Tomas Bata University in Zlín
Faculty of Technology

Doctoral Thesis Summary

Zlepšení mechanických vlastností vícesložkových vstřikovaných výrobků

Improving the mechanical performance of multicomponent injection moulded products

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Author:	Ashish Matta, M.Sc., Ph.D.
Study Programme:	Chemistry and Materials Technology
Study Course:	Technology of Macromolecular Compounds
Supervisor:	Prof. Ing. Tomáš Sedláček, Ph.D.
Reviewers:	Prof. Ing. Pavol Alexy, Ph.D.
	Prof. Mgr. Aleš Mráček, Ph.D.

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Abstract

The application of multicomponent injection moulded products is increasing due to emerging manufacturing trends like light weight, improved performance, cost efficiency, etc which creates the requirement for combining different materials. The performance of a product is achieved by combining the properties of different materials. However, joining is the major challenge in making multi-material structuring workable. Joining could be challenging because of the different properties of the two materials. Therefore, it is crucial to understand the various connecting techniques that are available for multi-material, metal-to-metal, polymer-to-polymer, and metal-to-polymer hybrid systems.

Research studies with polymer-to-polymer, and metal-to-polymer hybrid systems were primarily studied in presented doctoral thesis. Namely, three different polymeric material combination with their respective inserts were chosen, Polyketone-aluminium, Poly(phenylene)-aluminium and Elium-polybutylene terephthalate.

Polyketone studies analysed the possibility of joining Polyketone (PK) and aluminium insert into one structure by the means of injection insert moulding. This study investigated the relationship between joining strengths and moulding conditions, with a particular emphasis on holding pressure, injection speed, and mould temperature. Furthermore, joining strength results were assessed with each distinct moulding condition to determine how it affected the joining strength.

Poly(phenylene) studies investigated the influences of various surface treatments on the adhesion between glass-reinforced poly(phenylene) sulphide (PPS) and aluminium alloy during the injection over-moulding process. Adhesion strength was evaluated via the shear test.

Elium insert moulding studied the detailed procedure of using injection moulding to join two different materials to produce goods with improved utility properties. The polybutylene terephthalate (PBT) homopolymer of 20 % glass fibre reinforced is moulded onto the modified Resin Transfer Moulding samples of the Elium® composite sample by employing the injection moulding technique and using Elium® composite as an insert. Influence of various surface treatments was investigated, and the moulded samples were examined for mechanical characteristics such as tensile shear strength test to analyse the adhesion.

In summary, all of these studies explore the possibility of joining two dissimilar materials by inspecting the optimum moulding parameters and definite surface treatments and their association with attained bond shear strength.

Abstrakt

Použití vícesložkových vstřikovaných výrobků se zvyšuje díky nastupujícím výrobním trendům, jako je nízká hmotnost, zlepšený výkon, nákladová efektivita atd., což vytváří požadavek na kombinování různých materiálů. Výkonu produktu je dosaženo kombinací vlastností různých materiálů. Spojení je však hlavní výzvou při zprovoznění strukturování více materiálů. Spojování může být náročné kvůli odlišným vlastnostem těchto dvou materiálů. Proto je zásadní porozumět různým spojovacím technikám, které jsou k dispozici pro hybridní systémy multi-materiál, kov-kov, polymer-polymer a kov-polymer.

V této disertační práci uvádíme především výzkumné studie s hybridními systémy polymer-polymer a kov-polymer. K tomu byly vybrány tři různé kombinace polymerních materiálů s jejich příslušnými vložkami, Polyketon-hliník, Poly(fenylen)-hliník a Elium-polybutylentereftalát.

Polyketonové studie analyzovaly možnost spojení polyketonu (PK) a hliníkové vložky do jedné struktury pomocí vstřikovacího lisování. Tato studie zkoumala vztah mezi pevností spoje a podmínkami formování, se zvláštním důrazem na přídržný tlak, rychlost vstřikování a teplotu formy. Dále byly posouzeny výsledky pevnosti spoje pro každou jednotlivou podmínku lisování, aby se určilo, jak ovlivnila pevnost spoje.

Poly(fenylen) studie zkoumaly vlivy různých povrchových úprav na adhezi mezi sklem vyztuženým poly(fenylen)sulfidem (PPS) a hliníkovou slitinou během procesu vstřikování.

Vložkové lití Elium studovalo podrobný postup využití vstřikování ke spojení dvou různých materiálů za účelem výroby zboží se zlepšenými užitnými vlastnostmi. Homopolymer polybutylentereftalátu (PBT) z 20 % vyztužený skleněnými vlákny je nalisován na modifikované vzorky Resin Transfer Molding vzorku Elium® kompozitu použitím techniky vstřikování a použitím Elium® kompozitu jako vložky. Byl zkoumán vliv různých povrchových úprav a formované vzorky byly zkoumány na mechanické vlastnosti, jako je zkouška pevnosti ve smyku v tahu pro analýzu adheze.

V souhrnu všechny tyto studie zkoumají možnost spojení dvou odlišných materiálů kontrolou optimálních parametrů lisování a určitých povrchových úprav a jejich spojení s dosaženou pevností vazby ve smyku.

1. STATE OF THE ART

1.1 Injection Moulding Technology

Injection moulding is widely employed in today’s world as it is an extensively utilized production method. This technique involves the introduction of molten polymer resin and additives into a cooled mould through means of air or water. Once the resin has solidified, the resulting part is removed from the mould. Injection moulding provides an immense range of possibilities for its products, ranging from contact lenses to vehicle bumpers. It enables the creation of highly intricate shapes in a single operation, requiring minimal time. A design's part count can be decreased since complex parts can be produced via injection moulding. However, the main research focus is on the complexities of injection moulding for creating multicomponent products.

Reducing the weight of a car or an aircraft's components is one of the most direct methods for enhancing their performance. The utilization of lightweight materials in aerospace components enables improved range and speed, while simultaneously reducing operational expenses. Hence, this results in an overall improvement in the performance of the aircraft. It is for this reason that the production of multi-component injection moulding products has gained significant importance as it is a perfect match for the design requirements of various industries such as automotive, industrial equipment, and aerospace [1].

The joining of two dissimilar materials poses a significant challenge due to the fluctuating bond strength exhibited by different material combinations. The difficulty in joining two distinct materials stems from either their distinct chemical compositions or the substantial disparities in their physical properties [2]. An injection moulding machine as seen in can be modified to suit specific requirements. Despite the emergence of electric machines and the anticipated future significance of the latter in the market is higher, currently in-line screw machines that are propelled by hydraulics continue to be the most prevalent. A conventional injection moulding machine consists of three primary constituents: the clamping unit, the plasticizing unit, and the driving unit. The clamping unit is responsible for securing the injection mould, possessing the capability to clamp, open, and close the mould. The vital components include the tie bars, the opening, closing, and clamping mechanism, as well as the fixed and moving plates.

Prior to being injected into the mould, the plastic is melted within the injection unit or plasticizing unit. Both the plasticizing unit and the clamping unit are propelled by the drive unit. The maximum clamp force produced by an injection moulding machine is frequently employed to classify these machines.

1.1.1 Advanced Injection Moulding Technologies

Injection moulding is a popular manufacturing method for mass-producing items. Several innovative technologies have been developed over time to improve injection moulding efficiency, precision, and capabilities. Listed below are some advanced injection moulding technologies:

1. In-mould labelling
2. Gas assisted injection moulding
3. Thin wall injection moulding
4. Micro injection moulding
5. Multicomponent injection moulding

Multicomponent injection moulding

It is a process in which two or more different materials are injected into a mould to produce a single integrated part with multiple components. The components are typically injected sequentially or simultaneously, and they bond together during the moulding process. This process allows for the integration of different materials or colours within the same product.

While manufacturing products using injection moulding, there are various methods to choose from these advanced injection moulding technologies. The most used method is a joining of the components via multicomponent injection moulding technology. And therefore, its eminent to recognise joining technology and the different processes which employs for creating multicomponent injection moulding products.

1.2 Multicomponent Injection Moulding

It is a process in which two or more different materials are injected into a mould to produce a single integrated part with multiple components. The components are typically injected sequentially or simultaneously, and they bond together during the moulding process.

One of the main challenges for multicomponent injection moulding is to improve the joining mechanism. Joining technology has been acknowledged as a pivotal facilitative technology for innovative and environmentally friendly production within the vast array of manufacturing technologies. It is generally unfeasible to manufacture a product without the act of connecting due to the necessity of meeting functional specifications and technological limitations. In order to enhance the efficiency of the manufacturing process and ensure product functionality, it is customary to assemble products utilizing various components [3]. Therefore, understanding joining technologies is a crucial issue in manufacturing, and novel improved methodologies are constantly being researched and developed to find better solutions.

The process of joining can be complicated, nevertheless there are many methods, materials of choice, and helpful techniques. Messler [4] defines joining to be: "The process used to bring separate parts of components together to produce a unified whole assembly or structural entity". Campbell [5] considers joining as: "a large number of processes used to assemble individual parts into a larger, more complex component or assembly". This provides us with enough general understanding of the process and it most common uses.

The process of making multicomponent products can be complicated and include a variety of methods, materials, and techniques. Therefore, the various joining technologies can be divided broadly into the following 3 categories (Figure 1.1Figure 1.1). This bonding or joining process can be created in a different way as the result of any one or a combination of the following:

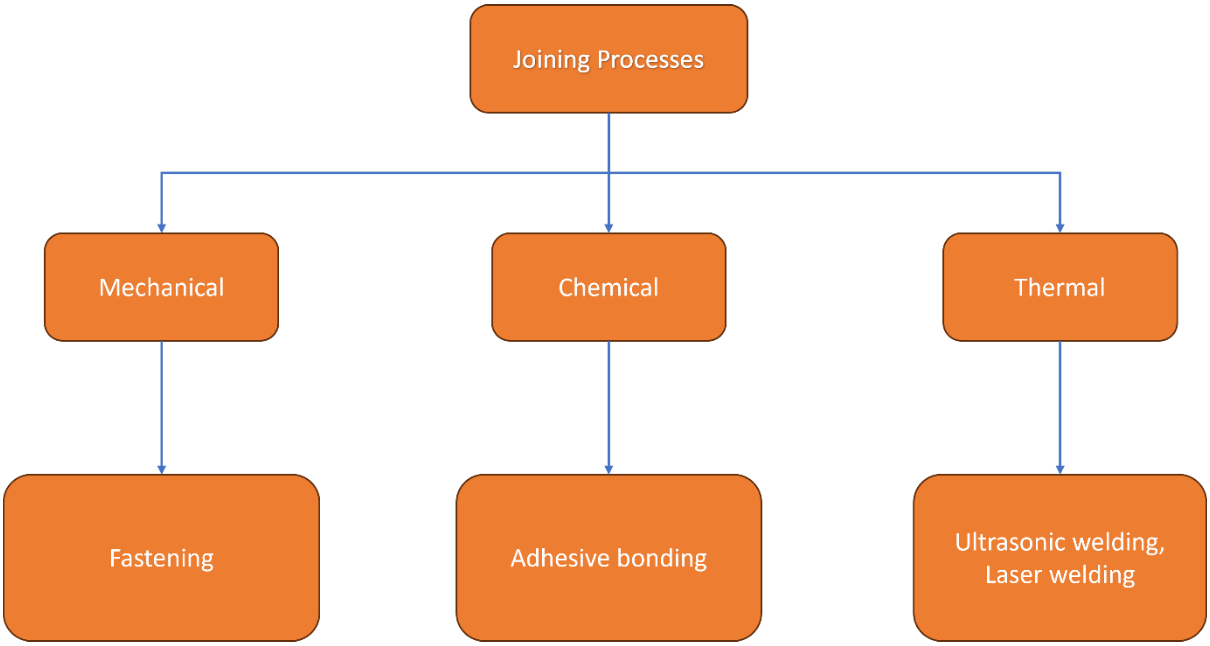


Figure 1.1: Joining process.

