REPUBLIC OF TURKEY
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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MANUFACTURING OF POLYMER/METAL MACRO COMPOSITES BY PLASTIC INJECTION MOLDING AND INVESTIGATING THE EFFECTS OF PROCESS PARAMETERS

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A thesis submitted by Burak YAVUZ in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 22.12.2015 in Department of Mechanical engineering, manufacturing engineering program.

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LIST OF SYMBOLS

GPa	Giga Pascal
τ	core shear stress
P	Pressure
d	Sandwich thickness
C	Core thickness
b	Sandwich width
D	Bending panel stiffness
E	Elasticity modulus
Δ	Total beam midspan deflection
G	Core shear modulus

LIST OF ABBREVIATIONS

ARALL	Aramid reinforced aluminum laminate
Al	Aluminum
BIW	Body-in-white
CAA	Chromic acid anodizing
CAE	Chromic acid etching
CPPP	PP Copolymer
GLARE	Glass Laminate Aluminum Reinforced Epoxy
HBU	High-pressure sheet metal forming
LDR	Limiting Drawing Ratios
PA	Nylon (polyamide)
PAA	Phosphoric acid anodizing
PC	Polycarbonate
PE	Polyethylene
PIF	Plastic Injection Forming
PP	Polypropylene
PS	Polystyrene
STRSW	Squeeze-type resistance spot welding

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ABSTRACT

MANUFACTURING OF POLYMER/METAL MACRO COMPOSITES BY PLASTIC INJECTION MOLDING AND INVESTIGATING THE EFFECTS OF PROCESS PARAMETERS

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Department of Mechanical Engineering

MSc. Thesis

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Manufacturing of hybrid materials in the combination of different materials gains great importance nowadays. These hybrids are also called macro composites and especially, polymer/metal macro composites are representative of this kind of unique combination to achieve improved quality of products in some fields such as electronics, automotive and aerospace.

In this study, a method for manufacturing polymer/metal sandwich structure is presented in which traditional plastic injection machine was converted to plastic injection forming (PIF). In this method, deforming of the metal and adhering the metal with polymer was done in one step. In the experimental study, a special mold within rectangular cavity was used in the PIF process. Aluminum (Al) plates with dimensions of 75x 115 x 1.5 (mm) were used as the metal part of the structure. The injected polymers were various types of polymers such as polystyrene, polypropylene and elastomer added polystyrene. The deformability of the aluminum plates were examined under different injection pressures. In order to provide adhesion between metal and polymer, an adhesive was applied on the metal plate prior injection molding. 3-point bending test was applied to determine the flexural strength and maximum deflection of the metal/polymer macro composites. The obtained results showed that plastic injection forming was acceptable for manufacturing polymer/metal macro composites in one step.

Key words: Polymer/metal hybrid structure, macro composite, plastic injection, bending strength

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ÖZET

PLASTİK ENJEKSİYON YÖNTEMİ İLE POLİMER/METAL MAKRO KOMPOZİTLERİN İMALATI VE İŞLEM PARAMETRELERİNİN İNCELENMESİ

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Farklı türden malzemelerin kombinasyonu ile hazırlanan hibrid yapıların üretimi günümüz dünyasında önem taşımaktadır. Makro kompozit olarak da adlandırılan bu hibrid yapılardan özellikle polimer/metal makro kompozitler, havacılık ve otomotiv sanayinde gelişmiş özellikleri sebebi ile yoğun olarak tercih edilmektedir.

Bu çalışmada, geleneksel plastik imalat yöntemlerinden plastik enjeksiyon kalıplama yöntemi, plastik enjeksiyon şekillendirme (plastic injection forming, PIF) yöntemine dönüştürülerek polimer/metal sandviç yapıların tek aşamada üretilmesi amaçlanmıştır. Bu yöntemde, metalin şekillendirilmesi ve metal-polimer adhezyonu tek adımda gerçekleştirilmiştir. Yapılan deneysel çalışmada PIF için özel olarak tasarlanmış dikdörtgen gravürlü bir kalıp kullanılmıştır. Sandviç yapının metal kısmı için 75x115x1.5 (mm) alüminyum plakalar kullanılmıştır. Enjekte edilen polimer için ise polistren, polipropilen ve elstomer takviyeli polistiren gibi bir çok polimer malzeme tercih edilmiştir. Farklı enjeksiyon basınçları altında alüminyum plakaların şekillendirilebilirliği incelenmiştir. Yüzeyler arasında adhezyonun sağlanması için plakalar ve polimer arasında adhesif malzeme uygulanmıştır. Polimer /metal makro kompozitlerin eğme dayanımının ve sehim miktarlarının tespiti için 3- nokta eğme testi uygulanmıştır. Elde edile sonuçlara göre, polimer/metal makro kompozitlerin tek adımda üretilmesinde, plastik enjeksiyon şekillendirme yönteminin tatmin edici sonuçlar verdiği görülmüştür.

Anahtar Kelimeler: Polimer/metal hibrid yapı, makro kompozit, plastik enjeksiyon, eğme dayanım

CHAPTER 1

INTRODUCTION

1.1 Hypothesis of Thesis

Polymers and metals have been used in different fields of industry. Each of the material has different advantages; metal materials have better mechanical strength whereas polymers are lighter. When these two classes of materials are integrated, a superior structure is possible to be obtained. The combined structures of polymer and metal can be found especially in automotive or aircraft industry for noise or vibration damping components. Also, these unique products provide weight reduction and decrease fuel consumption in automotive industry, sheet base components had been the main body element because of its high mechanical properties but nowadays companies would like to have same properties with lighter materials. Because of this reason, aluminum based materials come out to reduce the weight and fuel consumption and contaminant emissions, especially in automotive and aerospace industry compare to the steel sheet. Nowadays some high class automotive firms have already used this body panels with their vehicles. [1]

1.2 Literature Review

Most of the studies are focused on thermoplastic core materials. Thermoset resins have been used especially in aerospace industry since the early 1980's. GLARE® (Glass Laminate Aluminum Reinforced Epoxy and ARALL® (aramid reinforced aluminum laminate), are the most known materials in aerospace field. [2] These materials have been showed remarkable mechanical properties as fatigue resistance, impact resistance and damage tolerance. Increased manufacturing temperature and pressure are needed for a prolonged period despite of the fact that such thermosetting-based hybrid materials are often brittle and, for optimum consolidation of parts made from prepreg. [3]

Fast manufacturing times, high recyclability and low volatiles are major advantages of thermoplastic based laminates. These materials are mostly capable of reforming and reshaping components following manufacture, repairing easily, having remarkable characteristic in energy absorbing and high resistance to localized impact loading [4].

Polypropylene (PP) has remarkably balanced physical and mechanical properties in sandwich products. Kim et al [5] developed Aluminum/PP/Aluminum sandwich panels. They use aluminum sheet with 1.2mm and pre-rolled PP core material between 0.2 and they match their results with forming limit diagram. They achieved 65% weight saving with this process.

Burchitz et al [6] investigated new material concept, Hylite. Hylite is a basically sandwich panel which includes aluminum sheet and PP core materials was developed by Corus for automotive industry. Hylite has some remarkable results as sandwich structure provides 65% weight saving when it is compared to steel sheet and also 30% to aluminum sheet of equal stiffness, although costs remain prohibitive.

Polymer/metal combined structures induce the demand of assembly of them in different ways. The primitive method has been used for many years in which polymer and metal structures are assembled by an adhesive for sandwich material processes, a good surface treatment before adhesive application is needed. Furthermore, the geometrical shape of the polymer and metal components should be very compatible to have a combined structure having high mechanical strength. In most cases, metal part and polymeric part are fabricated separately by metal forming processes and plastic injection molding. Then, they are joined by adhesion bonding. Another method to obtain polymer-metal combined structures is conventional injection molding with metal inserts. Plastic plugs are good example for this method. [7].

Treatments can be classified as physical and chemical methods. Grit blasting, solvent degreasing and sandpaper using are the main physical procedures. These methods may change the topography. Flame treatment of plastics, using silane or maleic acid and anodizing procedures for metals is one of the major methods for chemical treatments. Chemical procedures provide chemical modification on applying surfaces. [8], [9] In literature, physical and chemical treatments can be applied on aluminum surfaces. Mcknight et al [10] studied on aluminum surface treatments and the results showed that etching of aluminum with chromic acid etching (CAE) was discovered to give remarkably developed performance compared to physical methods. On the other hand, chromic acid anodizing (CAA) or phosphoric acid anodizing (PAA) may be more convenient method especially in relation to the durability in wet conditions. Chromic acid can be an alternative however using chromic acid may be dangerous for safety because of its toxic and corrosive properties. Using silanes can be a strong alternative. . Much effort is being made to optimize the use of silane primers as a viable alternative to CAA and PAA treatments. It is now generally agreed that topography and oxide stability have a critical effect on resultant joint performance. [11]

Due to the developing technology, it has been realized that polymer-metal combined structures need new technologies including almost one step manufacturing in a fully optimized assembly line for metal and polymer components. Primitive methods are not sufficient to meet the geometrical accuracy or they bring large degree of manual labor within cumbersome manufacturing. Therefore, a conventional process, plastic injection molding is modified for manufacturing plastics covered with metal plates Dimensional tolerance of both polymeric and metal section is provided by this method in one step, which is called polymer injection forming (PIF).

Grujicic et al [12] reviewed metal-polymer hybrid applications with plenty different combinations such as micro-scale polymer-to-metal mechanical interlocking, in-coil or stamped-part pre-coating for enhanced adhesion and chemical modifications of the injection-molded thermoplastics to reach enhanced polymer-to-metal adhesion. For each of these approaches their suitability for use in load-bearing body-in-white (BIW) components was investigated. They searched the compatibility of these approaches with the BIW manufacturing process chain such as pre-coated metal component stamping, BIW construction via different joining technologies, BIW pre-treated and painting operations. It was found that micro-scale mechanical inter locking between the injection-molded thermoplastic polymer and stamped metal structural rib component methods are the most hopeful processes in polymer/metal hybrid technology.

Chen et al [13] studied on manufacturing of metal/polymer composites. During the manufacturing process, the injected polymer melt from the injection machine forces the sheet metal blank to deform according to the contour of the mold and the space between the formed sheet blank acts as the molding cavity of the polymer melt. They investigated mechanism adhesion bonding between the polymer and the surface of the formed sheet blank. They measured the experimental results of the main parameters which are the deformation characteristics and evolution of plastic strains of the sheet blank during the manufacturing process, the distribution of plastic strains and thickness of the formed sheet blank, and the effects of drawing-in of the flange on these and compare them with finite element analyses data (Marc finite element codes) according to the finite element analyses results. Shaped sheet blank can be divided five different areas according to deformation characteristics. Deep drawing and stretch forming is the most important parts of this process. In the earlier of the stage, the pressure of melting polymer increased from zero to some value (e.g., 30 MPa for friction coefficient of 0.05) deep drawing leads the process. Later then when the pressure keep increasing, stretch forming showed up. There is no deep drawing process in that situation.

Barinni et al [14] modeled metal polymer injection process to determine the mutual metal-polymer interactions and to supply in designing technology. They developed multi-physics numerical model. They aimed to determine the thermal and mechanical events that take place during the process inside the polymer and the metal and to clarify the mutual interactions between the polymer and metal by coupling the analyses of the phenomena that occur in the two regions. Later then modeling they experiment this case to an industrial material than they showed that model was working successfully.

The basic principle of the PIF process was not for obtaining polymer / metal combined structures. Firstly, it was aimed to deform sheets under viscous pressures and then it was developed a macro composite manufacturing method by some additional processes before injection forming for improving adhesion between polymer metal [15],[16].

Tekkaya et al [16] focused on non-Newtonian nature of thermoplastic melt as a pressure medium during polymer injection forming process experimentally. In this study they investigate presence of non-hydrostatic pressure distribution within the cavity and its effects on the final form of the manufactured sheet metal component. They reached some results that when injection rate higher, injection temperature and melt flow index of the processed polymer was increased, it was easy to get to the uniform pressure distribution and subsequently uniform forming of the sheet metal. Also if sheet metal region was established closer to the injection point, better forming performance can be achieved. [16]

1.3 Aim of the Thesis

There have been a few studies about plastic injection forming and researches are still continuing on the PIF process. In none of the previous studies, the investigation of the mechanical strength of the obtained hybrid structures was present. In this study, polymer/metal hybrid structures were obtained by PIF and a different adhesive material from previous studies was experienced for providing the adhesion between the polymer surfaces and metal surfaces. The effects of the injection parameters in deforming the metal component were investigated. Bending tests were applied to the hybrid structures.

CHAPTER 2

GENERAL INFORMATION

2.1 Plastic Injection Molding

Plastic injection molding is one of familiar methods of forming plastics from raw material to thermoformed product. This method is commonly used for thermoplastic materials which are melted, reshaped and cooled individually.

