thermal shock in the die happen between the billet and the forming die. The Sample No 1 is better flowability because it contains more liquid particles thus it results higher length wrought aluminium 6061 billet filled in the cavities of exhaust valve which it is 9mm. Appropriate reheating time is 15 minutes to get better semi-solid temperature of aluminium 6061 in the furnace set to temperature 670°C.Design die also influences the flowability of semi-solid state aluminium when compressed into forming die using hydraulic press. The maximum capabilities of hydraulic press are 155Bar which equivalent to 48.15 Ton-Force or 480 kN.

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CHAPTER 4

CONCLUSION

The pouring temperature and holding time has an effect on microstructure of aluminium 6061 feedstock billet. The specific combination of pouring temperature and holding time will produce a finer and globular microstructure of the feedstock billet. Lower pouring temperature at 660°C with holding time of 20s produced a finer globular and uniform microstructure compare to other processing parameter combinations. This characteristic gives results in increasing the material fluidity for better flow during shaping. The lower pouring temperature delivers a slower cooling rates effect from above to below the liquidus temperature, which in turn causes less superheat to be extracted by the copper mould. Hence, the slow cooling rate condition during the solidification stage promotes the formation of more nuclei, which turn to results in smaller and uniform grain size.

In thixoforming operation, higher reheating time will influence the billet contains more liquid thus liquid segregation occur when it compressed into the die. Low reheating time will cause the billet contains higher fraction solid and it cause when transfer into the die it solidified too quickly and hard to compress to form shape needed. Transfer times were important in order to prevent feedstock billet solidified quickly and heat loss excessively during thixoforming operations. Die forming must be heated until it exceeds the 100°C to prevent the thermal shock between the feedstock billet and the forming die. Sample no 1 showed the superior flowability due to additional liquid particle within sample thus resulted the highest length of the exhaust valve.