I. Mechanical – mechanical joining involves connecting materials without altering their chemical or physical properties significantly. It relies on physical forces to hold the materials together. Some common mechanical joining methods include fastening etc.

Fastening – it involves using fasteners such as screws, bolts, nuts, rivets or nails to join components together.

II. Chemical – chemical joining involves using chemical reactions to create bonds between materials. These bonds can be permanent or temporary, depending on the application. Some common chemical joining methods include adhesive bonding, welding etc.

Adhesive bonding – it involves using adhesives to join materials together. Adhesives are applied between the surfaces to be joined and it works by creating a chemical bond between the two surfaces.

III. Thermal – thermal joining involves using heat to join materials together. Unlike welding, which melts the base materials, thermal joining methods rely on heating the materials to a temperature where they become soft, allowing them to be joined together. Some common thermal joining methods include ultrasonic welding, laser welding etc.

Ultrasonic welding - it involves using high frequency ultrasonic vibrations to join two pieces of material together.

Laser welding - it utilizes a highly focused laser beam to join metals or thermoplastics together.

Multi-component moulding - the Figure 1.2 illustrates how we might divide the various multi-component moulding techniques into two categories. The first category includes the most prevalent processes, which create products with distinct interfaces. This comprises, insert moulding and over moulding. There is uncertainty in the interface between the two materials in the second group [6].

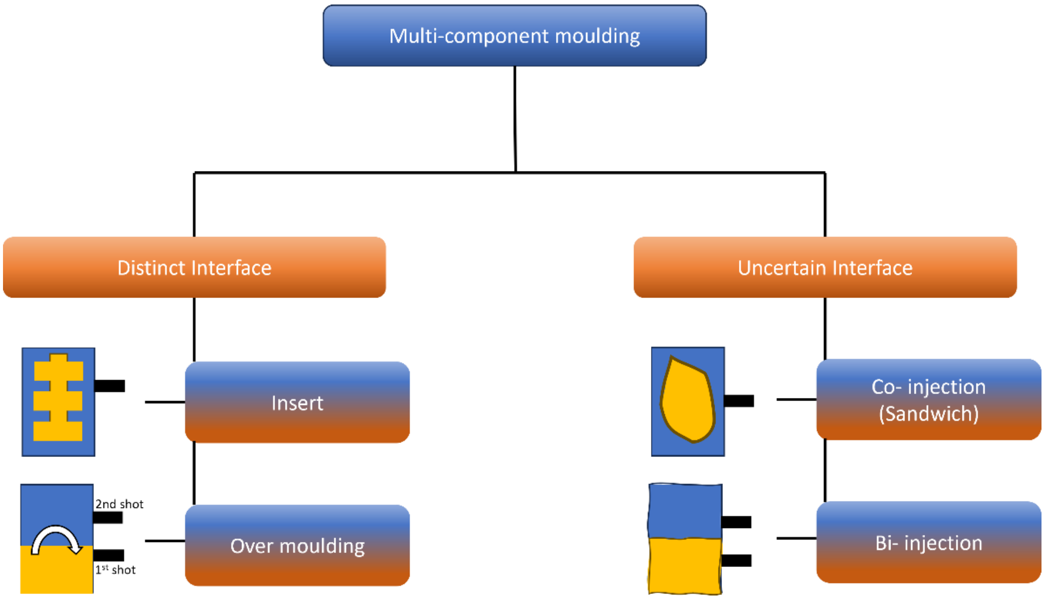


Figure 1.2: Multi-component moulding process.

Insert moulding – it is a process where a preformed component (usually metal or another plastic) is placed into the mould before the injection moulding process begins. The molten plastic is then injected around the insert, creating a single, integrated product.

Over moulding – it is process where the first material (usually a rigid plastic) is injected into the mould to form the base or substrate. Then, a second material (often a softer or elastomeric material) is injected over the first material to create the final product. It is commonly used for adding features such as soft grips, colour variations, or additional functional element to a product.

Co-injection moulding – this method involves injecting two different materials simultaneously or in a sequential manner. The materials are typically injected through separate nozzles or injection units into the same mould cavity. The primary purpose of co-injection moulding is to create a part with a skin and a core of different materials. It is commonly used in applications where a combination of properties from different materials is desired such as soft- touch grip or rigid plastic handle.

Bi-injection moulding – it is a subset of co-injection moulding and typically refers to a specific process where two different materials are injected into the mould to create a layered structure within the same shot. The two materials are injected through the same mould but different barrels or sources within the injection moulding machine.

1.2.1 Process variables of the Multicomponent Injection moulding

Each process variable can be categorised into one of the four main types such as temperature, speed, pressure, time. The relationship between the variables is interdependent, as each variable cannot be taken separately. These variables can be generally categorized into:

a) Temperature

Temperature related process variables include melt temperature, mould temperature.

Melt temperature is the temperature of the molten polymer inside the cylinder assembly. It is a critical parameter in the over-moulding process as it determines the temperature at which the polymer material is melted before injection into the mould. Regulating the melt temperature is essential for attaining appropriate material flow, preventing issues such as melt degradation or insufficient filling of the mould cavities. An excessively high melt temperature can result in thermal degradation and impact the material properties, while a temperature that is too low can lead to inadequate flow and incomplete mould filling. Optimizing the melt temperature ensures that the material maintains its structural integrity and achieves even distribution within the mould.

The *mould temperature* is the surface temperature of the mould. The mould temperature plays a crucial role in determining the cooling rate and the final properties of the over-moulded part. It influences the solidification process of the polymer within the mould cavity. Higher mould temperatures typically result in slower solidification, allowing for improved flow and reduced internal stresses. Conversely, lower mould temperatures promote faster solidification, affecting the surface finish of the part and reducing the likelihood of warping. Proper control of mould temperature is vital for achieving the desired balance between material flow, part quality, and cycle time in the over-moulding process. The mould temperature, injection speed, holding pressure, back pressure is one of our important parameters which will be optimized for the direction of our research work such as Metal - Polymer, Polymer – Polymer multicomponent insert moulding.

b) Speed

Speed related process variables include injection speed, screw rotational speed, screw recovery speed.

The *Injection speed* is the linear speed used to fill the mould with molten material according to the suit the characteristic of the product we need. The rate at which the molten material flows into the mould is dependent upon there being sufficient injection pressure available to maintain a consistent selected filling velocity. Inconsistency of the mould filling speed prevails if inadequate injection pressure is selected.

The *screw rotational speed* is necessary to plasticize the material as a result of rotating the screw to maintain stable flow. The faster it is rotated the higher the temperature. It is important to ensure that the correct speed is being used otherwise process instability will occur.

Another factor is the *screw recovery speed* is controlled by rotating the screw at a predetermined back pressure after plasticization.

c) Pressure

Pressure related process variables include injection pressure, holding pressure, hydraulic back pressure.

Injection pressure is an important parameter so as to maintain a consistent mould filling velocity. It is the force applied to propel the molten material into the mould cavity during the injection phase. This parameter significantly affects the flow characteristics of the material, the filling of the part, and the overall quality of the over-moulded component. Complex moulds or parts with intricate geometries often require higher injection pressures to ensure proper filling and replication of mould details. However, excessive pressure can lead to mould damage or the formation of excess material. Striking the right balance with injection pressure is crucial for achieving optimal part quality while avoiding potential drawbacks associated with excessive force during the injection stage.

The *holding pressure* is the pressure applied to the material after it has been injected into the mould cavity. It is critical for compensating for shrinkage as the material cools and solidifies. Adequate holding pressure ensures that the material completely fills the mould space, minimizing any voids or sink marks. Insufficient holing pressure may result in incomplete mould filling or the formation of defects. Optimizing holding pressure contributes to the dimensional accuracy, structural integrity, and surface finish of the part, ultimately influencing the overall quality of the over-moulded product.

Hydraulic back pressure When the screw is rotated, heat-softened (plasticized) material is pushed forward through the back flow valve assembly to the front of the screw. The pressure generated within, and by the molten material, forces the screw (and back flow valve assembly) to move backwards, thus refilling the vacated volume with molten material. Hydraulic back pressure has an influential effect on the melt temperature and homogeneity. The value selected corresponds to the type of material being processed, the shot capacity of the barrel being utilized, the plasticizing capability of the screw, the rotational speed of the screw, and the quality standards of the components to be moulded. The hydraulic back pressure is set either manually or electronically and the selected value should be maintained within some tolerances as the melt homogeneity is significantly influenced by the amount of back pressure selected and its consistency.

d) Time

Time related process variables include injection time, holding pressure time, cooling time.

The period from when the screw commences its forward movement to the point where the holding pressure is applied is called the *injection time*. Appropriate injection time ensures the mould is filled adequately before the material solidifies. Adjusting injection time can help prevent short shots or overpacking issues.

The *holding pressure time* is the time when the screw is held almost stationary in its most forward position so as to apply the necessary holding pressure to the molten material in order to pack the material into the mould cavities during the early stages of material solidification. The period of time used for the holding pressure to be applied should correspond with the time the gate takes to freeze off or, for the gate to sufficiently solidify.

Holding time is crucial for preventing premature ejection of the part, ensuring that it retains its shape and integrity. Insufficient holding time may lead to part distortion or warping, while excessive holding time can unnecessarily extend cycle times.

Cooling time is necessary for the molten plastic material to cool to a temperature which will enable the mouldings to be ejected from the mould without distortion. This time is dependent upon many factors, for example, the general shape of the component, the wall thickness of the component, and the type of material being processed. This time period is always the longest portion of the moulding cycle. During the cooling sufficient time is needed to retract the screw (sometimes called screw recovery, or dosing time) so as to refill the barrel with material. Longer cooling time can enhance part quality but may extend the overall cycle time [7].

All these process variables can influence the quality, consistency, and efficiency of injection moulding product. Therefore, optimization and adjustments should be made while considering the specific requirements of the part being produced.

Namely, mould temperature, injection speed, holding pressure, back pressure are our important parameters which will be optimized for the direction of our research work such as Metal - Polymer, Polymer – Polymer bi-components by utilizing multicomponent insert moulding.

2. FOCUSED RESEARCH AREAS

Bi-component structures are widely used in many industries, namely the automotive and transportation industries. Such components consist of often metal elements or polymer elements, known as inserts, which occupy a certain position in the component and are injection-moulded with a polymer melt. Most of the component's volume is occupied by a polymer [8]. Such hybrid components provide many advantages over standard parts, such as weight savings compared to purely metal parts, and superior mechanical properties compared to purely polymer parts. They can also outperform mechanically accomplished hybrid components, which must withstand inherent stress concentration from the holes for screws and rivets, as well as those aided by adhesives, which require additional curing time and/or specific curing conditions.