Nowadays, injection molded products can be used almost every manufacturing industries such as automotive food packaging, bottle caps, wire spools, computer electronic equipments With this functional process high quality, simple or complex products have been manufactured on a fully automated basis at high speed with materials. Some thermoplastic raw materials and application areas are listed in Table 2.10

Table 2.1 Some thermoplastic materials and their application fields. [17]

Material	Abbreviation	Properties	Typical Applications
Polypropylene	PP	Good chemical resistance	Packaging, containers
Polyethylene	PE	Good chemical resistance, flexible or semi rigid depending on grade. Weatherproof, good low temperature performance.	chemical drums, gas/water pipe and fittings, kitchenware

Table 2.1 (Continued)

PP Copolymer	CPPP	Good gloss, texture possible, low cost	Large automotive parts, plates and cups for children and picnics
Polystyrene	PS	Brittle, transparent. Poor UV stability. HIPS up to 7x impact strength of GPPS	Toys, packaging, cosmetic packaging TV cabinets, refrigerator linings, toilet seats
Nylon(Polyamide)	PA	Rigid, tough, hardwearing	Gears, bearings, automotive under bonnet parts
Polycarbonate	PC	Rigid, transparent, excellent impact resistance, good weather resistance, good dimensional stability	Crash helmet visors, vandal proof glazing, riot shields, car headlamp lenses, safety helmets

2.1.1 Historical Background

It is beneficial to investigate the beginning of the injection molding process to figure engineering and operation of modern day injection molding machines out.

The first injection molding machines were based around pressure die casting technology used for metals processing, with patents registered in the USA in the 1870's specifically for celluloid processing. More major industrial improvements did not appear until the 1920's when a series of hand operated machines were created in Germany to form thermoplastic raw materials. A simple lever adjustment was used to clamp a two piece mold together. With this method molten plastic was injected into the mold to manufacture the molded component. Because of the low process pressure this method was used limitedly. Furthermore pneumatic cylinders were combined to the machine design to close the mold, but these systems were not functional so only little improvement could be made. [18]

In 1930's Hydraulic systems were first executed to injection molding machinery as wider range of materials became available, but die casting technology was still the most important parameter for the machine design.

After 1950's in Germany major improvements of injection molding machinery designs occurred. Ancient machines were built on simple plunger arrangement to force the material into the mold even though these machines could not be sufficient as materials became more advanced and processing requirements became more complex.[18]

The most important development area with a straightforward plunger arrangement was that no melt mixing or homogenization could be readily imparted to the thermoplastic material. This was exacerbated by the poor heat transfer properties of a polymeric material.

One of the major improvements in machine design to solve this problem, which still applies to modern processing equipment today, was the introduction to the injection barrel of a plunging helical screw arrangement. The machine subsequently became known as a 'Reciprocating Screw' injection molding machine.

2.1.2 Injection Molding Cycle

2.1.2.1 The Injection Molding Cycle

Plastic injection process has been developed remarkably to the level where fully automated, closed loop, microprocessor controlled machines are the 'norm' even if injection molding production method is still comparatively simple process.

First of all raw material which is polymeric powder or granule to start the process is needed. Material transfer from a feed hopper to heated barrel, raw material is melted in the barrel and injected into a mold some form of plunger arrangement. The mold is clamped shut under pressure within a platen arrangement and is held at a temperature well below the thermoplastic melt point [18].

The molten material turns into solid form quickly with the mold and provides ejection of the component after a pre determined period of cooling time. Fundamentals of the plastic injection process for reciprocating screw machine are as follows.

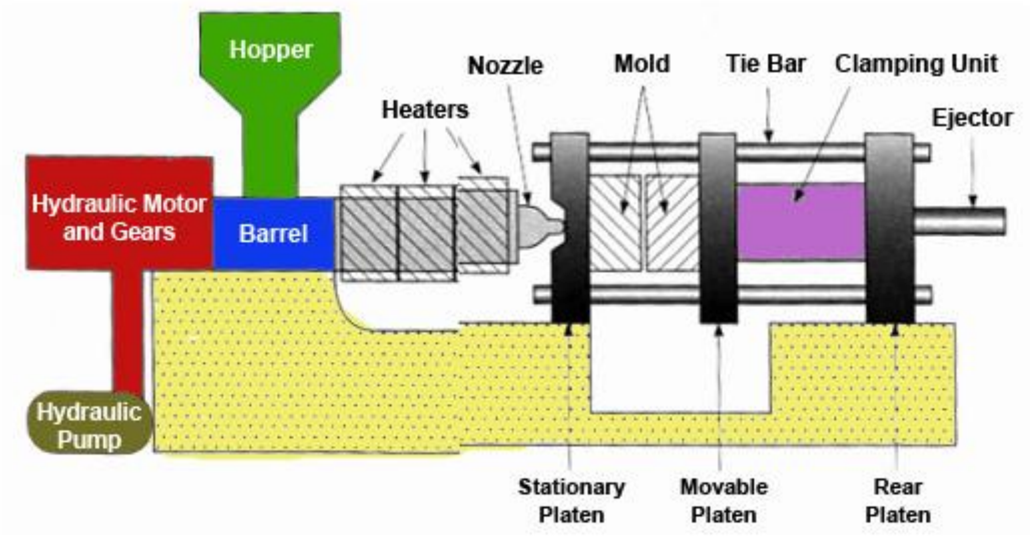


Figure 2.1 Schematic picture of thermoplastic injection molding machine[19]

2.1.2.2 Mold Closes and Clamping

The mold is closed within the platen arrangement and clamped using necessary force to hold the mold shut during the plastic injection cycle, in this manner preventing plastic leakage over the face of the mold. Currently molding machines have between 15-4.000 metric tones clamping force (150 to 4000 kN) Most of the machines have opening/closing and clamping of mold tools but in general they are two types. One of them is hydraulic structure where driven by a hydraulic piston arrangement which produce the necessary force to keep the mold shut for the injection process. Instead of hydraulic pistons, smaller auxiliary pistons may be used to execute the main movement of the platen and a mechanical blocking arrangement cause transfer locking pressure from a pressure intensifier at the rear of the machine, which progresses only by a few millimeters, through to the platen and tool[18].

Toggle Lock system is the other common clamping arrangement technology. With this design a mechanical toggle device, which is connected to the rear of the moving platen, is driven by a relatively small hydraulic cylinder, this benefits platen movement and also clamping force when the toggle joint is finally locked over rather like a knuckle arrangement.

2.1.2.3 Injection

In this step of the process, machine cycle the helical form injection screw locates 'screwed back' position with a charge of molten thermoplastic material in front of the screw tip roughly equivalent to or slightly larger than that amount of molten material required to fill the mold cavity. Length to diameter ratios in the region of 15:1 to 20:1, and compression ratios from rear to front of around 2 : 1 to 4 : 1 are two major design parameters which let the gradual densification of the thermoplastic material as it melts.

A check valve is built-in to the front of the screw like to let material pass through in front of the screw tip on metering (material dosing), but not cause material to flow back over the screw flights on injection. The screw includes within a barrel which has a hardened abrasion resistant inner surface.

In general, ceramic resistance heaters locates in the barrel. Ceramic resistance provides to increase temperature of the plastic material and make up for heat loss through the barrel wall principally. To achieve the modest indication of melt temperature thermocouples are fitted deep in to the barrel. So heat input can be closed loop controlled with a Proportional Integral and Derivative (PID) system. The screw (non-rotating) is driven forward under hydraulic pressure to discharge the thermoplastic material out of the injection barrel through the injection nozzle, which forms an interface from barrel to mold, and into the molding tool itself.[18].

2.1.2.4 Holding Pressure and Cooling

The screw is held in the forward position for a set period of time, usually with a molten 'cushion' of thermoplastic material in front of the screw tip such that a 'holding' pressure may be maintained on the solidifying material within the mold, thus allowing compensating material to enter the mold as the molded part solidifies and shrinks.

A set time in seconds from the start of the injection fill phase, by the position of the screw in millimeters from the end of injection stroke and the rise in hydraulic pressure as measured by a pressure transducer in the mold itself or in the injection hydraulic system are the three approaches to initiate the holding pressure.

When hold pressure no more has an effect on mold packing substanstance turns to solid form, the hold pressure may be decreased to zero this causes to minimize residual stresses in the resultant molding. The mold must be held shut for a set period of cooling time after the hold pressure phase has been finished.

This time let the heat in the molding to expand into the mold tool such that the molding temperature decreases to the point that the molding can be ejected from the mold without excessive distortion or shrinkage. This case usually needs the molding to decrease to a temperature below the rubbery transition temperature of the thermoplastic or Tg (glass transition temperature). Rely on the material type this temperature can be changed within a few degrees or over a temperature range.

Mold temperature control is joined into the tool usually by channels for pressurized water flow. Cooling unit or water heater can be connected to the mold depending on the processed material , type of substance and production rate needed.[17]

2.1.2.5 Material Dosing or Metering

In the cooling stage, the barrel is recharged with material for the next molding cycle. When injection screw rates because of its helical structure, plastic material which is granule or powder form is drawn into the rear end of the barrel from a hopper feed,

The throat hold on the hopper to the injection barrel is usually water cooled to avoid early melting and subsequent material bridging giving a disruption of feed. The screw rotation speed is commonly set in rpm which is calculated by using a proximity switch at the rear of the screw. Screw rotation may be set as one constant speed throughout metering or as several speed stages.

The material is gradually transferred forward on the screw flights and melted . It provides polymer was completely melted and homogenized when it comes in front of the screw tip. When the needed shot size is reached, the molten material located in front of the screw tip progressively pushes the screw

Increased shear is imparted to the material by restricting the backward movement of the screw, this is done by restricting the flow of hydraulic fluid leaving the injection cylinder. This is named to as `back pressure' and it causes to homogenise the substance and decrease the possibility of unmelted material transferring to the front of the screw[18].

2.1.2.6 Mold Opens and Part Ejection

After the cooling step finishes, mold is opened and the molding is ejected. This is commonly carried out via ejector pins in the tool which are coupled by an ejector plate to a hydraulic actuator, or by an air operated ejector valve on the face of the mold tool.

One of methods of ejection of molding is free fall. It can also drop into a collection box or on a transfer equipment such as conveyor or removed by an automatic robot which is named fully automatic cycle. In semi-automatic mode, the operator may get involved at this point in the cycle to remove the molding manually. Once the molding is clear from the mold tool, the complete molding cycle can be repeated over and over [18].

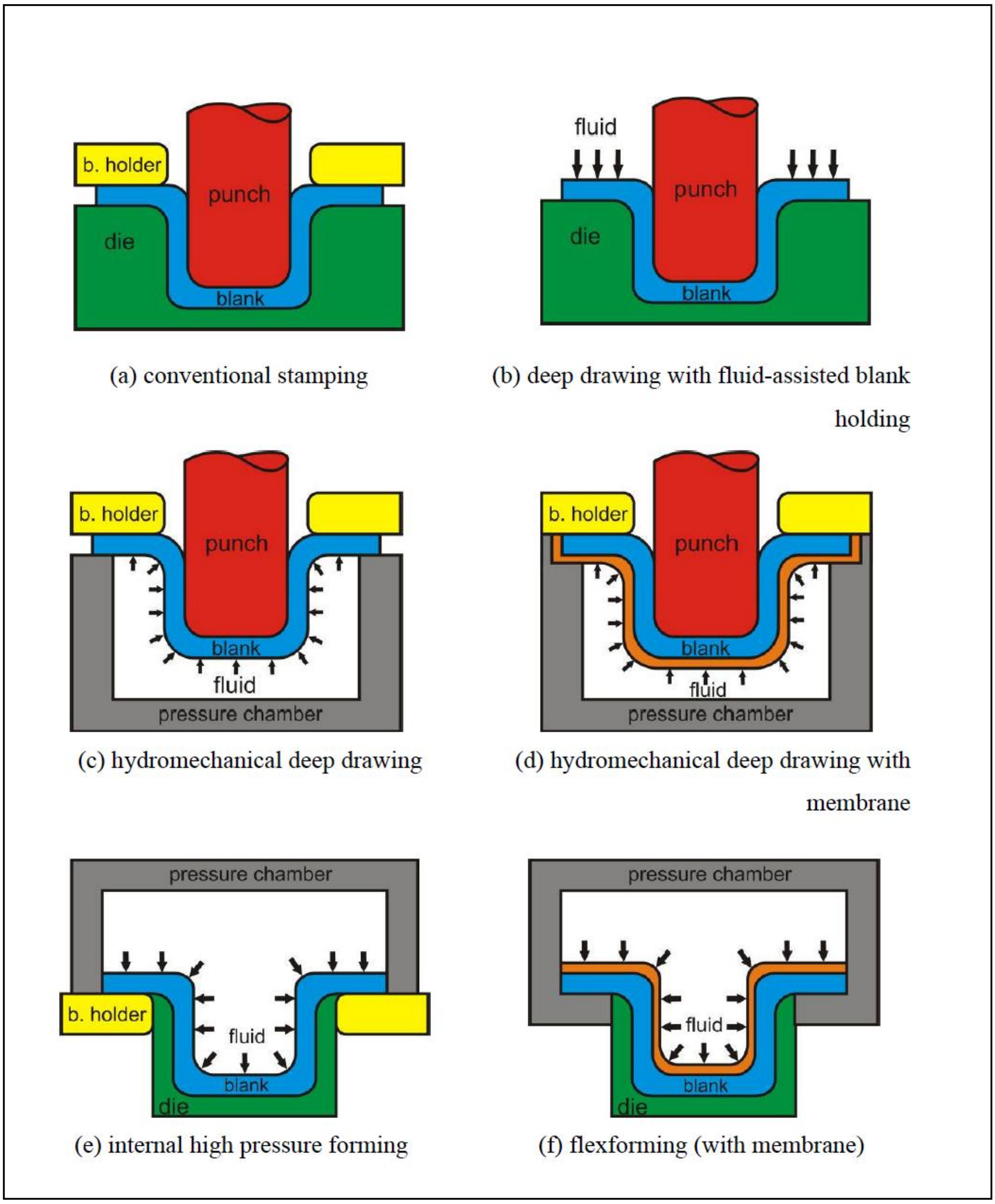
2.2. Hydroforming

Hydroforming is a production method for manufacturing complex hollow components from sheet metals, in most situations via circular tubes as a source material. Hydroformed component, a circular tube is inserted into a suitable die, sealed on both sides by two horizontal cylinders, and is subsequently formed to conform to the shape of the die cavity by internal hydraulic pressure are the main requirements to produce a hydroformed component.

