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OPTIMIZATION OF INJECTION MOLDING PARAMETERS FOR IMPROVING THE BONDING OF THERMOPLASTIC ELASTOMER TO EPDM RUBBER USED IN AUTOMOTIVE SEALING SYSTEMS

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School of Applied and Natural Science Department
Material Science and Engineering Master's Degree Programme

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Eylül Ezgi GÜNİNDİ tarafından Yüksek Lisans tezi olarak sunulan "Optimization of injection molding parameters for improving the bonding performance of thermoplastic elastomer to EPDM rubber used in automotive sealing systems" başlıklı bu çalışma EÜ Lisansüstü Eğitim ve Öğretim Yönetmeliği ile EÜ Fen Bilimleri Enstitüsü Eğitim ve Öğretim Yönergesi'nin ilgili hükümleri uyarınca tarafımızdan değerlendirilerek savunmaya değer bulunmuş ve 25.02.2022.tarihinde yapılan tez savunma sınavında aday oybirliği ile başarılı bulunmuştur.

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EÜ Lisansüstü Eğitim ve Öğretim Yönetmeliğinin ilgili hükümleri uyarınca Yüksek Lisans Tezi olarak sunduğum “Optimization of injection molding parameters for improving the bonding performance of thermoplastic elastomer to EPDM rubber used in automotive sealing systems” başlıklı bu tezin kendi çalışmam olduğunu, sunduğum tüm sonuç, doküman, bilgi ve belgeleri bizzat ve bu tez çalışması kapsamında elde ettiğimi, bu tez çalışmasıyla elde edilmeyen bütün bilgi ve yorumlara atıf yaptığımı ve bunları kaynaklar listesinde usulüne uygun olarak verdiğimi, tez çalışması ve yazımı sırasında patent ve telif haklarını ihlal edici bir davranışımın olmadığını, bu tezin herhangi bir bölümünü bu üniversite veya diğer bir üniversitede başka bir tez çalışması içinde sunmadığımı, bu tezin planlanmasından yazımına kadar bütün safhalarda bilimsel etik kurallarına uygun olarak davrandığımı ve aksinin ortaya çıkması durumunda her türlü yasal sonucu kabul edeceğimi beyan ederim.

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İmzası

Eylül Ezgi GÜNİNDİ

ÖZET

OTOMOTIV SIZDIRMAZLIK PROFILLERINDE KULLANILAN TERMOPLASTIK ELASTOMERIN EPDM KAUÇUK ILE YAPIŞMA PERFORMANSININ IYILEŞTIRILMESI IÇIN ENJEKSIYON PROSES OPTIMIZASYONU

GÜNİNDİ, Eylül Ezgi

Yüksek Lisans Tezi, Malzeme Bilimi ve Mühendisliği Anabilim Dalı
Tez Danışmanı: Doç. Dr. Nilay Gizli
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Sızdırmazlık profilleri aracın ses, toz, su ve ısı izolasyonunu sağlayan fonksiyonel parçalardır. Ethylene Propylene Diene Monomer (EPDM) veya Termoplastik Elastomer (TPE) esaslı olmak üzere iki çeşit sızdızmalık profili mevcuttur. Bunlar dinamik ve statik sızdırmazlık profilleri olarak adlandırılmaktadır. Dinamik profiller aracın hareketli kısmında kullanılmakta olup, ağırlıklı olarak mükemmel sızdırmazlık performansı ve oksijen, ozon ve kimyasal direncine sahip olan EPDM kauçuk kullanılarak üretilmektedir. Termoplastik elastomer malzemeler genellikle iç veya dış sıyırıcılar olarak bilinen statik profillerde tercih edilmektedir. Geri dönüştürülebilirlik ve çevre koruma konusuyla ilgili artan endişe ile termoplastik elastomerler, geri dönüştürülemeyen termoset kauçuklara göre önem kazanmıştır. Fiziksel olarak çapraz bağlı olduklarından, geri dönüştürülebilir olan termoplastik elastomerler, kolay işlenebilirlik özelliği veren bir termoplastik ve malzemenin esnekliğini ve elastikiyetini sağlayan bir elastomer içerir. Buna rağmen, otomotiv sızdırmazlık sistemlerinde henüz EPDM tabanlı kauçuk yerine tamamen TPE kullanımı gerçekleştirilemememektedir. Bunun yerine, bazı uygulamalarda bu iki malzemenin hibrit olarak kullanımı tercih edilmektedir. Bu uygulamaya en iyi örnek, yarı dinamik bir profil olarak sınıflandırılabilen cam kanal profillerinin EPDM bazlı kauçuk hamur ile üretilip, köşe kaynak bölgelerinde TPE malzeme kullanılması verilebilir. Enjeksiyon kalıplama ile gerçekleştirilen bu üretim esnasında, malzeme uyumluluğu, yüzey kalitesi ve proses koşullarından etkilenen EPDM profil ile TPE kaynağın yapışma performansı kritik önem taşımaktadır.