Recently, various approaches have been reported to solve the problem of achieving a reliable metal–polymer adhesive joint. Kajihara et al. applied abrasive jet blasting of the insert made of the aluminium alloy A5052 to obtain the most suitable surface microstructure. Glass beads and aluminium particles were used as abrasive materials. The highest shear strength was demonstrated by the samples with inserts blasted with aluminium particles [9]. Bonpain and Stommel investigated the effect of surface roughness on the shear strength of polymer (PA 66 + 30 GF) and aluminium (EN AW 3103) joints [10]. The samples were prepared in a shape used in the standard tests to assess the tensile strength of metals and polymers. It was demonstrated that if the surface roughness (Ra) was less than 10 microns, the adhesive failure of the sample occurred with no visible polymer residues on the aluminium surface. In contrast, when the Ra was higher than 10 microns, the cohesive failure was observed, i.e., the metal insert carried polymer residues. Gebhardt and Flesicher investigated the influence of an insert's surface treatment on the tensile and flexural strength of the resulting component [11]. They applied two types of coating and five types of mechanical treatment, namely phosphate coating, cataphoretic painting, grit blasting, laser structuring, electro erosion, thermal arc spraying, and laser micro pins. The samples with a cataphoretically painted surface had a higher loadbearing capacity of the joint compared to the phosphate-coated surface and approximately the same loadbearing capacity as the samples treated with laser structuring. The highest loadbearing capacity was measured for samples with laser micro pins. Another way to modify the surface of the insert is sandblasting with corundum or silicon. Li, Gong et al. studied the effect of surface roughness, obtained by sandblasting, on surface wetting characteristics by examining contact angles [12]. They experimentally demonstrated that the wetting angle decreases as a result of decreased surface roughness, leading to better copying of the surface texture by the melt and, thus, to increased strength of the formed metal–polymer joint.

The above-mentioned observations suggest that surface treatment of metallic inserts can significantly increase the loadbearing capacity of an adhesive joint; however, there is still a need for a rapid and straightforward method for surface modification/texturing that would not require prohibitively expensive tools and processes. The combination of mechanical and chemical approaches could be a pivotal step in achieving such a goal. As can be observed, these studies are really product specific. To obtain a range of different combinations of surface treatments on the substrates in injection moulding, and thus more breadth of data, the current study will compare adhesion strength of different surface roughness's achieved by combination of various surface treatments on metal inserts and polymer inserts.

2.1 Metal-polymer insert moulding

Automobile production has historically seen fierce competition between metals and plastics. The polymer metal hybrid (PMH) technologies, in contrast to each other, combine the two types of materials into a single part or subassembly [13]. There are scenarios when a single material class cannot adequately address the ever-growing issues facing engineering solutions. Multiple distinct material class can be used by combining various material classes to create so-called hybrids. These hybrid constructions are becoming more and more prominent, largely because due to their lightweight, cost-neutral design, which is frequently combined with stronger mechanical part-qualities [14]. Engineering interactions between metallic materials like steel or aluminium and thermoplastics produce favourable outcomes. Low density polymers allow for a substantial amount of design flexibility, especially when used in injection moulding, which makes it simple to functionalize the high strength and stiffness of metals. The degree of weight reduction that is feasible when considering the future of plastic-metal hybrids will increase the use of lightweight metals like titanium, magnesium wrought alloys, or aluminium [9]

In order to provide a solution tailored to each individual customer, the fundamental concept of PMH technologies (Figure 2.1) has been to integrate the structural and non-structural requirements of multiple elements into a single, fully optimized sub-assembly (by implementing the systems approach) [8]. Due to their high elastic modulus, tensile strength, strong fatigue resistance, high dimensional stability, low coefficient of thermal expansion, and low abrasion, carbon fibre reinforced polymer (CFRP) is widely utilized for structural applications [15]y research investigations [16, 17] demonstrate that the use of carbon fibre greatly enhances structural strengthening. Glass fibre is preferred by the engineering sector because it is less expensive than carbon fibre and because glass fibre reinforced polymers (GFRP) have high specific resistance and low heat conductivity. GFRP can be employed for structural reinforcement despite having fewer desired characteristics than CFRP due to economic considerations [18]. Connecting two materials that have varying mechanical and thermal properties is complicated. The combination of ketone, aryl ether, and aromatic groups in the aromatic Polyketone (PK) category of semi-crystalline engineering thermoplastics results in superb high-temperature characteristics and excellent thermal stability [19]. They also provide good resistance to the effects of the environment, high temperatures, built-in flame retardancy, superior friction and wear resistance, and impact resistance. Certainly, aromatic polyketones are among the world's best-performing materials. Due to its numerous uses in the chemical industry (compressor plates, valve seats, pump impellers, thrust washers, bearing cages), aerospace (aircraft fairings, radomes, fuel valves, ducting), and electrical (wire coating, semiconductor wafer carriers), Polyetheretherketone (PEEK) is the most commonly used member of aromatic polyketones.

Moreover, there is a broad range of metal-polymer combinations for creating polymer- metal hybrids. However, glass fibre reinforced PK was considered as a polymer material for preparing first bicomponent for this study as it is less expensive than PEEK, PAEK and could be an alternate for them in certain applications. Also, the combination of PK and aluminium is very promising, as PK offers good mechanical performance and aluminium has high strength to weight ratio [20]. Hence, this hybrid can offer a combination of lightweight, strength and corrosion resistance and tailored thermal and electrical properties. This can be advantageous in industries like aerospace and automotive, where weight reduction is critical for improving fuel efficiency and performance. Also, the surface structure of metals is known to have a substantial impact on metal–polymer bonding strength in general [21, 22]. The bonding strength can be improved by changing the surface roughness or modifying the surface chemistry via preparations of the surfaces of metal parts, such as abrasion, etching, and plasma treatment [23–25]. To improve the bonding of hybrid joints, laser structuring is used as an alternative to the mechanical blasting process when joining metal with plastics. In these cases, a pulsed laser is focused on a single spot on the material surface, resulting in extremely high local intensities [9,11]. Although sandblasting is often used because it is economical and enables creation of a wide range of unique surface topographies and roughness levels. Since different surface treatments can influence the bonding strength so only sandblasting was chosen as a pretreatment technique on aluminium inserts as the first bicomponent combination of this study was focused on optimizing the injection moulding processing parameters.

Furthermore, there is a broad range of metal–plastic combinations and various possibilities for surface treatments; hence the second study was focused on evaluating the influence of different surface treatments on aluminium inserts over-moulded with polyphenylene sulphide (PPS). Different combination of selected chemical and physical treatments were done on aluminium inserts, to evaluate the bonding strength achieved during injection over-moulding with glass-fibre-reinforced PPS. All the plastic/metal combination requires specific conditions to reach optimum mechanical performance. Various studies have investigated the joining of polymer–metal bi-components with polymers such as polyether-ether-ketone (PEEK), polypropylene, and thermoplastic polyurethane [24, 27–29]. The main reason for adopting PPS was that there has been very little research on combining PPS with aluminium, and thus there is little information available on combining PPS and aluminium [22]. A glass-reinforced polymer is preferred to increase toughness and strength [30]. PPS is very similar to PEEK but has a lower operating temperature. It is also less expensive; therefore, it could replace PEEK in applications where flexibility is not a key consideration.

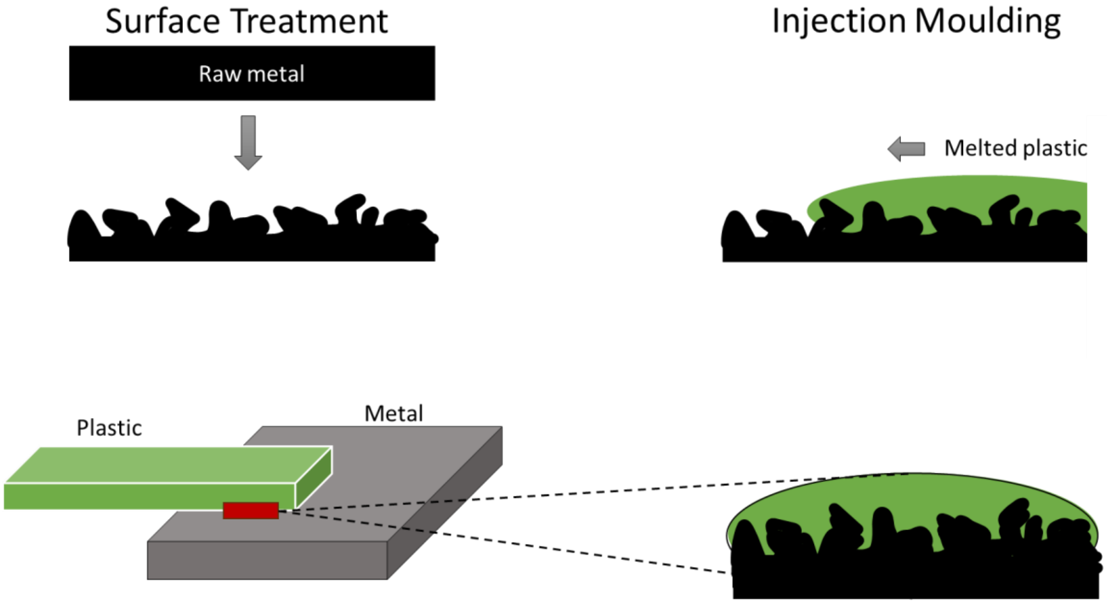


Figure 2.1: Process overview of the PMH technology.

2.2 Polymer-polymer insert moulding

This study investigates the detailed procedure of using injection moulding to join two different polymer materials to produce goods with improved utility properties. By combining the advantages of two different technologies, the two-component process gives a special benefit and produces composite items with excellent mechanical characteristics. In the automobile sector, composite materials are well-established for usage in lightweight applications. This often requires a combination of polymers with entirely different properties that are often considered incompatible. A distinctive polymer -polymer combination of polymers that has been investigated and some polymer-polymer insert moulding research are listed below in Table 2.1.

Table 2.1: Summary of the studies on multi-material injection moulding techniques.

Polymer matrix	Insert material	Improvement	Result
PC	ABS	Polymer-polymer adhesion and bond strength	An increase in polymer-polymer bond strength by high mold and thermal annealing [31].
PC	PS		No change in bond strength by addition of glass fiber[31].
PEEK	PEI		An increase in polymer–polymer bond strength by thermal annealing[31].
EOC and ethylene-butene copolymer (EBC)	PP	Interfacial strength	Accomplishment of adhesion bonding with PP inserts by controlling interface temperature [32].

In applications where thermal resistance and mechanical strength are critical, thermosets with better-known structural composites are preferred. In comparison to TPs, they have no melting behaviour, better thermal resistance, fewer fluctuations in modulus or strength with rising temperature, and improved creep qualities. Incorporating assembly and linking features into designs, on the other hand, has proven difficult [33]. Welding alternatives are limited, especially for technical fabric composites, and complex geometries bring about challenges.

Adhesive bonding, mechanical fastening, hybrid joints (combining adhesive and mechanical bonding), and co-curing two composite parts simultaneously with or without adhesive are common methods for attaching TP composite. Each approach has limitations, including as labour effort, cycle time, and eventually expense. Because cycle time in thermoset processing was historically prohibitively long for automotive applications, recent improvements in fast-cure thermoset processes have made their composites more practical.

Polybutylene terephthalate (PBT) materials reinforced with glass fibres are a type of thermoplastic composites that combine the benefits of glass fibre reinforcing and PBT polymer. It has better heat resistance, dimensional stability, and mechanical strength when coupled with glass fibres. This composite material gains increased stiffness and structural integrity by adding 20 % glass fibres to the PBT matrix. As a result, it is far less likely to distort during the moulding process. This combination retains the favourable qualities of PBT, such as high electrical insulation and chemical resistance, in addition to its reduced warpage properties. Fundamentally, the 20 % glass-reinforced PBT blend provides an ideal balance between strength and dimensional stability, which makes it a flexible option suitable for many different uses in engineering.

Elium® specimens prepared by RTM technology was insert moulded with PBT to create the bi-component samples. The main reason for choosing Elium® and PBT is because there is a limited information about joining of these two prospective materials which could bring novelty and offer potential options- to bi-component components and products exploited in automobile and aircraft industries. Various surface treatments like plasma, sandblasting, solvent induced chemical modification were applied to gain a better understanding of how the selected surface treatment procedure mainly via changing of mechanical interlocking mechanism affect the mechanical characteristics of the finished bi-component components.