Hydroforming process has many advantages to conventional forming process as cost and weight reduction in pieces and tools so in many industries mostly automotive and aircraft technology have used this method to manufacture complex hollow components.[20]

Figure 2.2 represents sheet metal hydroforming processes. First section of the Figure 2.2 (a) explains that general stamping process that includes general pieces as a rigid die, a rigid punch, a rigid bunk holder and a deformable metal sheet part. With the gravitational force acting on moving rigid punch, work part is getting the shape of die. A working fluid is taking place in sheet metal hydro forming process that fluid is supporting die.

At fist type, a pressurized fluid with a thin rubber that transferring pressure is been used instead of the blank holder. Progress is represented at Figure 2.2(b) and method is called as "deep drawing process with fluid-assisted blank holding" [21].Advantages of using soft-blank holder are reduced friction force and enhanced High Limiting Drawing Ratios (LDR). However, this process needs a fluid blank holding device and limiting productivity.



(a) conventional stamping

(b) deep drawing with fluid-assisted blank holding

(c) hydromechanical deep drawing

(d) hydromechanical deep drawing with membrane

(e) internal high pressure forming

(f) flexforming (with membrane)

Figure 2.2 Sheet metal hydroforming process [22]

At second type, rigid die is replaced by fluid that acting on a membrane (Figure 2.2d) during this process, punch is moving to the work part and this time the fluid applies a supporting counter pressure to the sheet acting like a soft die. This process is named hydro mechanical deep drawing. [22]

Pressure of fluid controlled by an adjustment device and pressure adjustment is the most important parameter of this progress. Uncontrolled low pressures can lead wrinkles on work part however rupture can be caused tear damages in too high pressures. At another type of this process, membrane is replaced by an o-ring that provides sealing (Figure 2.2-c).

To summarize the advantages of hydromechanical deep drawing process,

- Local thinning and uniform shape is guaranteed by friction forces that occurred between punch and work part by counter forces.
- Wrinkle is limited by the counter force that acting on all unsupported regions of the sheet causing circumferential tensile stresses.
- In o ring method, high drawing ratios (LDR) can be achieved with reduced friction.
- Process is very feasible for small batch production as there is only one rigid punch tool.

Disadvantages can be summarized by the increased cycle time, require of tool closure tool and higher force requirement of stamping & blank holding.

At third type, work piece is getting die's shape with pressurized fluid instead of using a rigid punch. There are two types of this process depending on membrane usage between fluid and work piece. Process without membrane is called "HBU (high-pressure sheet metal forming)" and sketched in Figure 2.2(d-e)[23].

This process is advised to be used for manufacturing of complex sheet parts and high volume small parts in figure 2.2.(e). Disadvantages of this method are low accuracy of positioning due to process and long cycle times. Membrane used process is known as "flexforming process" or "fluid cell forming process". Flexiforming is the only process that does not include blank-holder. Work piece is attached to the die with guide pins(Figure 2.2-f).[24]

2.3 Plastic Injection Forming

Polymer injection forming (PIF) is one of new progress in the manufacturing of plastic/metal macro composites. It is the combination of the "*plastic injection molding*" and "*hydroforming*" processes.

It can be described as one-step production process manufacture a composite between sheet metal and polymer using ordinary injection molding machinery [14, 16]. It is the combination of the plastic injection molding and hydroforming process.

Process starts with locating in position along its edge by means of the clamping unit of the injection molding machine. After that the sheet metal is located along its edge by means of the clamping unit of the injection molding machine. When plastic injection machine is ready to process, melting polymer is injected from the nozzle of the injection machine and flows along the sprue gate of the mold. Pressure of the polymer provides to deform the sheet metal blank according to mold cavity. Injection pressure is one of the major parameter in plastic injection forming. When pressure increases, deformability of metal is easier and also it causes to have better contact field between the sheet metal blank and the mold cavity

Greater contact area, the higher the pressure of the polymer melt that can be built up in the deformed sheet blank. It is an interrelated process. Thus, the plastic injection process technology is a combination of the injection molding and sheet metal forming processes. [25]

Following the injection stage melting polymer turns into solid form during this stage polymer adheres to the deformable metal sheet. After sufficient adhesion between metal and polymer, polymer occupies the space between metal sheets and finally macro composite which has metal and composite components is manufactured. Final shape of the composite depends on the design parameters of mold cavity. By means of this technology, a fully finished metal/polymer macro-composite part is manufactured in only one production step.

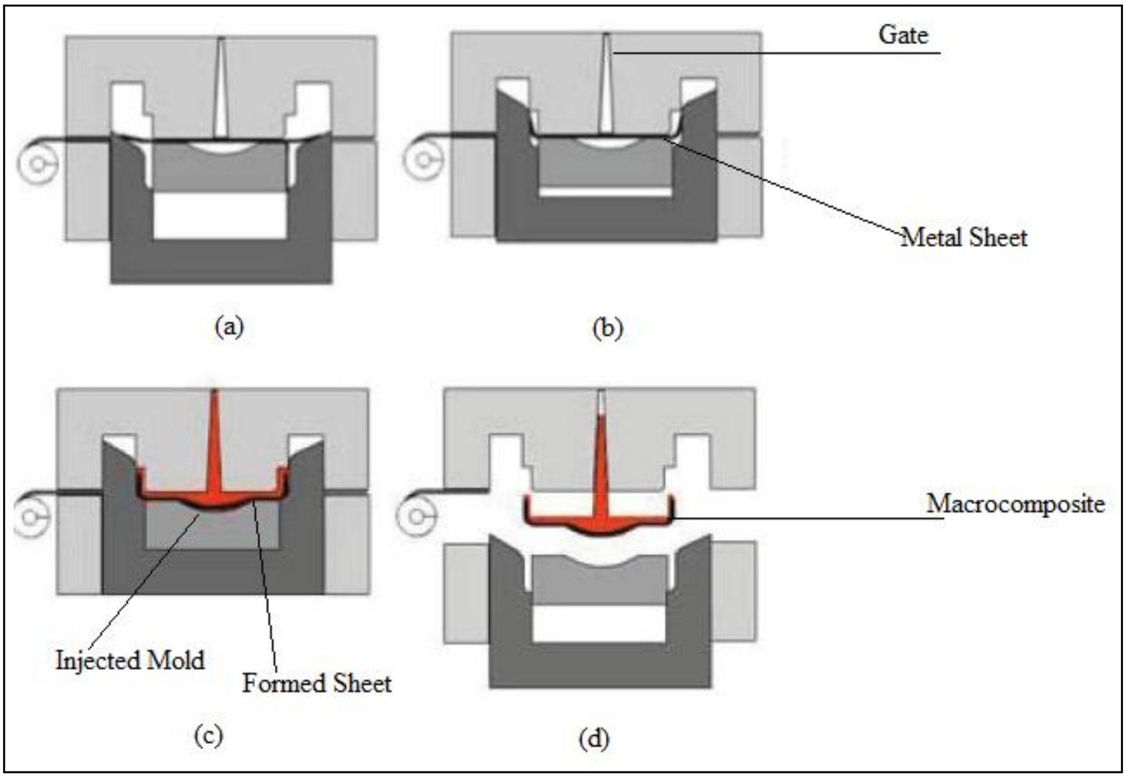


Figure 2.3Polymer injection forming process sequence [25]

The process sequence can be seen in Figure 2.3

a). A metal sheet is positioned between the open halves of a mold.

b).When the mold closes, the metal sheet is cut to the needed blank size. At the same time the blank can be shaped by deep drawing or by bending the sheet metal into the basic product shape.

c).After the mold is fully closed, the polymer is injected into the remaining cavity and a second, hydrostatic, deformation step is applied to shape the metal sheet into its definite form. In this stage of the PIF process, the physical adhesion between the metal sheet and the injected polymer is gained.

4. Finalising the production cycle, macro composite is manufactured and it can be ejected from the mold.

One of the most significant advantages of the PIF method is that the macro composite is obtained in this method takes place in a single step. Moreover, the fact that the machine employed in PIF is a traditional plastic injection machine renders the method quite practical. Plastic injection forming is based on forming the metal plate placed on the core of the injection mold with the pressure of the melt polymer injected. With the help of the pressure exerted through melt polymer, the metal place is shaped in exactly the same manner as metal sheet shaping methods. Flow of the metal plate within the injection mold through by drawing and thus changing its shape is insured. However much the PIF method appears before us as an alternative method for shaping metals, the main important implementation is the forming of polymer/metal-based hybrid structures. On the other hand, in the forming of hybrid structures, researches have used different adhesives and compatibilizers to obtain adhesion between the metal plate shaped and polymer surface injected and hardened[12]. The adhesive that is most commonly used in obtaining adhesion between the metal and polymer is silane. Boerio and Shah [26] used silane to insure adhesion between PVC and low-carbon steel. They injected the PVC material onto the metal plate after coating metal surfaces with silane. Preliminary processes such as polishing, sanding, searing were applied [12],13]. However, these processes enable a micro-level connection between the metal surface and polymer. In some cases, a macro-level connection can be administered to strengthen the connection, as well

Plastic injection forming method is an alternative method for parts that can be used especially in head board, bumper or car door modules in the automotive industry. Although the essence of the PIF method resembles hydroform shaping effects of plastic injection parameters on the quality of parts must be taken into consideration to be able to implement the method correctly [14-16]. For example, when the polymer shrinks or warpages, errors occur in the polymer comprising the core of the macro composite and as a result, the expected congruence of surfaces between the polymer-metal, precision decreases. Furthermore, injection pressure exerted excessively leads to flash formation in the plastic core of the sandwich structure, whereas low injection pressure causes formation of a poorly shaped metal plate. As a result of all these, it is understood that the PIF method requires experience on both shaping metals and producing plastic parts.

The PIF method was first applied in the shaping of metals by plastic injection pressure and it was secured by patent. However, studies on the use in macro-composite production and implementation to the manufacturing parts from different fields are ongoing. An investigation into the literature has revealed a limited number of studies on the implementation of the PIF method. Investigation of the mechanical properties of the product derived or investigation of vibrator isolation, sound isolation or heat insulation characteristics have not been seen in none of these studies. Just the limits of feasibility of the method were examined. The most probable reason for this is that when some properties of the product derived are desired to be investigated, it needs to be subjected to standard tests and sampling from a part is required for these tests. In this kind of situations, separation, delamination can be observed between the metal and plastic components of the sandwich structure unexpectedly. Silane and similar chemicals provides adhesion between the polymer and metal components in previous studies but mechanical locking implementations were applied to when this was not deemed to be sufficient As a result of the researches and trial runs carried out under the supported study, an elastomeric-based adhesive, a primer not experimented before was used between the metal and plastic layers. Becoming more active under the influence of temperature and pressure, primers are quite appropriate for the injection procedure. This is because pressure and temperature are active in the injection process. Moreover, different from ordinary acrylic- and epoxy-based adhesives, primers have a higher capability in terms of surface filling, as well.