Bu çalışmada, enjeksiyon proses parametrelerinin 65 ShA±5 sertlikteki EPDM bazlı kauçuk hamur ve TPE malzemenin yapışma üzerinde etkisi incelenmiştir, çalışmada kullanılan malzemeler ve kalıp tasarımı için optimum (çözüm seti) çalışma koşulları belirlenmiştir. Çalışma esnasında iki ayrı deney tasarımı planı üzerinden elde edilen numuneler üzerinden mekanik testler gerçekleştirilmiştir, elde edilen sonuçlar Minitab 17 programı kullanılarak istatiksel olarak analiz edilmiştir.

Birincisi deney tasarımında enjeksiyon hızı, tutma basıncı, giriş-bağlanma mesafesi, kalıp sıcaklığı, enjeksiyon sıcaklığı ve tutma süresi parametreleri kesirli faktöriyel tasarım ile incelenmiş olup, enjeksiyon hızı, enjeksiyon sıcaklığı ve kalıp sıcaklığı akış yönündeki parçanın yapışmasının tek başına pozitif etkilediği, tutma basıncının ise negatif etkilediği gözlenmiştir. Bekleme süresinin ise yapışma üzerinde önemli bir tekli etkisinin olmadığı sonucuna varılmıştır. Giriş-bağlanma mesafesi sonuçlarının etkisi tutarsız olarak yorumlanmıştır.

İkinci deney tasarımında giriş-bağlanma mesafesi ve tutma süresi parametreleri çıkartılacak yerine soğutma süresi eklenmiş, akış yönünde ve akış yönüne ters durumlardaki yapışma performansı incelenmiştir. Enjeksiyon sıcaklığı, kalıp sıcaklığı ve enjeksiyon hızı parametrelerinin parçanın yapışmasına tekli pozitif etkilesi olduğu doğrulanmış, kalıp sıcaklığının önemli derecede etkili olduğu sonucuna varılmıştır. Tutma basıncı ise, kalıp içerisine yerleştirilen EPDM numunesini hareket ettirmeyecek kadar yüksek seviyede ayarlanmalıdır. Soğutma süresi, tutma süresi gibi yapışma üzerinde tekli olumlu etkisi göstermemiştir. Parça tasarımına göre gerekli seviyede ayarlanması yeterlidir.

Çalışmada kullanılan kalıp tasarımı ve malzemeler için uygun enjeksiyon çalışma koşulları belirlenmiştir. Kopma testi sonrası TPE ve EPDM parçalarının yüzeyleri SEM analizi ile incelenmiştir. Ayrıca, ikinci deney tasarım çalışması sonrasında elde edilen çözüm seti ile gerçek bir sızdırmazlık profil üretimi ile parametrelerin doğrulama çalışması yapılmıştır ve elde edilen kopma mukavemet değerlerinin müşteri beklentilerini karşıladığı gözlemlenmiştir.

Anahtar sözcükler: Termoplastik elastomer, EPDM kauçuk, enjeksiyon kalıplama, yapışma performansı, polimer yapışma, deney tasarımı.

ABSTRACT

OPTIMIZATION OF INJECTION MOLDING PARAMETERS FOR IMPROVING THE BONDING PERFORMANCE OF THERMOPLASTIC ELASTOMER TO EPDM RUBBER USED IN AUTOMOTIVE SEALING SYSTEMS

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Sealing profiles provide sound, dust, water, and heat insulation for the vehicle. There are two kinds of sealing profiles based on EPDM or Thermoplastic elastomer (TPE). Dynamic profiles are used in the moving part of the vehicle and are mainly produced using an EPDM based rubber compound, which has excellent sealing performance and oxygen, ozone, and chemical resistance. TPE materials are generally preferred in static profiles known as inner or outer waist belts. With the growing concern about recyclability and environmental protection, thermoplastic elastomers have gained importance over non-recyclable thermoset rubbers. Thermoplastic elastomers, which are recyclable because they are physically cross-linked, contain a thermoplastic for easy processability and an elastomer for flexibility and elasticity. Despite this, it is still not possible to use TPE completely instead of EPDM-based rubber in automotive sealing systems. Instead, it is preferred to use these two materials as a hybrid. The best example of this application that can be given is the glass channel profile, produced with EPDM-based rubber compound extrusion and TPE material injected in the corner molding areas by injection molding. And the bonding of these materials has critical importance for this kind of application.