The thermoplastic resin, Elium® (30 %) composite in this study is reinforced with glass fibres (70 %) using the resin transfer moulding (RTM) process. This gives the composite a good strength, while an increase in the fibre volume fraction directly raises the materials' stiffness and ultimate tensile strength. The polybutylene terephthalate (PBT) homopolymer of 20 % glass fibre reinforced is moulded onto the modified RTM samples of the Elium® composite sample by employing the injection moulding technique and using Elium® composite as an insert. Influence of various surface treatments was investigated, and the moulded samples were examined for mechanical characteristics such as tensile shear strength test to analyse the adhesion.

3. AIM OF THE THESIS

This work aims on the development of state-of-art knowledge covering problems of 2k and multicomponent injection moulding techniques. To make these bi-component structures by 2k injection moulding, either a metal-polymer or polymer-polymer material combinations are utilized. Such components are manufactured by using one of the multicomponent injection moulding techniques, namely insert moulding. These structures often consist of metal element or polymer element, known as inserts, which occupy a certain position in the component and are injection-moulded with a polymer melt. To make these components, the most common challenges are optimizing the moulding process condition and material compatibility at the interface of the joining of the two dissimilar materials. These are the key factors which can impact the mechanical performance of these structures. So, the goal of this study is to optimize the moulding conditions and finding the different material combinations with the suitable surface treatments on the inserts to improve the appropriate mechanical performance of the prepared biocomponents.

This goal can be achieved by stepwise accomplishment of the following:

- Preparation of the substrates or inserts for injection moulding with the related surface pre-treatment techniques (metal or plastic) with different combinations.

- Suitable surface pre-treatment of the inserts (metal or plastic) with different combinations.

- Surface morphology analysis, material characterization and further optimization of these different treatments.

- Optimization of process parameters and insert over moulding of these inserts with defined polymeric material.

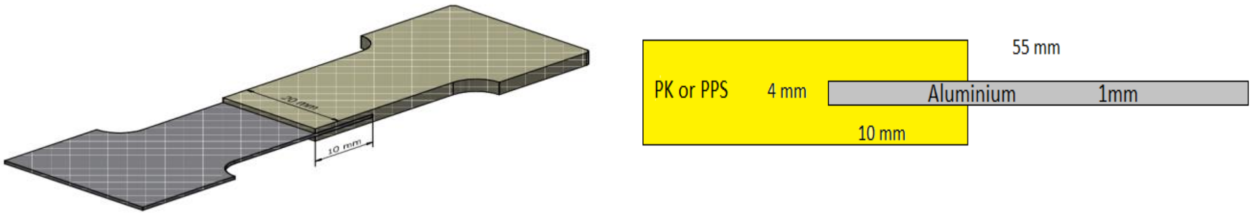
- Evaluation of mechanical strength of the prepared plastic/plastic or plastic/metal bicomponent.

4. EXPERIMENTAL PART

The research work in this thesis has preparations of three bi-components, namely two polymer/metal combinations a polymer/polymer combination and the materials, processes for preparation and characterisation techniques are discussed

4.1 Processes for testing samples preparation

Three different bicomponent testing samples were prepared with two metal/polymer and a polymer/polymer combination. Namely, PK-Al, PPS-Al (Figure 4.1) and Elium-PBT.



a) **b)**

Figure 4.1: PK-Al or PPS-Al shear test specimen (a) CAD model (b) side-view sketch.

4.1.1 *Preparation of substrates for polymer-metal insert moulding*

For *PK-Al*, the Al insert surface was treated with sandblasting. Prior to insert moulding, the bonding parts of Al inserts were cleaned with acetone.

a) Sandblasting

An SBC420 instrument was used to perform a comprehensive abrasion treatment on the substratum. Grain sizes ranging from 100 to 500 µm and slag (with the composition of 30% SiO_2, 40% AlO_3, and 30% CaO) were utilized as an abrasive material. The procedure was carried out for 50 seconds at a straight angle to the substrate surface, at a pressure of roughly 190 kPa, and at a distance of 8–10 cm from the nozzle.

For *PPS-Al*, five distinct suitable surface treatments were applied to the bonding parts of Al inserts (peripheral parts with dimensions of 10 mm × 20 mm). Firstly, the Al inserts were cleaned with acetone. This cleaning procedure was intended as a reference for the following comparison and is presented as the “untreated” specimen in the text below. The different surface treatments were undertaken to better understand the effect of the different surface treatments on the mechanical properties of the final testing specimens.

These treatments are referred to as “chemical 1”, “chemical 2”, “atmospheric plasma”, “sandblasting”, and “sandblasting and plasma (S+P) combination”. The details of the surface treatments are provided below:

b) Chemical treatment

Chemical 1: Bonding parts of Al inserts were dipped into etching solution (27.5 mL of H_2SO_4 (96%) + 7.5 mg of $Na_2Cr_2O_7$ + 65 mL H_2O). The solution was heated to 65 °C for 1–15 min before dipping the inserts. Subsequently, the treated inserts were rinsed with distilled water and dried at the same temperature for 10 min in an oven.

Chemical 2: Bonding parts of Al inserts were treated in the same way as with chemical 1, but NaCl was used instead of $Na_2Cr_2O_7$.

c) Plasma treatment

For surface modification of the Al inserts, a Plasma Beam Standard/PC was used at ambient temperature and atmospheric pressure. This is a device for cleaning and activating surfaces that has two nozzles with a maximum surface distance of 12 mm [15]. Completely clean and oxide-free surfaces can be obtained, as they are chemically struck by oxygen or air.

The surface energy was measured with contact angles at different distances and different times. The distance (8 mm) and time (20 s) were optimized to obtain the maximum effect from the plasma beam. The distance of 8 mm between the nozzle and the surface of the treated inserts was fixed. The gas used for the plasma treatment was introduced to the Al inserts. The discharge gas (compressed air) was generated using a frequency of 20 kHz and plasma power of 300 W AC, the gas flow rate was 11.2 L/min, and the cooling gas was maintained at 23.7 L/min. Unleaded air was used as a cooling gas.

d) Sandblasting

The same equipment mentioned previously was used for these studies as well. However, there were changes in the parameters and the size of abrasive material. 120 µm grain size and the slag (with the same composition SiO_2 30%, Al_2O_3 40%, CaO 30%) was used. The process was performed at a pressure of about 110 kPa and a distance of 8–10 cm from the nozzle for 50 s, at a right angle to the substrate surface [35].

e) S+P combination

Sandblasting was undertaken in the same way as described above; this was followed by plasma treatment. Inserts were cleaned with acetone after sandblasting and dried before plasma treatment.

4.1.2 Preparation of substrates for polymer-polymer insert moulding

To prepare *Elium-PBT,* first Elium® sheets were prepared using optimized laboratory resin transfer moulding process. It is a composite manufacturing technology generally used to produce high-quality, complex-shaped parts made of fabrics reinforced polymer matrices. The efficiency of the resin transfer moulding process lies in its ability to produce intricate and high strength composite components with excellent surface finish, making it a preferred choice for various industries. In this specific instance, the process involved using a thermoplastic acrylic resin Elium® as the matrix and possess 3 layered nonwoven fibreglass textiles as the reinforcement with a density of 6.81 g/m². The two-piece aluminium mould, having dimensions of 270 x 160 x 1 mm, was employed for shaping of the final composite semi products. The resin transfer moulding process comprises several key steps, each of which contributes to the overall success of the manufacturing process.

The first step in the RTM process consisted of the mould preparation precisely designed to ensure accurate reproduction of the part geometry. The two-piece aluminium mould was carefully assembled to create a cavity that matches the desired dimensions of the final product to achieve the intended specifications of the specimens used for subsequent injection moulding process. Next, the fiberglass fabrics was fixed within the mould for integration with the thermoplastic acrylic resin. Unlike some composite manufacturing processes, moisture removal from the reinforcement material was deemed unnecessary in this case, therefore, the material was not subjected to a vacuum process for moisture elimination, streamlining the overall manufacturing process. Finally, dispensing of the reinforcing materials in the mould was carried out using a single-component pressure vessel. The pressure vessel ensured controlled and uniform dispensing of the resin, facilitating the impregnation of the glass fibres, and enhancing the overall quality of the final composite part.

Once the mould was filled the curing phase began. The applied curing conditions, mould temperature of 80 °C and curing time of 6 minutes, were defined based on preliminary optimizing experiments. During this curing period, the thermoplastic acrylic resin underwent a chemical reaction, transforming from a liquid to a solid state. This phase was critical for achieving the desired mechanical properties and structural integrity of the final composite part. After the curing process was complete, the two-piece aluminium mould was opened, revealing the newly formed composite component. Samples from prepared composite sheets were cut out using laser system. The laser cutting system uses non-contact approach for cutting the material and a laser beam is used to cut out the precise shape from the sheets [36]. Elium Insert samples with the dimensions of 55 x 20 x 1 mm were cut out with a controlled laser cutting speed of 900 mm/min^{-1}. For *Elium-PBT*, bonding area of Elium® inserts (peripheral parts with the dimension of 10 x 20 mm) were cured with selected suitable surface treatments before the over-moulding to increase the mechanical performance of the adhesion with the over-moulded material. Three distinct surface treatments were applied to the inserts. Firstly, the Elium® inserts were cleaned with isopropyl alcohol to remove any contaminants or impurities from the surface. The different surface treatments were done to better understand the effect of the surface treatment process on the mechanical properties of final testing specimens. These treatments are referred to as – solvent-induced swelling, atmospheric plasma jetting, and sandblast roughing. The details of surface treatments are defined below:

a) Solvent Induced Treatment

Bonding parts of Elium® inserts were dipped into toluene as an etching solution for 25 minutes. Subsequently, the treated inserts were rinsed with distilled water and dried at room temperature for 10 minutes During the 25-minute immersion period, the toluene penetrates the surface of the Elium® composite, causing controlled swelling. This swelling can lead to an increase in the thickness of the material. The solvent interacts with the polymer matrix, promoting molecular expansion and altering the structure of the surface. To assess the effectiveness of the solvent-induced swelling, the thickness of the composites is measured both before and after the process. The measurements reveal an increase in thickness between 0.11mm and 0.125 mm, indicates the extent of swelling and modification achieved through the solvent treatment.

b) Plasma treatment

The same equipment mentioned previously was used for these studies as well with the same parameters. The Elium® composite surface was exposed to the plasma jet for periods of 5, 10, 15 & 30 seconds.

c) Sandblasting

The same equipment mentioned previously was used for these studies as well to perform a comprehensive abrasion treatment on the Elium® substrate. For this studies, two different grain sizes of abrasive materials were utilized. Grain size of 120 µm and another ranging from 400 to 500 µm and slag (with the same composition of 30 % SiO_2, 40 % AlO_3, and 30 % CaO) were applied. The process was performed at a pressure of about 0,2 MPa keeping substrate-nozzle distance between 8-10 cm at a perpendicular direction to the substrate surface for 30-40 sec. The goal was to achieve variation in surface roughening, modifying mechanical interlocking and adhesion.

4.1.3 Preparation of bi-component specimens

For preparing all the three bi-components, PK-Al, PPS–Al and Elium®-PBT, A Mitsubishi180 MEtIII (Yokohama, Japan) electric moulding machine with a 46 mm diameter screw was used with different process parameters discussed below in detail.