2.4 Macro Composite Structures

2.4.1 Background

Macro composites, can be also called sandwich structures. These structures are the combination of face and core materials. In these structures a weak (low elasticity modulus) and lightweight core material sandwiched between two strong (high elasticity modulus) and heavy face materials.(Figure 2.4)

Selecting thinner or thicker face material depends on the desired product property. Thin face material is selected to reduce the weight or very thin layer of viscoelastic core substances between two thick face materials are chosen to increase damping.

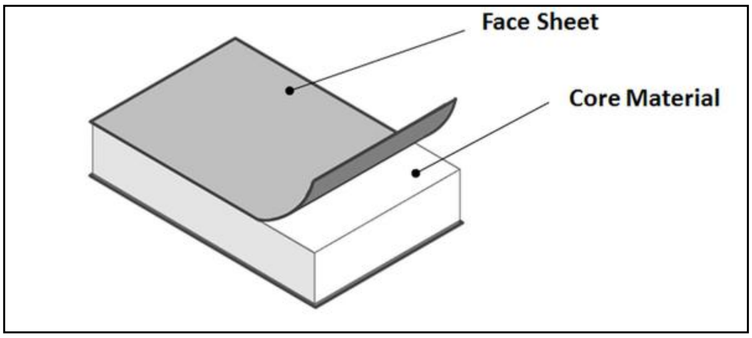


Figure 2.4 Schematic of sandwich structure [27]

High stiffness giving high flexural rigidity, high tensile and compressive strength, impact resistance, surface finish, wear resistance and environmental resistance such as chemical, UV, heat are the most desired properties for the face materials and for the core materials density, shear modulus, shear strength, stiffness perpendicular to the faces and thermal and acoustical insulation [28]. Face materials are classified metallic or non-metallic also core materials can be divided balsa wood, honeycomb cores, corrugated cores, metallic foams, homogenic elastomers a cellular foams. These types are shown in Figure 2.5

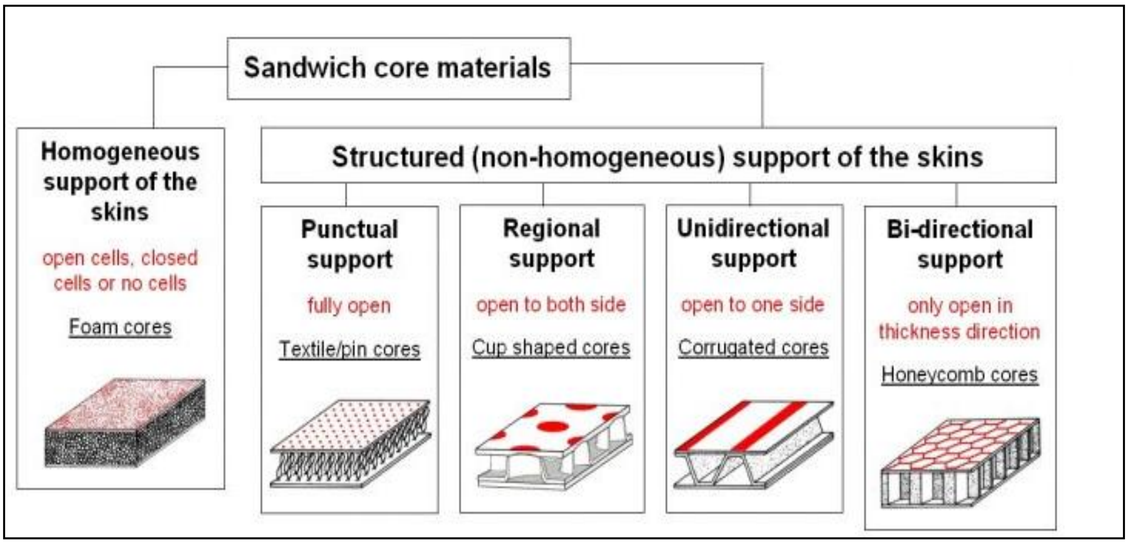


Figure 2.5 The core materials types of sandwich structures [29]

When we compare to the core types, honeycomb sandwich structures are more capable of high bending stiffness and strength-to-weight ratios than cellular foamed cores. On the contrary, honeycomb structures are more expensive and hardly to manufacture. Polyurethane (PUR), Polystyrene (PS), Polyvinylchloride (PVC) and Polymethacrylimide (PMI) are the most preferred cellular substance. Polyurethane is the cheapest material and also it can be produce continuous process. Polystyrene foam has better mechanical and thermal insulation than Polyurethane foam and can be used in load-carrying structures.[30]

Polyvinylchloride foam has better mechanical properties than those of both polyurethane and polystyrene but it is more expensive. Furthermore poor resistance to heat is the major disadvantage of polyvinylchloride foam. Polymethacrylimide is much more expensive than others but it has the best mechanical properties when we compare to each others.

In order to design the core material for honeycomb structures, aluminum, impregnated glass an agamid fiber mats are the most popular raw materials. In most of the foam cored and honeycomb cored sandwich structures grace layers resists bending loading. Also, the core part of the sandwich carries out the transverse shear loads (similar to the middle part of an I-beam) which is beneficial to the faces to remain in place.

On the other hand core layer material carries a partition of the bending loads are also in corrugated core construction. [31]

When we compare to the sheet metals, sandwich structures have lower lateral deformations, higher buckling resistance and higher natural frequencies because of their high bending stiffness-to weight ratio. For this reason sandwich structures can me manufactured lower weight than sheet metals at the same loading and boundary conditions, strength and buckling performance.

Vibration damping is the one of major advantage of sandwich composites. Noise and vibration properties of product can be developed with laminated metals wit adding much weight and cost. These consequences result to reduct or eliminate of sound absorbing materials and mastics used in automobile body panels for controlling cabin noise[32].

2.4.2 Manufacturing of Polymer/ Metal Macro Composites

There are different methods in manufacturing sandwich structured hybrid materials. The methods can change according to the components of the hybrid structure. Simple classification of is given below about manufacturing methods sandwich structures.

Honeycombs;

- *Polymer honeycomb core with metal sheet faces*
- *Metal honeycomb core with metal sheet faces*

The honeycombs are produced by corrugating process. During the process pre-corrugated metal sheets are stacked into blocks and bonded together firstly. After the adhesive between the sheets are applied, blocks can be cut from the stack. The process is shown in Figure 2.6

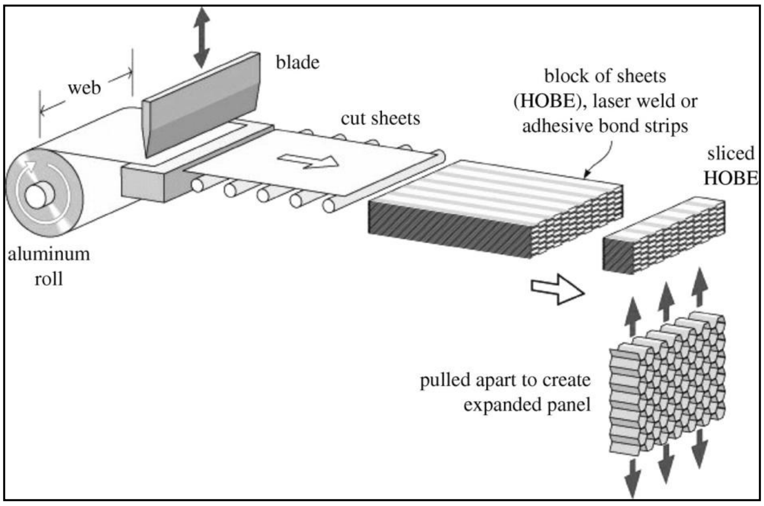


Figure 2.6 Schematic of the manufacturing of honeycomb cores (corrugating and expansion process [33]

Presses can be added the process if diversity of the thickness of honeycomb sandwich composite needed. This process is named ‘crushed-core-process

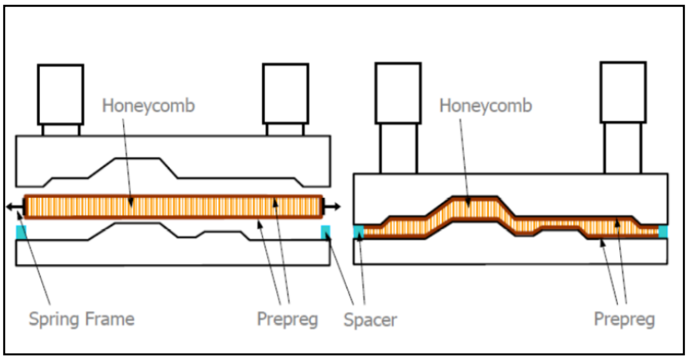


Figure 2.7 Open and closed press for forming honeycomb structure [30]

Cellular foam sandwich material can be produced with the device is called double-band rolls. Foam is spilled on lower face material and adhered by self pressure and heat is executed to upper and lower face materials.

Laminated plates;

- *Polymeric core with metal sheet face.*
- *Fiber mat layers.*

Laminated metals are shipped to stamping plants in a continuous coil or steel sheets. Then, the parts are stamped and shipped for assembly. There is no necessary for a joining process to other structures since it can be welded to chassis as they are basic plates because the core is very thin as minimum 0.001 inch. The weld type mostly applied to add is squeeze-type resistance spot welding (STRSW) but MIG weld can also be applied if there is a problem about accessing to attachment points but weld contamination from the core may arise. Also applying windshield urethane adhesive is another alternative to join laminated metals on chassis. [30]

PIF is alternative method among these methods for manufacturing polymer/metal sandwich structures with different geometrical shapes. [7, 13-16]

2.4.3 Industrial Applications of Sandwich Structured Macro Composites

The concept of using two separated faces is thought to have been first discussed by Duleau, in 1820, and later by Fairbairn experimentally. First commercial products were seen in 1930's . First executions tried in military devices during World War II as most of new technology. The first mass production of sandwich laminates (with balsa core) was for Mosquito aircraft produced in England shown in Figure 2.8. Now sandwich structures are one of the biggest manufacturing methods and their applications can be used from trains, automobiles and fast ferries to buildings, cold chamber isolations and roofs as shown in Figure 2.9

Figure 2.8 RAF mosquito [34]

Figure 2.9 Roof panels [35]

Some other examples of applying sandwich structures are vehicles. Main benefits of these structures are thermal insulation, loading capacity and lightness. For example 3M Company has been produced sandwich panels for aircraft design as shown in Figure 2.10. This material provides lightness and it helps to reduce fuel consumption.

Furthermore, this product has some advantages as prevent from impact damages and moisture ingress. Airbus also chooses sandwich panel structures for their window panel as given Figure 2.11

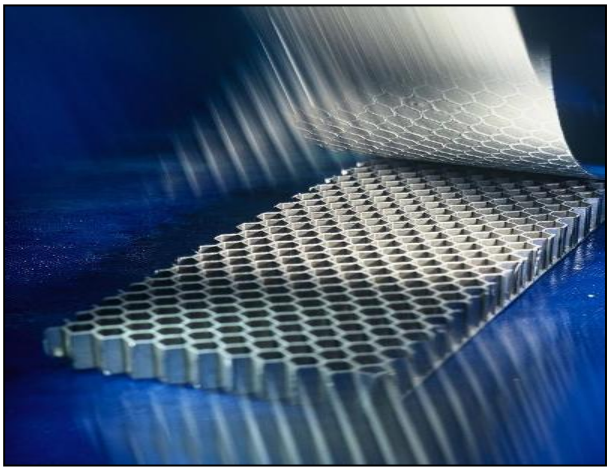


Figure 2.10 3.M Sandwich panel sample [36]   Figure 2.11Airbus window panel [37]

There are plenty of companies which manufacture or use the many types of sandwich structure. Econcore is one of them and this firm manufactures most of the sandwich panel’s type. Products can be used many of industries as transportation, automotive and building panels with PP, PA, PC, polyethylene terephthalate (PET) and akrinonitril butadien Sterne (ABS) raw materials.

Bondal steel is one of the laminated sandwich kind which produced by ThysenKrupp Steel AG. Company applies this material as dash panels and oil pumps of their automotives. Dynalam is similar with Bondal steel and it is produced by Roush. They are utilized as engine covers, transmission covers and body panels in automotive industry. [30]

CHAPTER 3

EXPERIMENTAL SETUP

3.1 Equipment and Method

3.1.1 Material

Macro composites generated in the experimental study have two components; polymer and metal. Metal component is aluminum (1100 series) and its characteristics are given in Table 3.1. Aluminum plates were supplied in two different thicknesses, namely, 0.5 mm and 1.5 mm. Width and length of the plates were115x 75 mm.