In this study, the effect of injection process parameters on the bonding of 65 ShA±5 EPDM-based rubber compound and TPE material was investigated, and optimum (solution set) process conditions were determined for these materials and mold design. During the study, mechanical tests were carried out on the two

component test samples obtained from two different experimental design plans, and the results were statistically analyzed using the Minitab 17.

The injection speed, holding pressure, gate-joint distance, mold temperature, injection temperature, and holding time parameters were investigated using a fractional factorial design in the first design of experiment study. It was observed that injection speed, mold and injection temperature have positive direct effects on the bonding performance in flow direction, while holding pressure has a negative single effect. It was seen that the holding time did not have a significant effect on adhesion. The effect of the gate-joint distance variable was interpreted as inconsistent.

In the second experimental design, the gate-joint distance and holding time parameters were removed, the cooling time was added to the design, and the bonding performance in the flow direction and across direction was examined. It has been confirmed that the parameters of injection and mold temperature and injection speed have positive effects on the adhesion of the EPDM and TPE materials, with the mold temperature has a significant effect. Holding pressure should be adjusted high enough so as not to move the EPDM insert into the mold. The cooling time did not have a single positive effect on the adhesion, as did the holding time and should be set high enough according to the part design.

Optimum (solution set) injection process parameters for EPDM and TPE materials and mold design used in the study were obtained. After the tensile strength test, the surfaces of the TPE and EPDM parts were examined by SEM analysis. Additionally, a real sealing profile was produced with the set solution obtained in the second design of the experiment study for verification, and it was observed that the bonding strength results at those process parameters fulfilled the customer expectations.

Keywords: Thermoplastic elastomer, EPDM rubber, injection molding, bonding performance, polymer bonding, design of experiment.

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Eylül Ezgi Günindi

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1.INTRODUCTION

Automotive sealing systems (weather-strips) act as a barrier between the sheet metals of the vehicle for sound, noise, water, dust, and heat isolation. They increase the comfort of the user by absorbing vibrations and shocks and also provide good aesthetic integrity to the vehicle. There are two main kinds of sealing systems that are installed on different visible and non-visible parts of the vehicle: static and dynamic profiles. Body/door-mounted, windshield, hood, rocker panel, and trunk seals that are mainly produced with EPDM-based rubber compound can be classified as "dynamic seals". They are used in the moving part of the vehicle, and each sealing profile has a unique design and functional performance. Inner and outer waist belts that can be made with thermoplastic elastomer materials are classified as "static seals." They are placed around the glasses of the vehicle. Glass run channels may be produced with EPDM or TPE materials according to customer expectations. Glass run channels produced with EPDM-based rubber compounds and thermoplastic elastomers in the injected areas can be classified as "semi-dynamic seals" (Figure 1). They are produced through the extrusion process of EPDM-based rubber compounds and the injection of thermoplastic elastomer (TPE) into corner moldings. This could be an example of a hybrid application in automotive sealing systems (Standard Profil, 2021).