To inject the polymer in order to create the *PK-Al* bi-component specimen (Figure 4.1), the injection moulding parameters (injection speed, back pressure, holding pressure, mould temperature) were varied to optimize the processing conditions and the parameters which remain constant are listed in Table 4.1. Prior to over moulding, the blast-damaged Al inserts were cleaned with isopropyl alcohol and allowed to dry for 50 sec The mould was sealed for a duration of 15 sec, to heat the Al workpiece to mould temperature because the polymer melt would freeze upon contact with a cold metal insert, which would lead to the failure of the micron-size roughness features' apprehension.

Table 4.1: Injection moulding process parameters which were kept constant.

Drying temperature (°C)	70 for 4 hours
Nozzle temperature (°C)	257
Zones 1,2,3 and 4 temperatures (°C)	245, 234, 224, 220
Cooling time (s)	*15*

To fabricate the *PPS–Al* bi-component specimen, as presented in Figure 4.1 the process parameters listed in Table 4.2 were set for injection moulding. For PPS materials in industrial applications, injection temperatures of 300–340 °C, pressures of 80–130 MPa, and a holding pressure of 80% of the injection pressure are recommended [14]. Generally, the injection moulding process parameters significantly influence the bonding strength of PPS–Al bi-component parts with the same surface roughness, so for this research, the parameters were kept constant to facilitate the description of the effects of the surface treatment. The mould was kept closed for 15 sec before injection to heat the Al insert at 120 °C. A cold Al insert would cause polymer melt freezing upon contact, and consequently cause the apprehension of its micron-size roughness features to fail [30].

Table 4.2: Injection moulding process parameters.

Injection Speed (mm/s)	130
Injection pressure (MPa)	60
Cooling temperature under the hopper (°C)	40-50
Zones 1, 2, 3, and 4 temperatures (°C)	290, 310, 330, 330
Nozzle temperature (°C)	310
Holding pressure (MPa)	45
Holding time (s)	7
Cooling time (s)	15
Mould temperature (°C)	120

The same electric moulding machine was used to create the *Elium®-PBT* specimens. Injection moulding conditions are listed in Table 5.3Table 4.3. The process was conducted with both treated and untreated Elium® composites, incorporating three different surface modifications. Additionally, different mould temperatures were employed. The untreated Elium® composites underwent insert moulding with three different mould temperatures: 40 °C, 80 °C, and 120 °C. This temperature variation was chosen to investigate the impact of mould temperature on the quality of the over-moulded parts and to identify the optimal processing conditions for untreated Elium® composites. The chosen melt temperature, reaching up to 260 °C, was employed ensuring sufficient melting of Elium® composite for effective over-moulding. A pressure of 80 MPa was applied during the injection phase to force the molten material into the mould cavity, and a holding pressure of 50 MPa for 10 second period was maintained to prevent any shrinkage or deformation. The injection temperature, pressure, and holding pressure parameters remained consistent during over-moulding manufacturing to maintain a standardized comparison across different heating of the used mould. In contrast, for the treated samples, the over-moulding process was carried out only with a mould temperature of 120 °C. This elevated temperature was selected to facilitate enhanced bonding between the Elium® composite and the over-moulded PBT filled with 20 wt.% of glass fibres.

Table 4.3: Injection moulding parameters.

Injection speed	80 mm/sec
Injection pressure	80 MPa
Injection unit temperature	220-260 °C
Nozzle temperature	260 °C
Holding pressure	50 MPa
Holding time	10 sec
Cooling time	25 sec
Mould temperature	40-120 °C

5. RESULTS AND DISCUSSIONS

This chapter is divided as polymer-metal insert moulding studies and polymer-polymer insert moulding studies. For PK-Al bi-components, mechanical performance with respect to different moulding parameters was discussed in detail. For PPS-Al and Elium-PBT bi-components mechanical performance was assessed with respect to different surface treatments on inserts.

5.1 Polymer-metal insert moulding studies

5.1.1 Discussion on varying the injection speed & back pressure

First, with a constant holding pressure, shear strengths for PK-Al were compared with varying injection speed and back pressure dependence. Table 5.1 presents the findings. Shear heat is typically produced at the cavity-polymer contact by high injection speeds. Better strengths are therefore displayed, and earlier research [19] has also demonstrated a positive association between injection speed and strength. But in this instance, the surface textures were already completely packed with polymer, therefore the joining strength was not much affected by variations in injection speeds (Figure 5.1). Also, as can be seen in Figure 5.2, at back pressure 3 with injection speeds 30, 50 and 70; the strengths were 100, 101 and 101 respectively. At back pressure 5, the strengths were 102, 110, 95. And when the back pressure was 7, strengths were 101, 97, 123. Therefore, no consistent trend regarding shear strength has been observed in this investigation when injection speed is varied.

Table 5.1: Injection moulding parameters with varying injection speed and back pressure for PK GF 15 processing.

Mould temp. (℃)	**Injection speed (mm/s)**	**Back pressure (MPa)**	**Holding pressure (MPa, sec)**	**Surface roughness (Ra; µm)**	**Shear strength mean (N)**
60	30	3	45,10	4.76 ± 0.67	100 ± 13
60	30	5	45,10	4.56 ± 0.42	102 ± 15
60	30	7	45,10	4.47 ± 0.45	101 ± 11
60	50	3	45,10	4.32 ± 0.53	101 ± 11
60	50	5	45,10	4.26 ± 0.36	110 ± 15
60	50	7	45,10	4.55 ± 0.51	97 ± 9
60	70	3	45,10	4.53 ± 0.47	101 ± 11
60	70	5	45,10	4.40 ± 0.39	95 ± 12
60	70	7	45,10	4.39 ± 0.55	123 ± 16

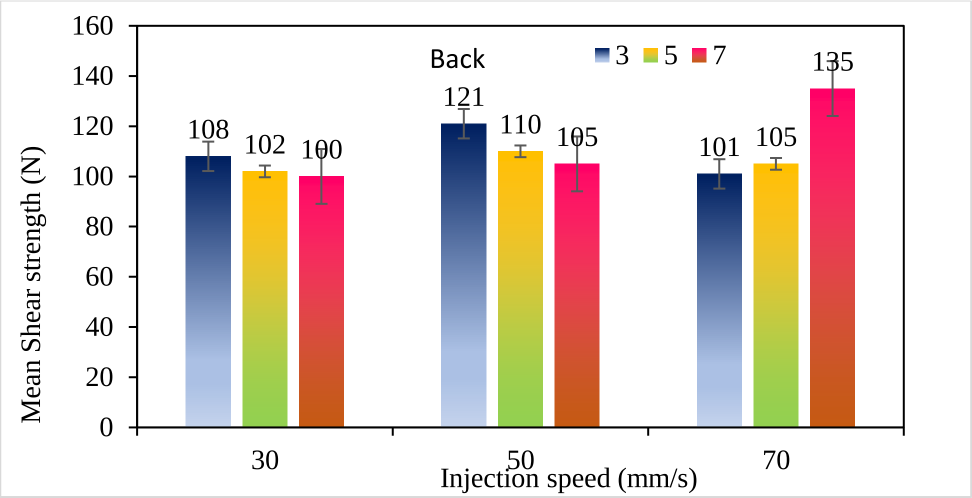


Figure 5.1: Bar graph representation of mean shear strength Vs injection speed for PK-Al.

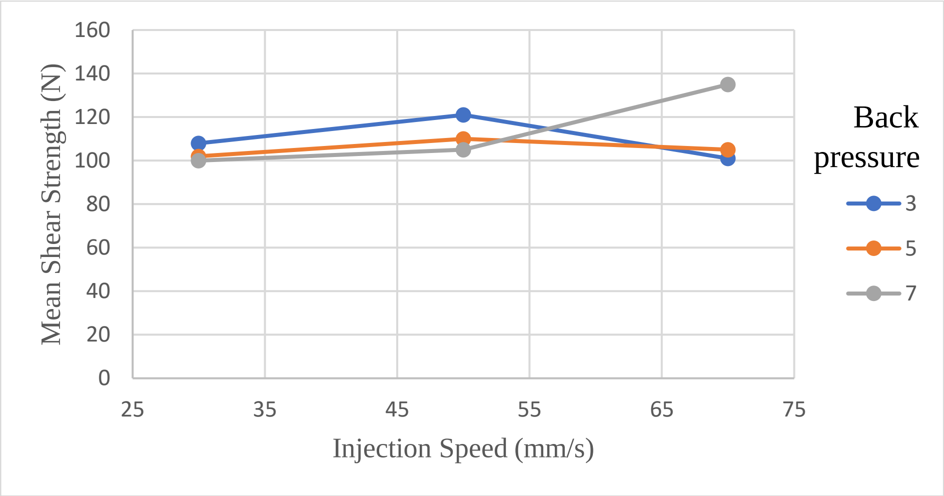


Figure 5.2: Mean shear strength Vs injection speed for PK-Al with varied back pressure.

5.1.2 Discussion on varying the holding pressure

Holding pressure typically describes the pressure kept in a closed system or vessel to keep it sealed or to support particular operations. It is the force exerted on the mould cavity following the first injection stage. In order to account for shrinkage when the material cools and hardens, it is utilized to pack the material into the mould. It also aids in ensuring that the final part's dimensions and form match those of the mould.

The holding pressure dependence for PK-Al was assessed once the maximum shear strength was attained, at injection speeds of 70 and back pressures of 7, the holding pressure was varied from 30 to 70 MPa. The results are presented in Table

5.2, and PK GF 30 was used because an increase in fibre concentration often improves the mechanical properties [37].

Table 5.2: Injection moulding parameters with varying holding pressure used for PK GF 30 processing.

Mould temp. (°C)	**Injection speed (mm/s)**	**Back pressure (MPa)**	**Holding pressure (MPa, sec)**	**Surface roughness (Ra; μm)**	**Shear strength mean (N)**
60	70	7	30,10	4.35 ± 0.38	107 ± 10
60	70	7	60,10	4.33 ± 0.34	134 ± 8
60	70	7	75,10	4.19 ± 0.46	145 ± 24

As can be seen in Figure 5.3Figure 5.3, holding pressure had a positive corelation with shear strength. To guarantee that the polyketone material completely wraps and clings to the aluminium insert, increased pressure can help the substance flow more easily. The stronger bond between the two materials is facilitated by this enhanced covering.

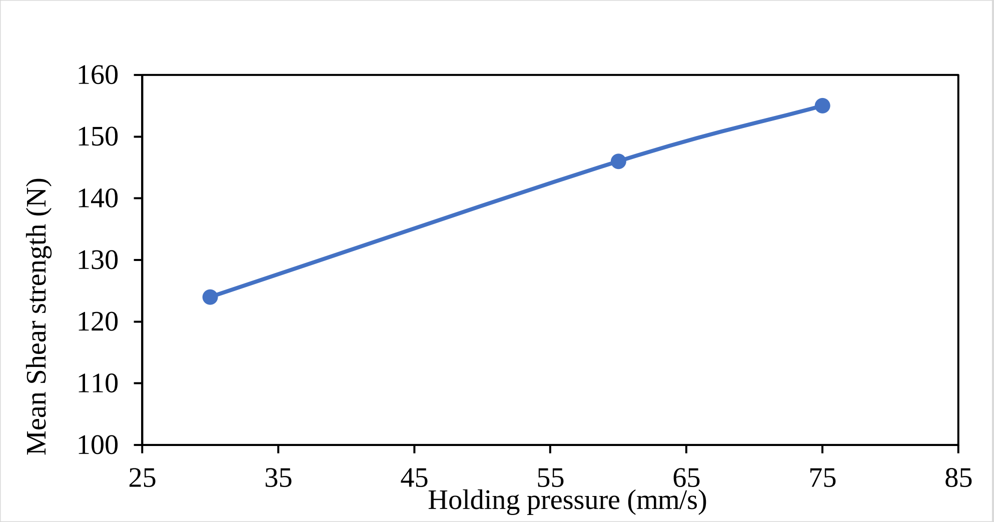


Figure 5.3: Comparison of mean shear strength Vs holding pressure for PK-Al.