Different polymers were used for the polymer material that will form the core of the sandwich structure. Basically, three main polymeric materials were used: polystyrene PS (LGH-306, LG Polymers Inc.), polypropylene PP, (Sabic Inc.) and thermoplastic elastomer; (TPE). Moreover, among these materials, elastomer (styrene-ethylene-butylene-styrene, SEBS-g-MA) - reinforced polystyrene, titan dioxide particle (Nabond Inc.)- reinforced polystyrene , titan dioxide reinforced polypropylene were also prepared under laboratory conditions and used in the injection procedure. Properties of polymeric materials are given in Table 3.2

Table3.1 Properties of Aluminium (1100-0) series

Properties	
Elastic modulus (GPa)	70
Tensile strength (MPa)	90
Yield strength (MPa)	35
Hardness (Brinell)	23
Elongation at break (%)	35

Table 3.2 Properties of the commercial polymers used in the experimental study

Property	Polystyrene	Polypropylene	Thermoplastic Elastomer, TPE1 (PP/EPDM)	Thermoplastic Elastomer, TPE 2 (PP/SBS)
Elasticity module (GPa)	2-3	1-2	0.23	0.25
Flow index (g/10 min)	7.5	6.2	10	15
Rigidity	93 (R-Scale)	68 (Shore D)	65 (Shore A)	70 (Shore A)
Extension at break (%)	10	25	600	600

Thermoplastic materials were provided commercially as given Table 3.2. First one, thermoplastic elastomer is coded as TPE1 and the second one is coded as TPE 2 . The specifications are given in Table 3.2. TPE1 (Arel Plastik Inc.) contains polypropylene and EPDM rubber (%13) (ethylene propylene diene monomer). TPE2 contains polypropylene and styrene block copolymer (%30) (Termopol A.Ş.).

The prepared materials under laboratory conditions are given in Table 3.3 Titan dioxide (anastase) particles were used as reinforced material PP and PS. The average particle size of TiO_2 is 20 nm.

SEBS-g-MA (Kraton Inc.) was also added to the polypropylene with 5% and 15% ratios (wt). Its melt flow index is 20gr/10 min and density is 0,98 gr/cm^3.

3.1.2 Material Preparation

Compounding has taken place in the double screw extruder at our unit (Rondol, Micro Lab). Materials prepared are given in Table 3.3 respectively.

Table 3.3. Components and codes of the prepared materials

Material components	Coding	Rate (%.wt)
Polystyrene and SEBS-g-MA	PS/SEBS-g-MA/ 5	SEBS ratio 5%
	PS/SEBS-g-MA/ 15	SEBS ratio 15%
Polystyrene and TiO_2	PS/TiO_2	TiO_2 ratio 5%
Polypropylene and TiO_2	PP/TiO_2	TiO_2 ratio 5%

L/D ratio of extruder used being 20, mold exit temperature is 220 °C for PS and 180 °C for PP. Screw rotation speed, on the other hand, was taken as 180 rpm and 120 rpm respectively. Photograph of the extruder is given in Figure 3.1

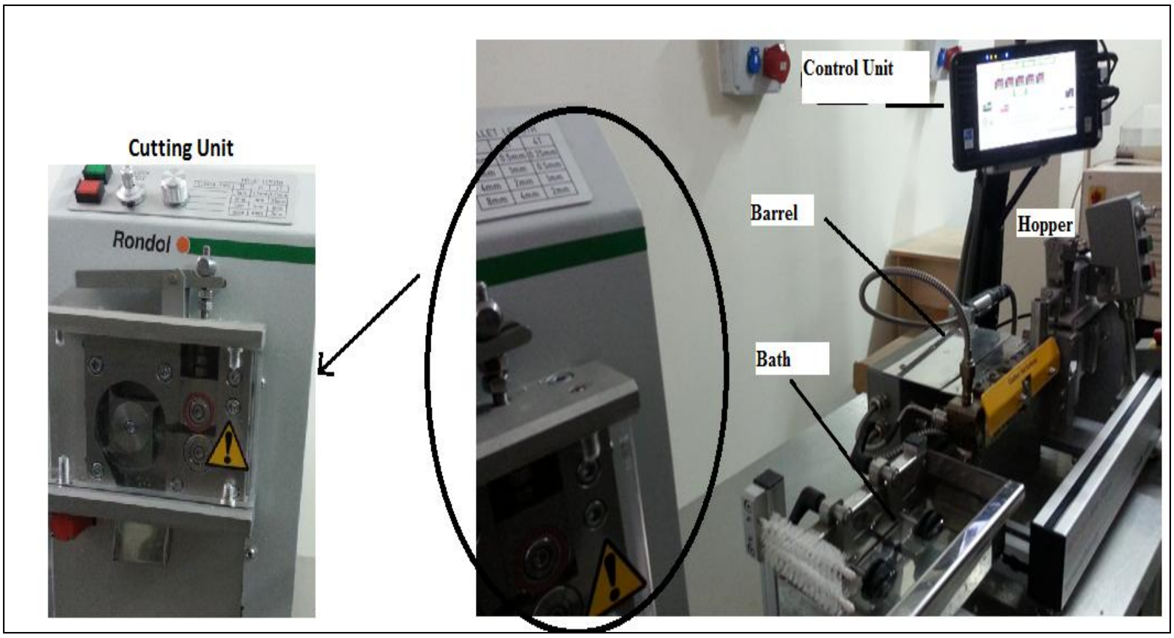


Figure 3.1 Photograph of double screw extruder

3.1.3 Characterization of Polymeric Materials

Differential scanning calorimetry (DSC) analysis and melt flow index (MFI) tests were held for the characterization of polymeric materials. Weight of samples used in DSC analysis is between 6.5-7.5 mg. Temperature interval used in analysis being 40-180 °C tests were held at a heating and cooling rate of 10°C/min.

MFI test was held on the Ceast 7021 device. Test conditions for PP and PS is 190°and 200°C -5 kg weight respectively according to ISO 1133-1991.

3.1.4 Forming of Polymer/Metal Sandwich by Plastic Injection Forming

As already known, the plastic injection method is one of the traditional manufacturing methods used in shaping plastics. It is a method carried out by way of injection of melted polymer into the mold and hardening in the mold (Figure 3.2). Plastic injection forming, PIF, on the other hand, is a manufacturing method in which metal plates and polymer are shaped in the same mold, simultaneously (Figure 3.3). In the experimental study, a 40-ton plastic injection machine (Yelkenciler, Turkey) was used. Photograph of the machine is given in Figure 3.2.

Figure 3.2 40-ton plastic injection machine employed in the experimental study

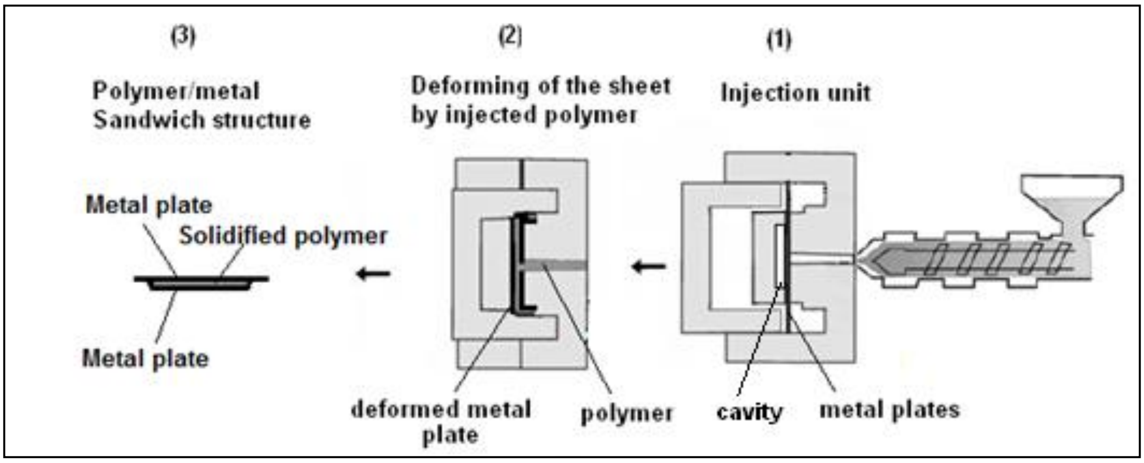
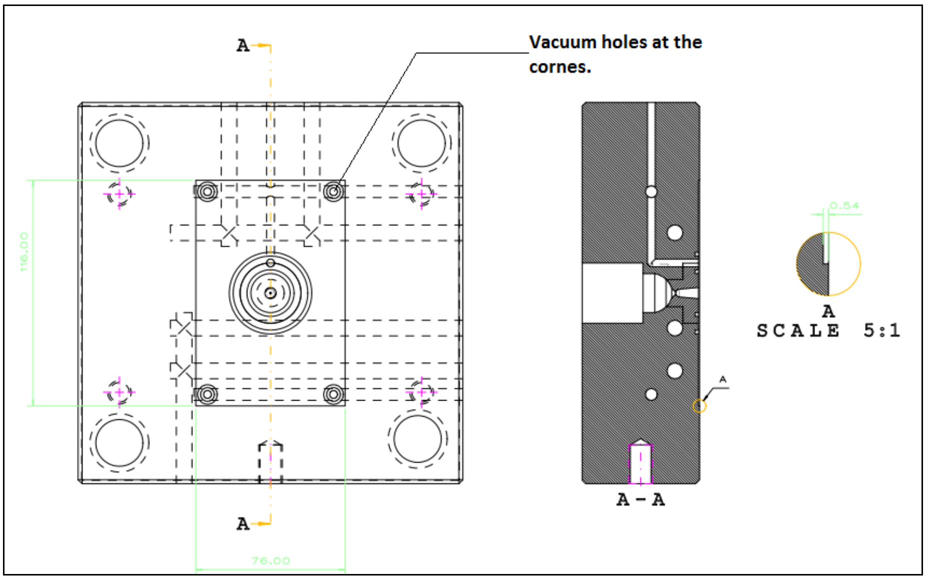


Figure 3.3. Steps of the plastic injection forming method (PIF)

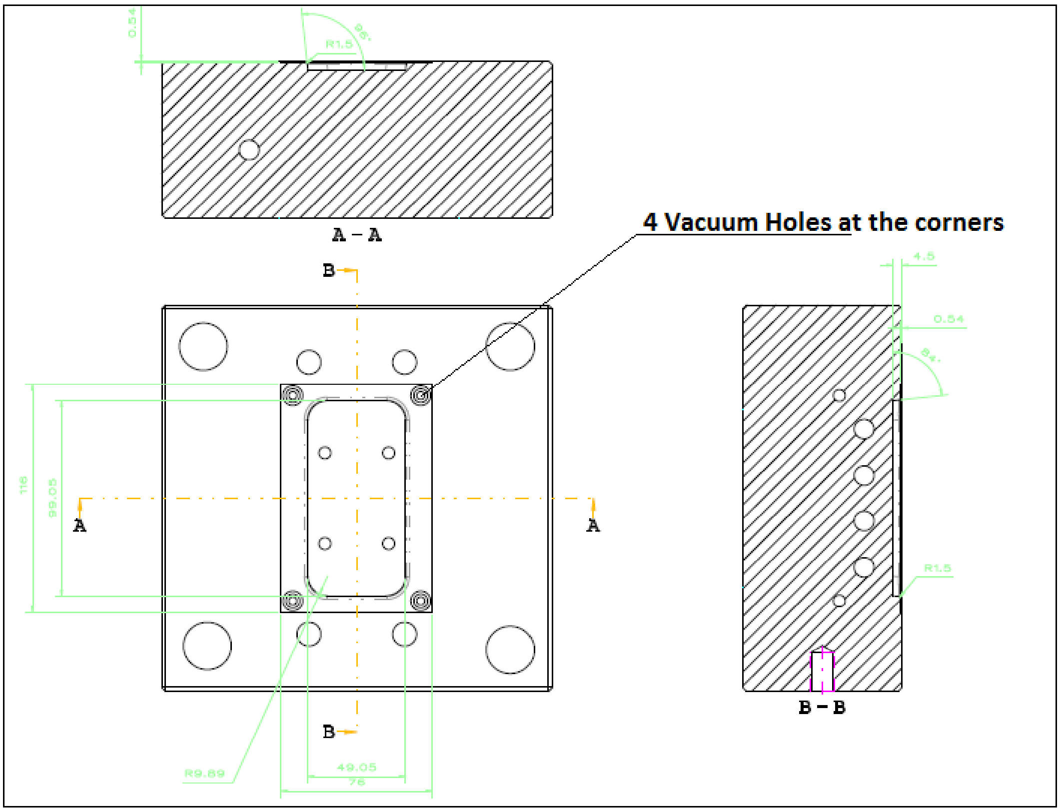
A rectangular cavity was designed in order to obtain bending specimens over macro composite sample (Figure3.5).