5.1.3 Discussion on varying the mould temperature

After the optimisation of moulding parameters like injection speed, back pressure and holding pressure, shear strengths of the optimised PK-Al specimens at different mould temperatures (60 ºC, 90 ºC, and 120 ºC) were compared, it is evident that higher mould temperatures generally lead to increased bond shear strength. This can be attributed to improved material flow and intermolecular bonding at elevated temperatures.

Shear strengths achieved with varying mould temperature highlight the importance of mould temperature in influencing the bonding strength of injection over moulded samples. The results are presented in Table 5.3Table 5.3

As the mould temperature was varied from 60 °C to 120 °C, the highest shear strength was achieved for temperature of 120 °C (Figure 5.4). Thus, can be concluded, moulding temperature has a positive corelation with shear strength.

Table 5.3: Injection moulding parameters with varying mould temperatures used for PK GF 30 processing.

Mould temp. (°C)	**Injection speed (mm/s)**	**Back pressure (MPa)**	**Holding pressure (MPa, sec)**	**Surface roughness (Ra; µm)**	**Shear strength mean (N)**
60	70	7	75,10	3.94 ± 0.45	144 ± 25
90	70	7	75,10	4.0 ± 0.44	154 ± 43
120	70	7	75,10	4.19 ± 0.45	168 ± 62

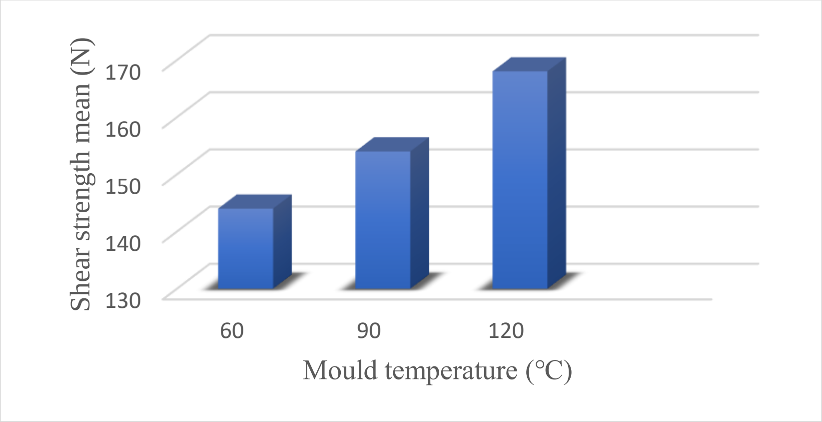


Figure 5.4: Comparison of shear strength Vs mould temperature for PK-Al.

5.1.4 Discussion on varying the surface treatments

Surface morphologies of Al inserts with several surface treatments used for making PPS-Al specimens were studied:

Scanning Electron Microscope (SEM)

The surface microstructures of the Al inserts captured by SEM are presented in Figure 5.5Figure 5.5. While only trivial changes in the surface morphologies could be found for the AL substrates after plasma treatments, the surface roughness of the chemically treated and sandblasted inserts significantly increased. Moreover, visible surface holes and sharp scratches could be detected for the chemical 2 treatment. On the other hand, sandblasted specimens exhibited apparent rough and eroded structure patterns.

The reason that only trivial changes in the surface morphologies could be found after plasma treatment was that this treatment only cleans and soothes the treated surface. No sharp scratches or surface holes were observed after the chemical 1 treatment, in contrast to the chemical 2 treatment, as chemical 2 produced more surface erosion because of chemical erosion. On the other hand, sandblasting led to a dramatic increase in the surface roughness, as it is a mechanical treatment undertaken by bombarding the sand particles on the treated surface.

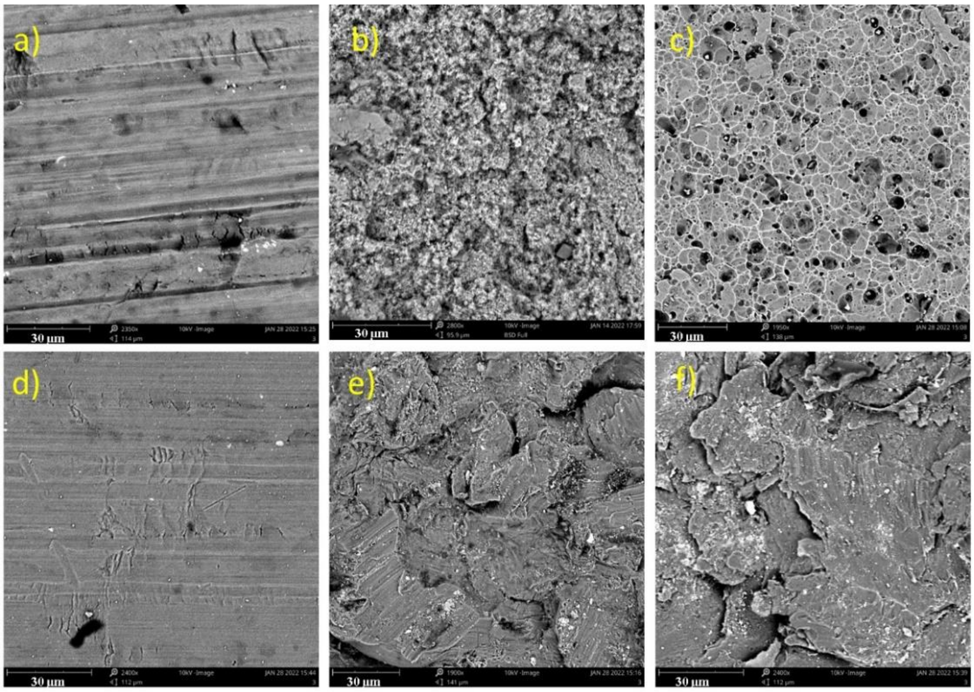


Figure 5.5: SEM images of the surfaces of the (a) untreated, (b) chemical 1, (c) chemical 2, (d) plasma, (e) sandblasting, and (f) sandblasting + plasma inserts.

Surface roughness

In general, the roughness and pore size of a morphology surface crucially affect the adhesion, and they can be influenced by affecting the thermoplastic melt at the level of the metal substrates’ micron-size roughness [13]. A rough topography encourages polymer to flow into metal cavities and increases the overall area at the interface.

The highest roughness was obtained for chemical 2 and this treatment had the highest bonding strength as well (see Figure 5.6, which is ordered by surface roughness). However, the S+P treatment had a lower bonding strength than the chemical 1 and sandblasting treatments, despite having higher roughness.

Therefore, it cannot be concluded that a higher roughness means a higher bonding strength.

In general, plasma-treated surfaces usually involve an increase in bonding strength; hence, this was chosen as a preferred method of surface treatment along with sandblasting. However, unlike in a previous study [38], it did not prove to be successful for Al and PPS in our research.

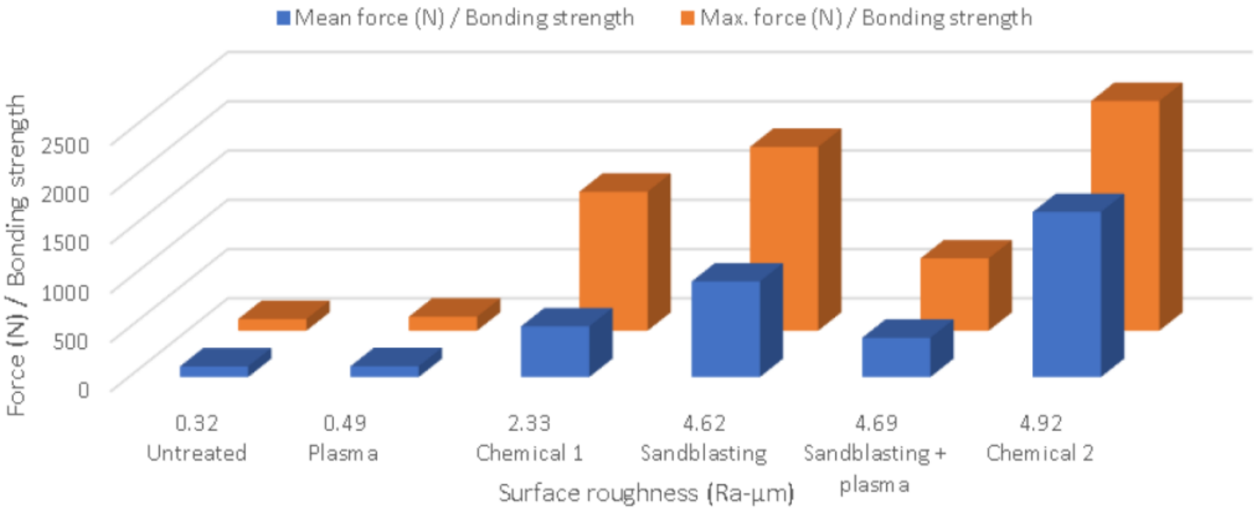


Figure 5.6: Comparison of bonding strength vs. surface roughness for PPS-Al.

Figure 5.7 shows 3D images of the surface-treated Al inserts obtained with a 3D optical microscope. These are in good agreement with the data presented in Table 3.

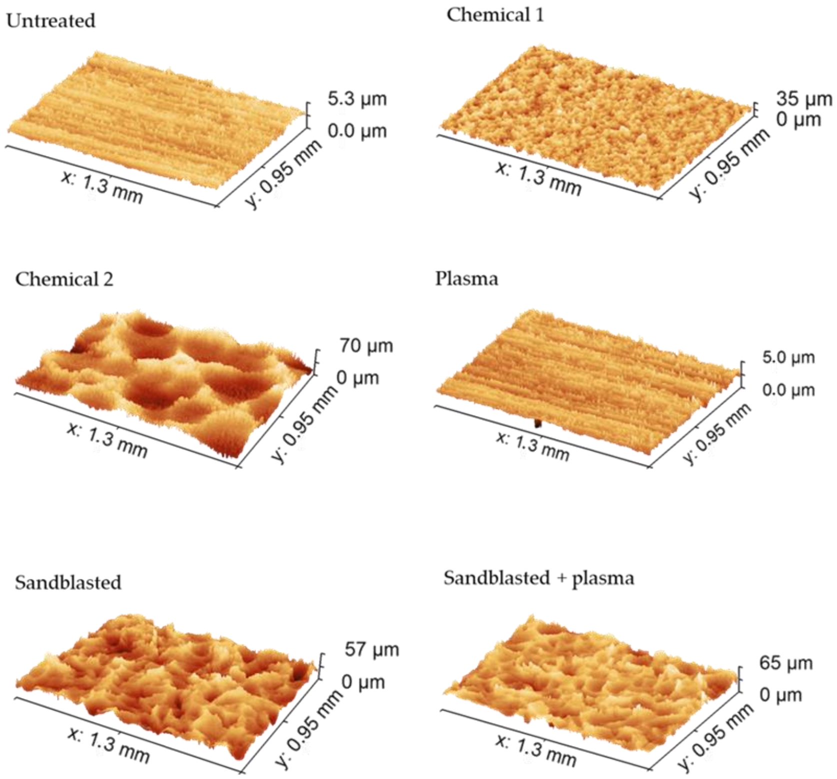


Figure 5.7: Three-dimensional (3D) images of Al substrate surfaces obtained with a 3D optical microscope for PPS-Al.

Contact Angle

Aluminium possesses low surface energy with contact angles of 80°. A contact angle change indicates that the surface has been treated effectively. A reduction of the contact angle indicates an increase in surface energy, which in general leads to an increase in bonding strength.

The contact angle measurement results can be seen in Figure 5.8. It is obvious that they were drastically reduced after the chemical and plasma treatments. On the other hand, sandblasting only modestly decreased the contact angle, which was expected since only the topography changed, not the chemical structure.

5.1.5 Discussion on evaluated mechanical performance

After the surface treatment, all six types of aluminium inserts (eight pieces in each treatment) were used for injection over-moulding. Lap shear strength tests were performed to observe the effect of metal surface treatment on the bond strength between the metal part and the polymer. It should be noted that there were no residues on either the Al insert of the polymer material or the PPS of the metallic substance after the lap shear strength test. Adhesive failure was moreover proved by a comparison of the roughness (Sa) before and after the shear test, as shown in Table 5.4.

Table 5.4: Surface roughness (Sa; µm) measured by optical profilometry of Al substrate surfaces for PPS-Al.

	Reference	**Chem. 1**	**Chem. 2**	**Plasma**	**Sandblast**	**Sand + Plasma**
Roughness *(Sa; µm) before shear test*	*0.5±0.1*	*3.1±0.6*	*7.9±1.4*	*0.90±0.1*	*6.5±0.8*	*6.7±0.5*
Roughness *(Sa; µm) after shear test*	*0.4±0.2*	*3.1±0.5*	*8.0±1.2*	*0.5±0.1*	*6.5±0.7*	*6.2±0.2*

The determined bonding strengths for PPS–Al inserts are presented in Table 5.5. The mean force was calculated from the average of eight pieces from each treatment, and the maximum force represents the highest value achieved from the eight pieces. As can be seen, as well as having the highest roughness among all the substrates, the chemical 2 treatment also had the highest bonding strength. Nevertheless, it cannot be concluded that the bonding strength is directly proportional to the roughness, as the chemical 1 treatment had a higher bonding strength than the S+P treatment despite the lower roughness.

Table 5.5: The bonding strength and surface roughness of PK-Al fabricated with different surface preparations.

Types of Aluminium Inserts	**Surface Roughness (Ra; µm)**	**Deviation of Surface Roughness (Ra; µm)**	**Bonding Strength / Max. Force (N)**	**Bonding Strength / Mean Force (N)**
Untreated	*0.32*	*± 0.06*	*119*	*108*
Chemical 1	*2.33*	*± 0.83*	*1411*	*515*
Chemical 2	*4.92*	*± 1.86*	*2332*	*1676*
Plasma	*0.49*	*± 0.09*	*142*	*110*
Sandblasting	*4.62*	*± 1.49*	*1866*	*970*
Sandblasting + plasma	*4.69*	*± 1.27*	*734*	*399*

As can be seen in Figure 5.8Figure 5.8 (where the substrates are ordered by contact angle), the plasma treatment obviously reduced the contact angles but did not raise the adhesion or bonding strength much. Moreover, the bonding strength was negatively affected (reduced) when plasma was applied after sandblasting, thus resulting in excellent bonding strength in sandblasted specimens, greater than the S+P samples despite their higher contact angle. This effect could have resulted from the prevention of the PPS melt stream from effectively in-leaking into the created surface knobs due to the increased substrate surface energy.

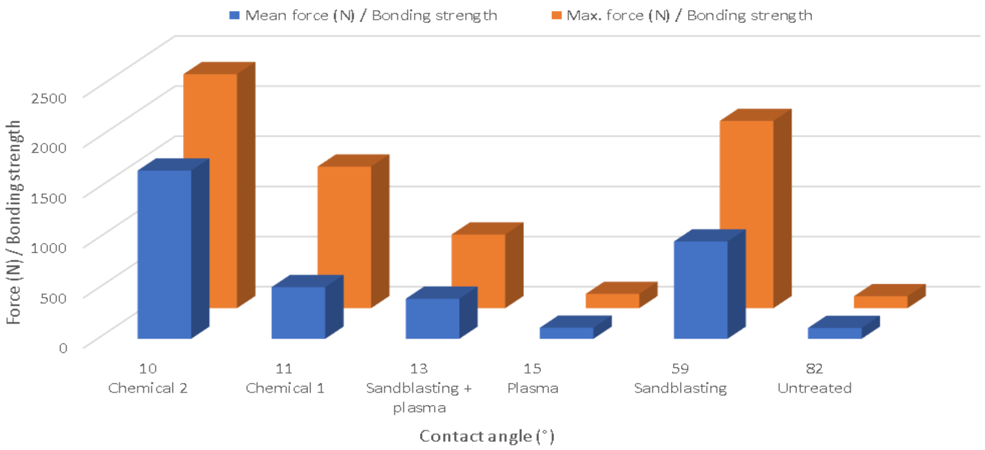


Figure 5.8: Comparison of bonding strength vs contact angle for PPS-Al.

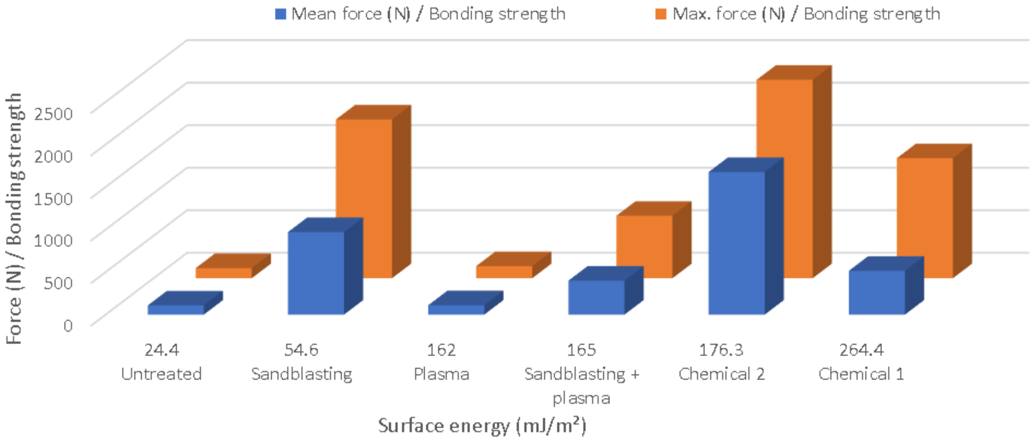


Figure 5.9: Comparison of bonding strength vs surface energy for PPS-Al.

5.2 Polymer-polymer insert moulding studies

5.2.1 Discussion on varying the surface treatments

Surface morphologies of Elium inserts with various surface treatments used for creating Elium®-PBT specimens were studied using:

Scanning electron microscopy (SEM)

The surface microstructures of the Elium® inserts captured by SEM are presented in Figure 5.10. While only trivial changes in the surface morphologies could be found for the Elium® inserts after solvent induced, the surface roughness of the sandblasted and plasma-treated inserts increased significantly. Since the grain size of the slag was smaller and thus less aggressive for sandblasting II in comparison to 400-500 µm of grain size for sandblasting I, sharp scratches and rough eroded plates were detected for sandblasting I treatment, contrary to a lesser number of rougher eroded plates for sandblasting II. Additionally, as can be seen, also plasma treatments have led to increased roughness with the duration of treatment mainly because the increase in plasma exposure duration has weakened the surface layer due to such high energy and allowed the fibres to come out of the Elium® surface. Nevertheless, 30 sec of plasma exposure has led to uncoating an extend fibre areas (see Figure 5.10) as well as to the final bonding strength decrease.

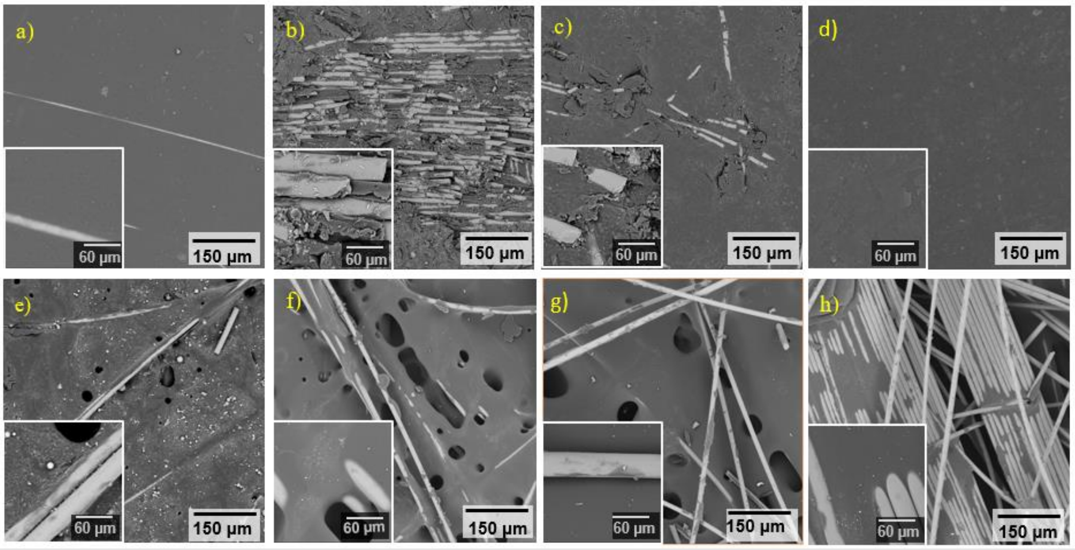


Figure 5.10: Scanning electron microscopy (SEM) images of the surfaces of the (a) Untreated (b) Sandblasted I (c) Sandblasted II (d) Solvent induced (e) Plasma 5 sec (f) Plasma 10 sec (g) Plasma 15 sec (h) Plasma 30 sec.

Surface roughness analysis

Generally, adhesion is strongly affected by the morphological surface's pore size and roughness. These variables can be changed by altering the thermoplastic melt at the substrate's micron-scale roughness level [13]. Rough topography expands the total area at the interface by promoting polymer flow into the substrate's voids. Defined values of surface roughness by profilometry experiments are stated in Table 5.6, while they are interconnected with shear strength in Figure 5.12.

Sandblasting I caused more roughness on the substrate than Sandblasting II and achieved more shear strength as well. Since plasma treatment typically results in a stronger bonding, therefore, it was selected as the preferred surface treatment technique [38] and it has proven to be the second highest bonding strength at 15 sec plasma treatment. However, Plasma 30 sec had a lower bonding strength than

Plasma 15 sec despite having higher roughness. The more duration of plasma exposure led to uncoating of fibres because of the high energy of plasma for a longer period. This uncoating of Elium® from fibres on the substrate surface caused the release from the matrix and consequently this fact led to lower bonding strength and moreover to its high deviation for various samples. As it is clear from Figure 5.11, while plasma treatment has increased the surface roughness by rather uniform polymer clearance causing unfolding of the glass fibres from the Elium® composite's surface, increased roughness caused by sandblasting was evidently incurred by casual hard particles blasting.