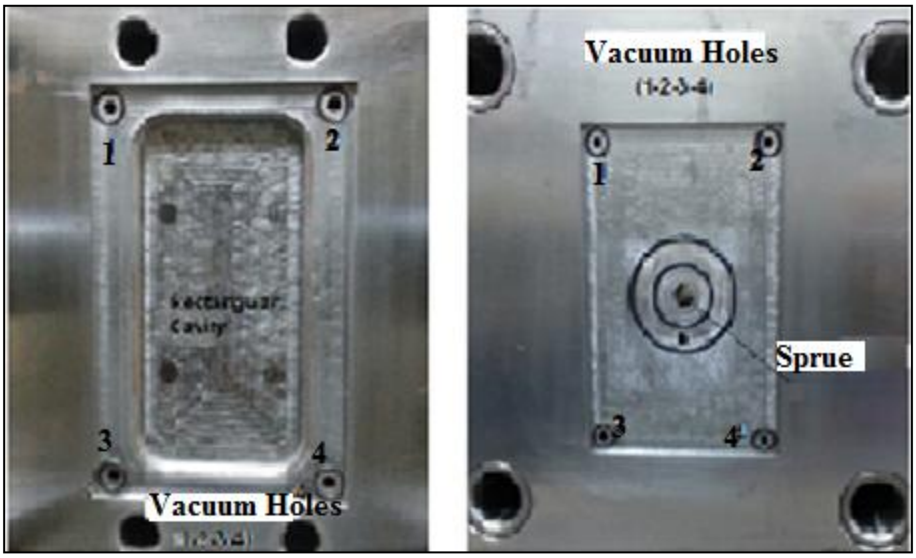
(a) Stationary mold half

(b) Figure3.4 Technical drawing and photograph of plastic injection mold for PIF

Figure 3.4 (Continued)



(c) Movable mold half



(c) Photograph of the mold

A depth was considered around the cavity according to the plate thickness. Therefore, the metal plate could be housed by this depth. Vacuum holes also were considered in order to keep the metal plates in position during injection cycle by the vacuum air .

Firstly, 0.5 mm-thick aluminum plates were placed into the mold and ideal injection conditions were tried to be set through the injection procedure. Experimental study was carried out especially on injection pressure and injection speed settings due to their effectiveness of metal forming [16] values influential in the shaping of the metal plate. Experiments were carried out with injection pressure between 30 to 60 bars and injection speed of 23 cm^3/s – 28 cm^3/s.

3.1.5 Surface Treatments Applied to Metal Plates

Two series of aluminum plates were provided, one of them is with hole, the other is without hole as given in Figure 3.6. Aluminum plate with a hole would be placed on the stationary mold half, while the plate without hole would be placed on the movable mold half, on injection machine. But prior injection molding, some treatments were applied onto the surfaces of the aluminum plates in order to achieve better adhesion between the polymer/metal surfaces. In this regard, mechanic cleaning was carried out for surface treatments. 3M's diapad (Handsanding Sponges-red series) abrasive sponges were used. The sponges are covered with aluminum oxide particles. With the sanding of metal surfaces with 3M diapad, both cleaning of the oxide layer on the surface and enhancement of the contact surface area polymer were provided.

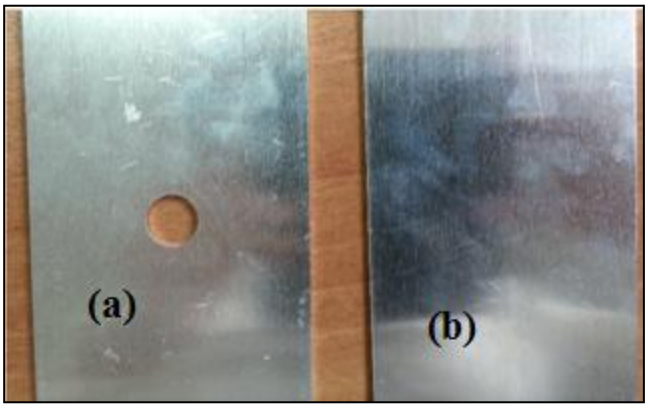


Figure 3.5 Aluminum plates for PIF process a) for stationary mold b) for moveable mold

Following the roughening procedure, plates were washed with alkaline soap, then washed with acetone and pure water respectively and finally dried.

A thin layer of primer (EMS 30-35 Metsan Inc.) was applied on the surfaces after the surfaces of the plates have been cleaned. Usually being elastomeric based, primers are different from acrylic- or epoxy-based adhesives. Adhesive properties of primers become evident with temperature and pressure. This is why it is very suitable for plastic injection procedure, in which both temperature and pressure are applied. EMS 30-35 consists of methylene chloride, synthetic elastomer and antioxidants.

3.1.6 Mechanical Tests

3-point bending test according to ASTM C393 was applied on Zwick 1455 Universal tensile test device. Test speed was taken as 5 mm/min. To obtain mechanical test samples, samples were cut under 3400 bars with the water jet method from the polymer/metal sandwich structured macro composites.

CHAPTER 4

FINDINGS AND DISCUSSIONS

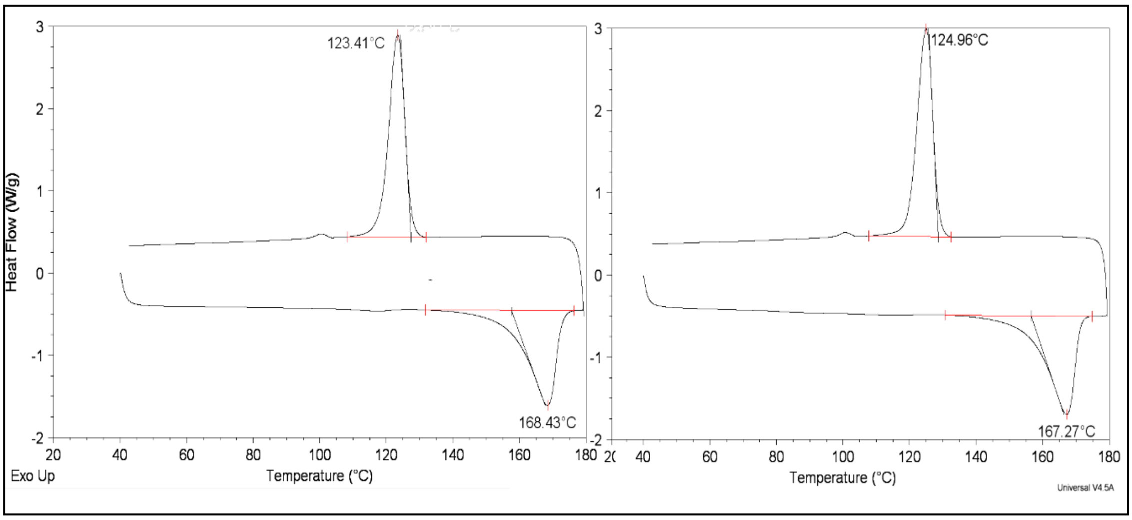
4.1.Material Characterization

Melt flow index results and thermal properties of the prepared materials were reported in Table 4.1 and Figure 4.1. MFI result of the PP/TiO_2 was 5.12 g/10 min while pure PP showed 6.2 g/10 min. It was clear that the presence of inorganic particles increased the viscosity. The MFI results were important for setting the injection parameters for PIF.

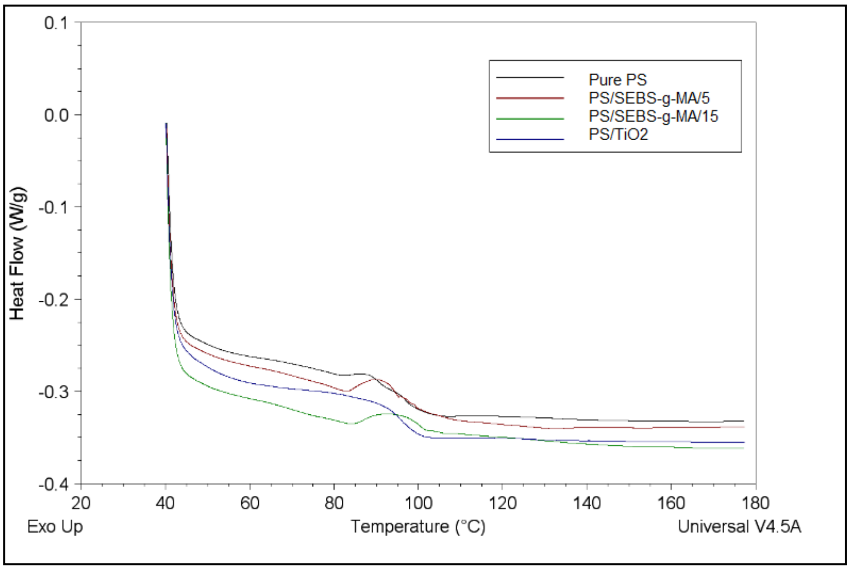
Table 4.1 Flow index values of materials prepared

Material	**Flow Index Value , MFI (g/10 min)**
PS	7.50
PS/SEBS-g-MA/ %5	7.15
PS/SEBS-g-MA/ %15	6.85
PS/TiO_2	6.50
PP	6.2
PP/TiO_2	5.12

The DSC results of the pure PP and titan dioxide added PP are given in Figure 4.1. Melt temperature and crystallization temperature of the titan dioxide added PP did not change apparently in accordance with pure PP. The little change in melt temperature showed that melt temperature or mold temperature on injection molding machine could be kept constant for PP and PP/TiO_2 but the decrease in MFI indicated that injection rate (cm^3/sec) should be increased as the material was changed from PP to PP/TiO_2. DSC results of PS based materials showed similar properties with the pure PS. Just the shifting of glass transition temperature was observed. All these results show that thermal properties of the prepared polymer materials did not show critical difference and they maintained their thermal stability.



a)DSC results of PP based materials



b)DSC results of PS based materials

Figure 4.1 DSC results of the prepared materials

4.2 Forming of Polymer/Metal Macro Composites Through Plastic Injection

Forming of polymer/metal sandwich-structured macro composites through plastic injection method was aimed at within the scope of this thesis. However, preliminary studies were carried out within the scope of the study to determine the forming limits of metal plates through injection pressure in a plastic injection mold. The aim here is to shape the metal plate without wrinkling or tearing while deforming it with injection pressure. Firstly, 0.5 mm-thick aluminum sheet was tested. During the forming of plates through the PIF method, injection pressure was taken into consideration first. This is because the basis of the PIF method resembles hydroform forming of the sheet metals. In hydroform shaping, metal sheet placed into the mold is formed by way of the pressured liquid applied. High-pressure liquid material with the pressure factor in PIF is the molten polymer.

Upper and lower limits of the injection pressure selected being between 30 bars and 60 bars while the plate 0.5 mm in thickness is being formed, photos of the changes in the plate after the forming procedures and of the polymeric material injected to each plate formed are given in Figure 4.2 Insufficient forming was observed when the pressure is 30 bars and flash formation due to exertion of excessive pressure was observed when the pressure is 60 bars. Moreover, when a 60-bar pressure was exerted, tearing was identified in the flange part of the plate being formed. The reason for such tearing is excessive pressure exertion as is seen when metals are formed in pressing machines or faulty mold design. No tearing occurred and ideal forming was achieved when the injection pressure was 50 bars. Thus, it was found out that there were no faults in mold design and that the appropriate injection condition had to be selected.

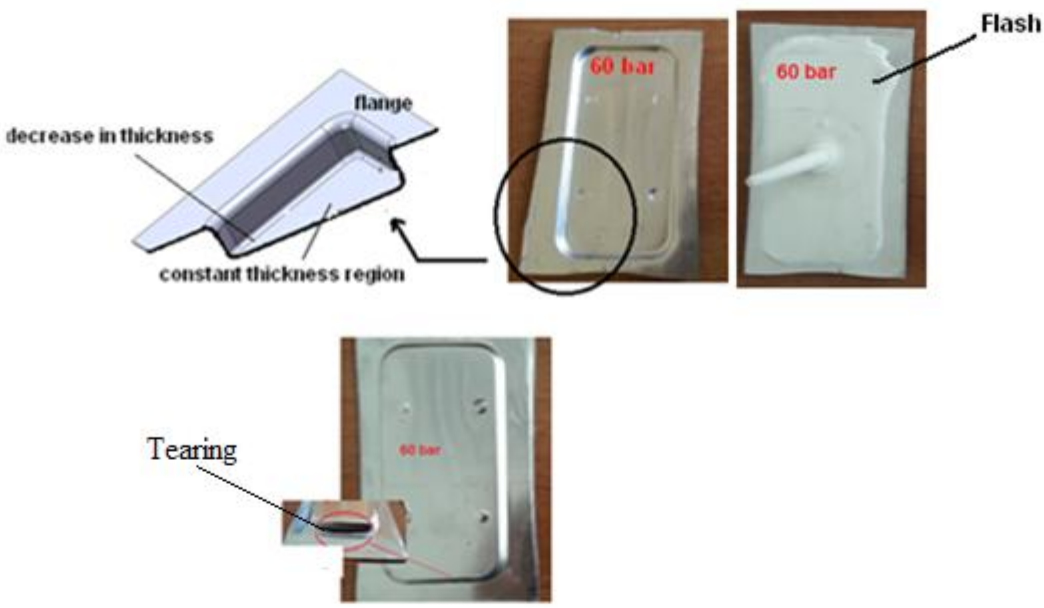


Figure 4.2 Forming limit of a 0.5 mm-thick plate through the PIF method under the influence of different injection pressures

Experimental tests were carried out on the injection rate under injection conditions other than the injection pressure, as well. Rate of injection (cm^3/s) is the material sent into the mold within the unit time. Such value must be increased as the material becomes viscous. This is because both higher injection pressure and a higher injection rate are required so that more viscous materials can fully fill in the mold. Within the scope of this Study, as the metal plate is formed with the material injected into the mold, it is important that a sufficient amount of the injected material is available. Regardless of the pressure, when the material is sent in an insufficient amount and the mold is not fully filled, the resulting metal plate is faulty because the plate cannot take the shape of the mold cavity entirely. As a result, the plate is shaped unsatisfactorily.

Injection rate was experimented between 20 (cm^3/s) and 28 (cm^3/s) were exerted as injection rate. An injection rate of 24(cm^3/s) was observed to insure ideal forming for pure PS within such value interval which is expected to differ depending on the material. Other injection conditions are constant, values are: mold temperature 40°C, melt temperature 220°C, holding pressure 35 bars, cooling time 10 seconds. When results obtained by researchers who carried out studies relating to the PIF process; Luccheta and Baesso [38] found melt temperature and clamp pressure effective. Yang and Parng [39] and Guscther and Altan[15] used the PIF method only for forming purposes, did not get any hybrid structures and they took the change in the thickness of the metal plate and mold cavity into consideration too. Likewise, when Tekkaya et al. [16] investigated the PIF method in terms of forming limit of metal, they considered injection pressure and injection rate to be efficient. As a result of the studies carried out within the scope of the thesis, injection pressure and injection rate were discovered to be efficient in the forming of the plate, when the specifications of current plastic injection machine and the mold designed were taken into consideration.

Plates 1.5 mm in thickness were also tested within the scope of the study. However, in order to be able to use the plates 1.5 mm in thickness in the PIF method, the channel on the mold into which the plate will be placed has to be deepened to fit 1.5 mm first. Therefore, within the aim of the study, polymer/metal sandwich samples were first obtained from the plate 0.5 mm in thickness. Later, after the mold was revised, a 1.5 mm-thick plate was used.

After the experimental conditions were set as given above, PIF process was applied according to the principle given in Section specified in 3.1.4. Photograph of the polymer/metal macro composite is given in Figure 4.3

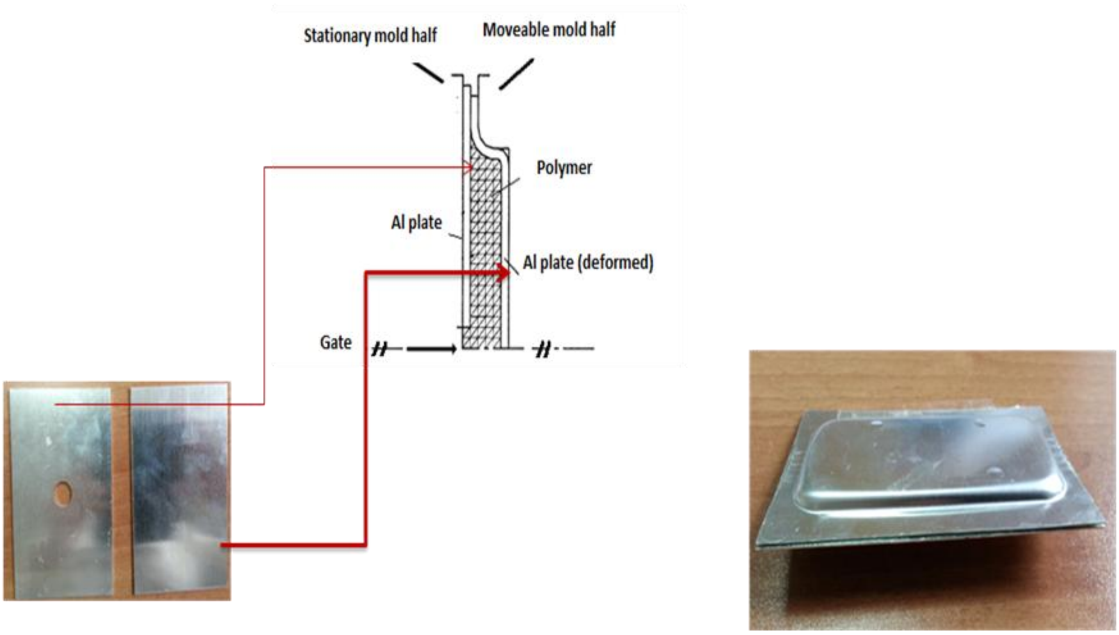


Figure 4.3 Polymer/metal macro composite by the PIF method

Plates, which were quite thin, lost their regularity during the drilling of a hole into their centers (8mm diameter) and a very slight concave occurred, which resulted in insufficient forming during PI process. Therefore, experimental studies continued with 1.5 mm-thick. Similar forming problems were not observed with the 1.5 mm thicken aluminum plate.

As flow index values of the materials decreased in conformance with the MFI values, injection rate increased. For example, injection rate for pure PS was increased to 24 cm^3/s, whereas it was increased to 27 cm^3/s for polystyrene containing 15% SEBS. Injection rate was assumed as 28 cm^3/s for polymeric materials containing titan dioxide particles. Injection pressure was held at 50 bars and other injection conditions were taken constant as set (mold temperature 40 °C, melt temperature 220 °C, ironing pressure 35 bar, cooling time 10 seconds.

4.3 Experimental and Numerical Evaluation of the Bending Test

In order to apply three-point bending test, samples were cut from the sandwich structure with water jet (Figure 4.4).

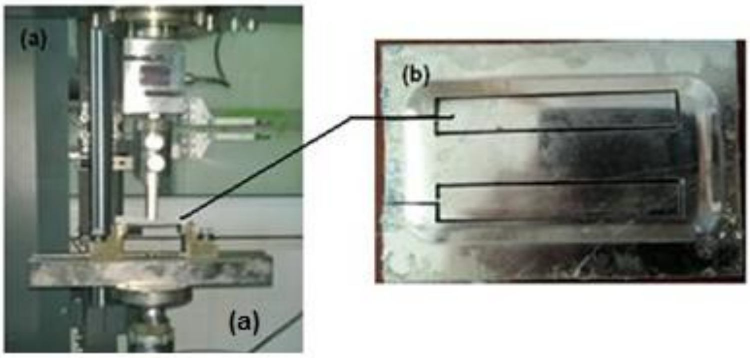


Figure 4.4 (a) Three point bending test (b) Samples obtained from the macro composite by a water jet

Only PS group materials were tested with 0.5 mm-thick plates as stated above. Bending results obtained with a plate thickness of 0.5 mm are given in Table 4.2. Results obtained with an aluminum plate that is 1.5 mm in thickness, on the other hand, being provided in Table 4.3, bending graphics are shown in Figure 4.6.

Table 4.2 Bending results for 0.5 mm-thick plates

No	Material	Max. Bending Strength, (MPa)	Deflection (mm)
1	PS	26.95	3.93
2	PS/SEBS-g-MA/ 5%	34.78	6.33
3	PS/SEBS-g-MA/ 15%	35.39	6.65

When bending test results of 0.5 mm and 1.5 mm thickness sandwich structures were compared, 0.5 mm macro composite had better bending strength but worse deflection values. This is because while the plastic injection mold was being revised for plate thickness, while the depth of the hole into was deepened, the mold cavity was kept constant. For this reason when the sheet material was getting thicker there was left smaller space for polymeric core material. As shown in Figure 4.5, samples with thicker cores displayed higher bending strength. (The mold could have been rendered deeper using machining but in case of emergence of a problem also in the present case, it is not possible to restore the mold. Due to the necessity of repetition of some tests, depth of the mold cavity was not changed. Such risk was not taken until the studies were over and studies went on with the present status of the mold. Recommendations and reasons for different thickness are provided in the conclusion part under the heading "Recommendations).

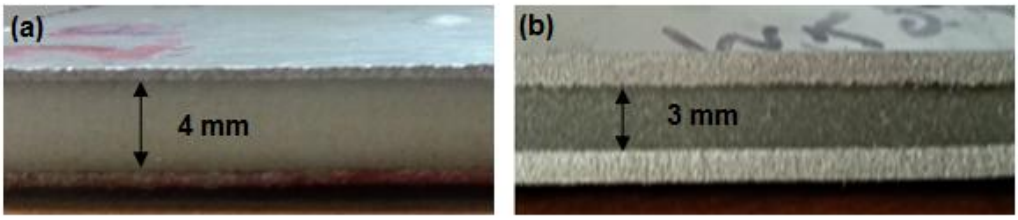


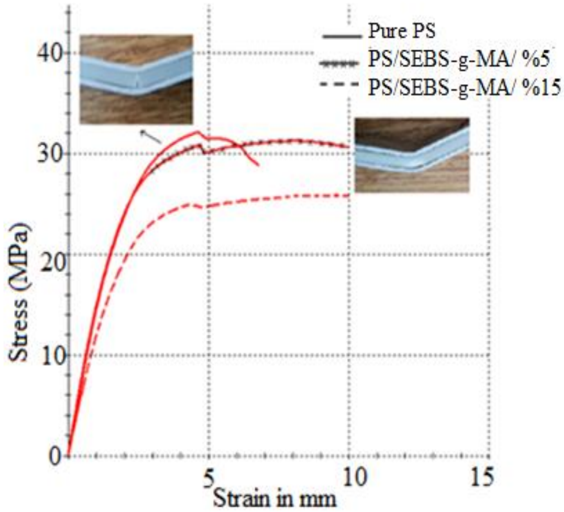
Figure 4.5 Sections of polymer/metal sandwich macro composites obtained by PIF method (a) 0.5 mm plate (b) 1.5 mm plate

As can be seen in the previous studies in the literature [40] the load was carried by the core section of the sandwich; therefore, results of bending strength were higher than compared with the same group of materials 1.5 mm in thickness (Tables 4.2 and 4.3, no 1-2-3).

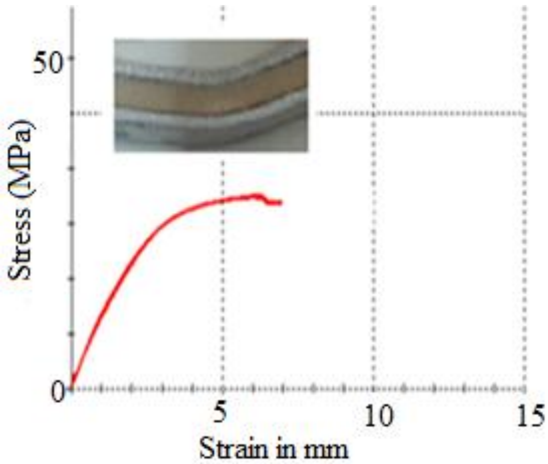
Table 4.3 Bending results of plates 1.5 mm in thickness

No	Material	Max. Bending Strength (MPa)	Deflection (mm)
1	PS	32,52	7,09
2	PS/SEBS-g-MA/ 5%	31,23	8,04
3	PS/SEBS-g-MA/ 15%	25,84	8,97
4	PS/TiO_2	30,90	6,67
5	PP	29,37	9,36
6	PP/TiO_2	28,7	8,29
7	PP/EPDM (TPE 1)	27,34	9,39
8	TPE (2)	24,62	9,96

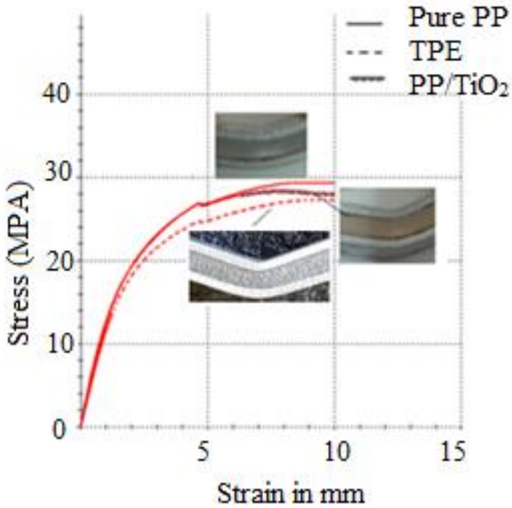
When the bending curves are investigated, linear area can be observed where tension and strain increase proportionally. However, after a certain point, linearity of this behavior breaks down. Although the proportion appears to change at different points for each curve, all graphics increase proportionally until the 25-30 MPa value, permanent deflection starts in sandwich samples after this value.