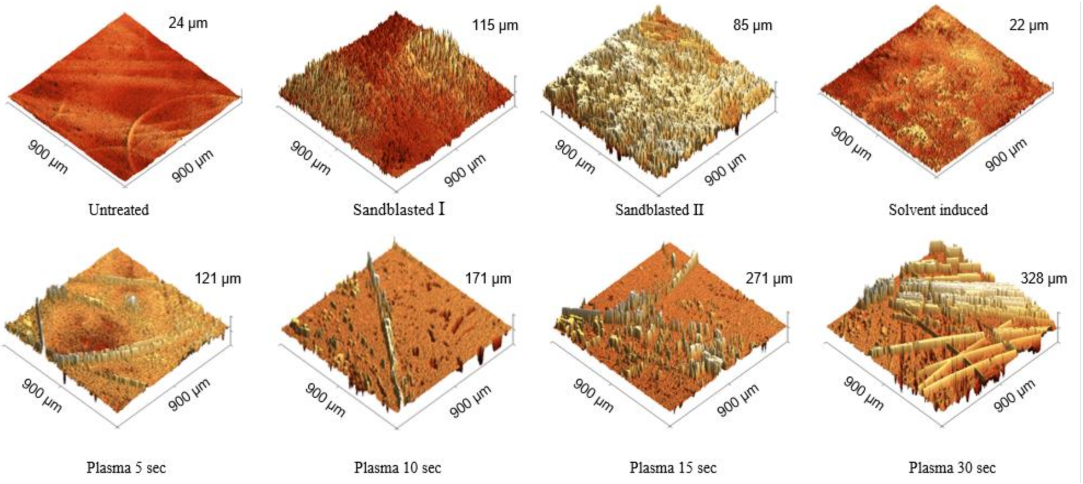


Figure 5.11: Three-dimensional (3D) images of Elium® substrate surfaces obtained with a 3D optical microscope.

Table 5.6: Roughness average values and their standard deviations caused by utilised surface treatments defined via optical (Sa, Sz) and contact (Ra, Rz) profilometry.

Surface treatment	Sa (µm)	Sz (µm)	Ra (µm)	Rz (µm)
Untreated	1.2 ± 0.2	18 ± 3	0.47 ± 0.05	2,9 ± 0,5
Sandblasting I	8 ± 0.5	100 ± 4	6 ± 0.3	27 ± 2
Sandblasting II	7.8 ± 0.4	123 ± 7	2.7 ± 0.03	18 ± 2
Solvent induced	2.3 ± 0.4	65 ± 3	0.6 ± 0.03	2,6 ± 0,3
Plasma 5 sec	7 ± 2	117 ± 12	6.7 ± 0.4	36 ± 2
Plasma 10 sec	8.2 ± 0.7	172 ± 4	10 ± 2	50 ± 8
Plasma 15 sec	10 ± 2	210 ± 17	12 ± 2	67 ± 9
Plasma 30 sec	28 ± 2	303 ± 18	27 ± 4	131±19

Mechanical performance

All the moulding samples were combatted by the successful connecting of plastics that were injection moulded with Elium® inserts. There was no discernible variation in the appearance of the samples that were moulded under any of the conditions. It should be observed that following the lap shear strength test indicates that there was no cohesive failure, as there were no residues on PBT's surface or the polymer material's on Elium® insert.

5.2.2 Discussion on varying the mould temperature

Comparing the treated samples with non-treated samples at different mould temperatures (40 ºC, 80 ºC, and 120 ºC), it is evident that higher mould temperatures generally lead to increased bonding shear strength (Table 5.7). This can be attributed to improved material flow and intermolecular bonding at elevated temperatures.

The results highlight the importance of both surface modification techniques and mould temperature in influencing the bonding strength of injection over moulded samples. While higher mould temperatures generally lead to improved results, the specific surface modification method plays a crucial role, with sandblasting of the Elium® glass fibre composites showing promising results.

Table 5.7: Shear strength of composite samples prepared from untreated Elium® inserts and over moulded with varying mould temperatures.

Mould temperature (°C)	Mean shear strength (N)
40	394 ± 205
80	456 ± 216
120	700 ± 197

While the moulding temperature was varied from 40 °C to 120 °C for the untreated inserts, the highest shear strength was achieved for temperature of 120 °C (see Table 5.7). Thus, temperature of 120 °C was chosen for moulding and preparing samples with surface treated inserts.

5.2.3 Discussion on evaluated mechanical performance

Comparison of shear strength defined by tensile testing was employed for evaluation of surface modifications effect on mechanical performance of insert moulded products manufactured at a constant mould temperature of 120°C. The impact of surface modifications can be observed from the achieved values presented in Table 5.8. As it is clear, the highest mechanical performance was achieved with sandblasted samples.

Table 5.8: Shear strength of Elium® inserts fabricated with different surface treatments.

Surface treatment	Mean shear strength (N)
Untreated	700 ± 198
Sandblasting I	2159 ± 425
Sandblasting II	1687 ± 248
Solvent induced	780 ± 285
Plasma 5 sec	1407 ± 808
Plasma 10 sec	1544 ± 768
Plasma 15 sec	1944 ± 602
Plasma 30 sec	1279 ± 603

The values indicate the force experienced during the tensile test, reflecting the material's strength and the effectiveness of the surface modification are presented in Figure 5.12 for better illustration. The results suggest that sandblasting I produced the highest shear strength, indicating superior bonding strength compared to other modifications. Plasma treatments, although effective, exhibited slightly lower strength in comparison to sandblasted. Also, with its longer duration resulting in reduced strength. Especially at plasma 30 sec, a drop in shear strength was observed while optimised duration for plasma treatments was achieved at plasma 15 sec. Solvent-induced swelling showed the lowest shear strength, suggesting that this modification might have a lesser impact on enhancing the bonding strength.

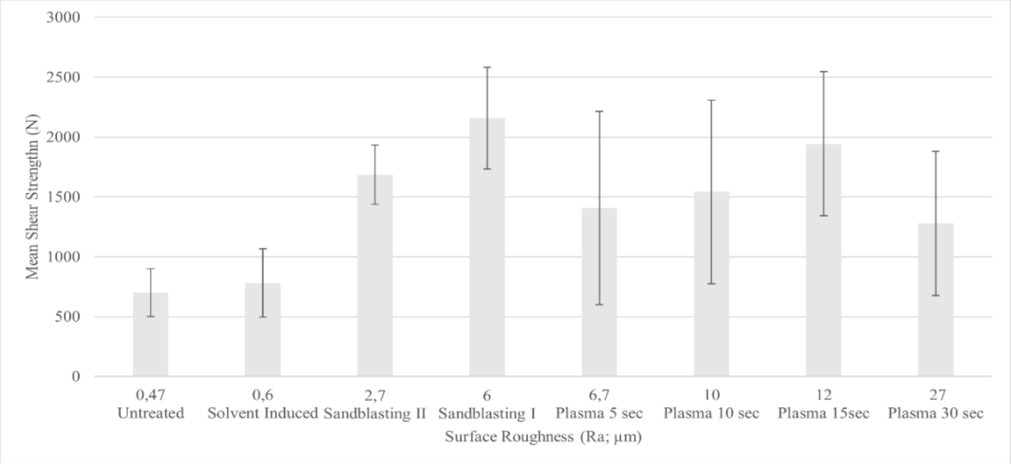


Figure 5.12: Effect of performed surface treatments on shear strength of tested Elium®-PBT samples expressed together with achieved average surface roughness (Ra).

6. CONCLUSION

Multicomponent injection moulding is a significant development in the manufacturing industry that has many benefits over conventional single-material injection moulding techniques. This method allows for decreased production costs, better design freedom, enhanced product functioning, and less environmental effect by integrating various materials into a single injection moulding cycle. However, despite its great potential, multicomponent injection moulding is not without challenges. Material selection, compatibility, process synchronization, and tooling design are all complex tasks that require careful attention and experience. Addressing these issues necessitates interdisciplinary collaboration, new approaches, and ongoing research and development.

Through this thesis the challenges of joining the two different elements for making the bicomponent was investigated with regards to three different material combinations.

Polymer-metal

PK-Al assessed the optimization of the process variables during multicomponent injection moulding process. Effect of moulding conditions on the joining strength between polyketone and aluminium insert was examined, and the findings are summarized as below: The joining strength revealed positive correlations with both holding pressure and mould temperature. Back pressure likewise displayed a positive corelation with the joining strength. However, injection speed didn’t show any consistent trend when varied it along with back pressure. Even though the highest joining strength was achieved by the greatest injection speed but no significant effect on the joining strength was observed by varying injection speed.

Therefore, further research focused on varying injection speed would be helpful in evaluating their influence with different surface substrate treatments and different material combination as it can cause different tendencies of strength variations. *PPS-Al* examined different combinations of mechanical and chemical treatments for aluminium substrates and their effects on the adhesion between metal and poly(phenylene) sulphide. The conclusions can be formulated as follows.

The results indicated that the surface roughness had a remarkable effect on the bonding strength, which was presumably connected with the intrusion of the thermoplastic melt into the metal substrates’ micron-size roughness features. This effect was enhanced by the increased temperature of the metal substrates during the over-moulding process. However, the roughness was not entirely responsible for the good adhesion. Adequate pore sizes and their micro-structuring, determining the active surface of the substrates with the same roughness, also played vital roles in good bonding. On the other hand, the experiments did not reveal any direct correlation between surface energy and bond strength for this type of polymer/metal connection, as shown by Figure 5.9. Though the atmospheric plasma treatment increased the surface energy, it did not lead to an improvement in the bonding strength, unlike in previous studies. Instead, its application following sandblasting led to a decline in strength, probably due to the opening of small pores. Therefore, further studies focused on more detailed descriptions of the effect of the roughness topography, in potential combination with plasma treatment, would be helpful in assessing their influence on the bonding strengths of plastics with different polarities.

Polymer-polymer

This study aimed to produce a hybrid thermoplastic bi-component by assembling a thermoplastic composite, i.e., Elium® reinforced with glass fibres (70 %) and a thermoplastic polymer, 20 % glass-filled PBT, by investigating and making use of insert moulding. The insert -moulding process parameters and surface roughness produced by various treatments at the interface have been investigated as potential solutions to the adhesion challenge caused by the incompatibility of the layers.

The first major finding was that the mould temperature had a positive correlation with bonding strength. A 120 °C mould temperature produces stronger bonding strength compared to 40 °C and 80 °C. The second substantial finding was that, despite surface roughness significantly impacting bonding strength, it was likely caused by the thermoplastic melt penetrating the substrate's micron-sized roughness characteristics. However, roughness was not solely accountable for the good adherence. Good bonding also depends on the active surface of the substrates having the same roughness, which is determined by the appropriate pore size and micro-structuring. Roughness values can be deceiving because the presence of uncoated fibres leads to losing the structural integrity of the Elium® on the surface. Therefore, it can help in achieving the higher roughness values however not achieving the higher bonding strength (Figure 5.12).

Therefore, the results shown in this paper show many points of interest for further investigation on this topic, especially the pore size, and the geometry of the pore structures should be explored and analysed to gain a comprehensive understanding of the mechanism influencing the interfacial surface.

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CURRICULUM VITAE

Name: Ashish Matta
Date of birth: 28th July 1991
Place of birth: Delhi, India
Permanent address: 67 Shivpuri, India
Affiliation: Faculty of Technology, Tomas Bata University in Zlin, Namesti T.G. Masaryka 275, 76272 Zlin, Czech Republic
E-mail: matta@utb.cz
Education: **2020 – to date**

Tomas Bata University in Zlin, Faculty of Technology,

Ph.D. studies in Chemistry and Materials Technology, Specialization: Technology of Macromolecular Compounds

2012 – 2014

Footwear Design & Development Institute, Noida, India

M.Sc. Footwear Technology

2009 – 2012

Delhi University, Delhi, India

B.Sc. Polymer Science

List of publications

MATTA, A.; Sedlacek, T.; Kadleckova, M.; Lengalova, A. The Effect of Surface Substrate Treatments on the Bonding Strength of Aluminium Inserts with Glass-Reinforced Poly(phenylene) Sulphide. Materials 2022, 15, 1929.

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Conferences attended

October 5-9, 2021, 6th International Conference On Competitive Materials and Technology Processes, Miscolc-Hungary, Poster presented – Achieve Bonding Strength Between Metal & Polymer.

Ashish Matta, M.Sc., Ph.D.

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Zlepšení vlastností vícesložkových vstřikovaných výrobků

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