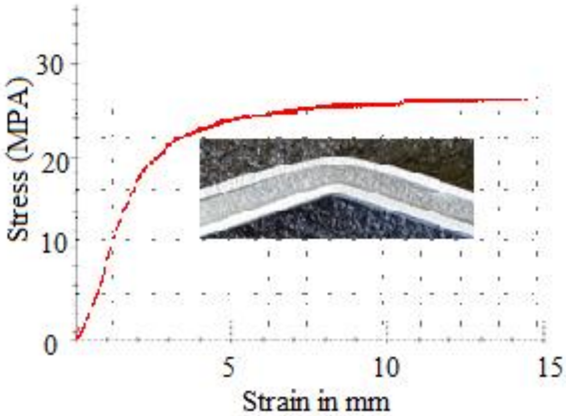
(a) PS based without TiO_2



(b)PS/TiO_2



(c) PP-based materials



(d) TPE 2 (PP/SBS)

Figure 4.6 Bending results of polymer/metal macro composites

After setting up the conditions for plastic injection forming process with 1.5 mm thicken sheets, three different polymeric cores were experienced as virgin polystyrene, SEBS-g-MA added polystyrene about 5% (wt) and 15% (wt), respectively. The injection pressure was kept constant but the injection rate was increased according to the injected polymers due to the higher viscosity of SEBS. After obtaining polymer/metal hybrid structures with different polymeric components, 3-point bending test was applied to the specimens that were cut in a sandwich structure with two metal skins and one polymeric core. The results of the bending test are given in Figure 4.6 as stress-displacement graphs. According to the graphs in Figure 4.6, in the first stage of the bending test, load increases proportionally with deflection, which is in the elastic region. For virgin PS material and PS/SEBS-g-MA/%5, until about 31 to 32 MPa of stress value, linear elastic behavior is observed. For PS/SEBS-g-MA/%15, although the limit of strain for elastic behavior is the same as the others, approximately 4.5 mm, the stress value is lower for this core. The failure appearance of the skin layers is observed at approximately 25 MPa. This is due to the presence of SEBS-g-MA in higher amount, which reduced the elastic modulus and the strength of the core region against the load. For all three components, after the first appearance of the failure in skin, load suddenly decreases. Especially, virgin PS could not carry the load anymore, and a crack occurred in the core section of the structure as given in Figure 4.6. On the other hand, the elongation of the other structures is more due to the elastomeric nature of the SEBS-g-MA. No crack occurrence was observed in the presence of SEBS-g-MA but lower bending load was seen.

Furthermore, when the adhesion layers were investigated by means of the images taken by stereo optical microscope (Soif XLB 45-B3) as given in Figure 4.7, it has been seen that PP/TiO_2 had difficulties in full contact with the metal surface. Circles given in Figure 4.7 identify the regional gaps between metal surface and polymer.

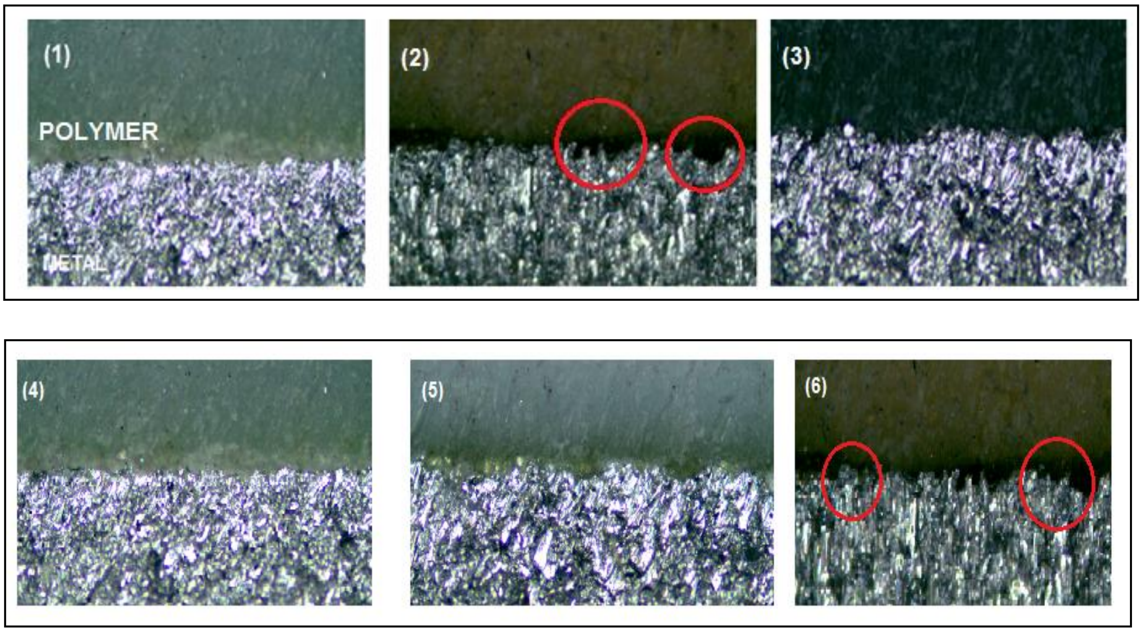


Figure 4.7 Images of adhesion zones of polymer and metal layers (X 45) – (1) pure PP, (2)PP/TiO_2 (3)TPE (4) pure PS (5) PS/SEBS-g-MA/15 (6) PS/TiO_2

When PS- and PP-based samples are compared in general, polystyrene showed a brittle character in material tests as it is harder than polypropylene. TPE materials, on the other hand, gave higher deflection in lower tension values due the presence (EPDM, SBS) within their structures.

Discussing the results in terms of success of the study, polymer/metal shaped sandwich structures were manufactured in a single step using the plastic injection method. When bending tests are taken into consideration, bending strength was observed to be 26.39 MPa when test was applied to the polystyrene sheet sample. On the other hand bending strength of the sandwich structure with polystyrene core which is material number 1 given in Table 4.3 is 32.52 MPa. It is observed that bending strength has increased significantly when the samples got thicker.

When results obtained are required to be compared to previous studies in the literature, no composite structures with the same structure and manufactured with the same method were encountered. Different materials have been used in sandwich structures in which layer by layer adhesion method. Some of the researches [41] polystyrene and PVC foam was applying for core material and fiber mat was used in the surfaces. The method is the technique of adhesing layer by layer. Macro composites geometries are in the form of classic cover glass. Bending strength obtained is between 20-30 MPa. Herranen et al. [42] used PVC and HDPE materials and mat layers in their studies and the bending strength they obtained was between 13-19 MPa. Layer by layer adhesion method was employed. A sandwich structure overlapping with the materials used in the study was not encountered.

If numerical evaluation is taken into account, the panel rigidity of the polymer/metal structures was calculated to see the effect of the polymeric core and the thicknesses of the specimens. Deflection values were obtained experimentally, and then the following equations were applied. First, core shear stress (τ) was determined by Eq.(1), given below:

$$\tau = \frac{P}{(d+c)^b} \qquad (1)$$

Where P is the load, d is the sandwich thickness, c is the core thickness, and b is the sandwich width. Face sheet stress (σ) is calculated by the Eq.(2) where t is the face sheet thickness and L is the span length. The schematic picture for dimensions is given in Figure 7. In the PIF process, the thicknesses of the face sheets (upper and downward) could not be equal to each other after processing because one side of the metal sheet was formed during the injection of the polymer material. Therefore, the thickness of the deformed sheet became approximately 0.1 to 0.2 mm smaller after deforming.

$$\sigma = \frac{PL}{2t(d+c)^b} \tag{2}$$

The bending panel stiffness (D) is obtained by the formula given by Eq.(3) , where E is the modulus of the face sheet.

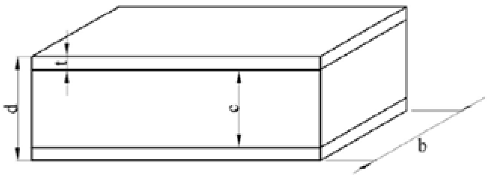


Figure 4.8 Dimensions of sandwich specimen

$$D = \frac{E(d^3-c^3)b}{12} \tag{3}$$

Eq. (4) is used for calculating the deflection of the sandwich specimen,

$$\Delta = \frac{PL^3}{48D} + \frac{PL}{4U} \tag{4}$$

Where Δ is the total beam midspan deflection. In this equation, U is the panel bending rigidity, and it is determined by Eq.(5) where G is the core shear modulus.

$$U = \frac{G(d+c)^2 b}{4c} \tag{5}$$

The panel rigidity of the polymer/metal structures calculated by Eq. 5 was reported in Table 4.4. and 4.5. The panel rigidity decreased as the elastomer content increased but there was not an apparent trend according to the core material, which was probably due to uncontrollable factors such as the effect of the water jet cutting of the bending specimens or the effect of adhesion between the core and skins.

Table 4.4 Deflection results of the polymer/metal hybrid structures

Cores of the hybrids	Maximum Force (N)	Deflection at maximum force (mm)	Panel rigidity (Nmm^2)
PS	2560	7.09	5.90
PS/SEBS-g-MA/%5	2371	8.04	4.74
PS/SEBS-g-MA/%15	2090	8.97	3.69

Table 4.5 Panel rigidity for polymer/metal hybrid structures with different thicknesses of Al sheet

Polymer/metal hybrid structures	Maximum Force (N)	Deflection at maximum force (mm)	Panel rigidity (Nmm^2)
PS with 1.5 mm Al sheet	2560	7.09	5.90
PS with 0.5 mm Al sheet	1320	3.93	7.85

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Plastic injection method, one of the traditional methods employed in plastic manufacturing is used for generating polymer/metal sandwich structured macro composites with a different design and application; Polymer Injection Forming. This method is capable of manufacturing complex geometries and products can be used to wider fields such as automotive, white goods or aircraft industries. Results obtained have been articled:

-Metal plates were shaped through the plastic injection forming method. Aluminum plates took the shape of the injection mold cavity with the pressure exerted by the molten polymer. At this stage, injection pressure and injection speed were the most influential parameters on forming. Such parameters as holding pressure, cooling time and mold temperature were observed that they were not to primarily effective on the forming of the metal plate. 50 bar of injection pressure gave defectless parts. 24 cm^3/s of injection rate was selected for pure PS and PP but with the increment of viscosity of the molten material, injection rate was increased to 28 cm^3/s.

- Polymer/metal sandwich-structured macro composites were obtained after determining proper injection conditions. Plates 0.5 mm and 1.5 mm in thickness were used. As a result of bending tests, the macro composites with a thin plate revealed a higher bending strength and lower deflection as they have a thicker core compared to sandwich structures with a 1.5 mm-thick plate. This is because the actual load in the sandwich structure is generated by the polymer-based core. And deflection of the composite was thicker. On the other hand, when the same injection mold was used and the plate thickness was increased, thickness of the polymeric core in the sandwich structure decreased due to the decrease in the volume between the plates formed. As a recommendation for future studies, different cavities with different depths and geometries can be experienced.

-When the results of bending strength were investigated according to the change in the core polymer, higher deflection values were obtained with lower bending strength values within the elastomeric-based materials presence such as SEBS-g-MA, EPDM and SBS. For example, whereas maximum bending strength and deflection values of a sandwich structure derived with 1.5 mm-thick plates with a pure PS core were 32.52 MPa and 7.09 mm respectively. PS/SEBS-g-MA/15 gave 25.84 MPa and 8.04 mm of bending strength and deflection, respectively while 24.62 MPa of bending strength and deflection value of 9.96 mm was observed for the commercial TPE containing SBS. When the core part of sandwich structures contains TiO_2 particles, a higher bending strength was obtained compared to core structures containing elastomer. This is because increasing rigidity in the polymer material due to the presence of titan dioxide.

-It can be claimed that plastic injection forming a prosperous and flexible method for manufacturing polymer/metal hybrid structures in one-step manufacturing. Also, wide variety in selection of polymeric materials and skin surfaces increase the attractiveness of the process.

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PUBLISHMENTS

Conference Papers

1. M.E.Altan ve B.Yavuz (2015)"Polimer/Metal Hibrid Yapıların Plastik Enjeksiyon Yöntemi İle Şekillendirilmesi" 1. Ulusal Plastik Teknolojileri Sempozyumu.
2. M.E.Altan ve B.Yavuz (2014)"A Novel Method for Manufacturing Polymer/Metal Hybrid Structures A Novel Method for Manufacturing Polymer/Metal Hybrid Structures