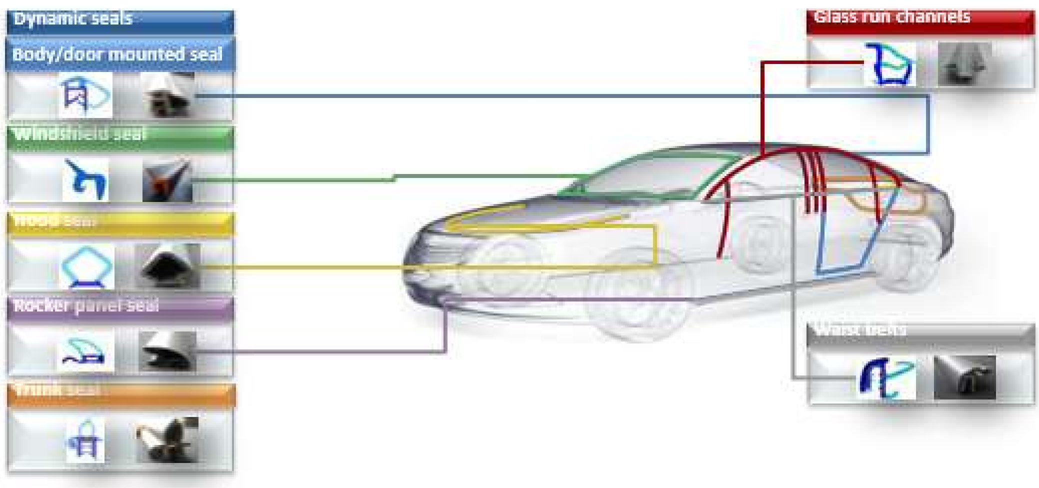

Figure 1 Automotive sealing systems’ positions on the vehicle

1.1. Production of Automotive Sealing Systems

Automotive sealing systems are produced with a tailor-made design for each vehicle model. Before the production phase, profile design and verification are carried out with specific simulation programs and process trials, and technical requirements are defined with functional specifications. With the frozen design data, extrusion dies, injection molds, and other required tools and equipment are produced or supplied. Extrusion dies are made according to the defined material flow behavior (rheology). Simulation tools are used to obtain accurate cross sections in short time. The extrusion method differs based on the material type chosen according to the weather-strip. EPDM-based rubber compounds are required to be heated for vulcanization, whereas thermoplastic elastomers can be shaped cold, just like thermoplastics. They are processed at 180–220 °C (process temperatures may reach to 260 °C depending on the material type) and formed during the cooling phase. Figure 2-3 depicts an example of the process steps and differences between the EPDM and TPE extrusion processes for weather-strip production (Standard Profil, 2021).

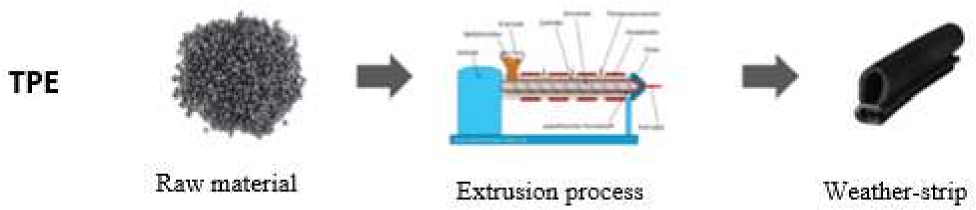

Figure 2 Weather-strip production with thermoplastic elastomer (TPE) (ExxonMobil, 2015)

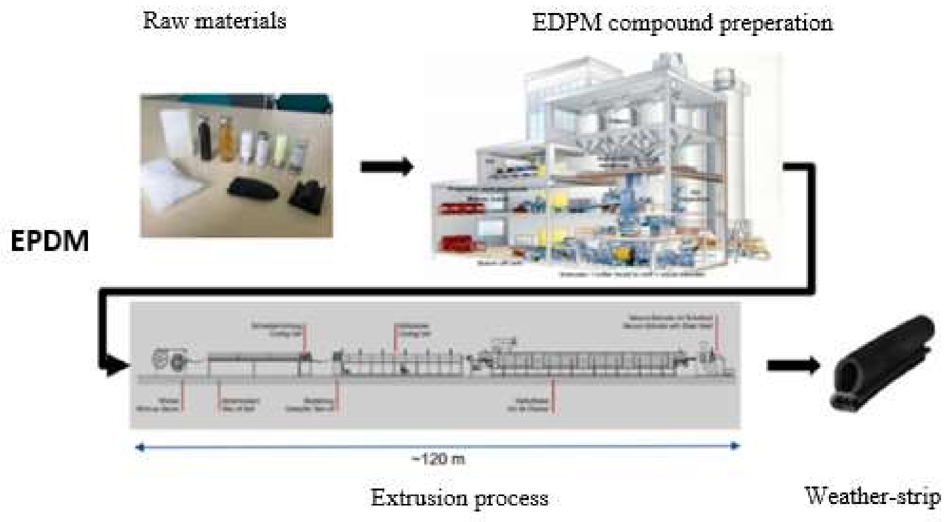

Figure 3 Weather-strip production with EPDM based rubber compound (ExxonMobil, 2015)

After the extrusion process, the sealing profiles, which have different geometries, are cut and, bonded with each other or any other material using injection molding to obtain a final shape based on the position of the vehicle body.

The properties and quality of a weather-strip is determined by its functional performance, resistance to weather, UV, ozone, and aging conditions, and aesthetic performance. The requirements differ according to the application area and part design. That's why design capability, process capability, material selection, and testing competencies are critical to meet different customers' expectations. In the production of weather-strips, EPDM-based thermoset rubbers are widely preferred thanks to their high resistance against ozone and severe atmospheric conditions, high elasticity, and a wide range of hardness. However, TPE materials also have numerous advantages over thermoset rubbers, including easy processing, short cycle times, and recyclability. EPDM scraps, on the other hand, are waste and cannot be recycled during and after the process shown in Figure 4 (Standard Profil, 2021, ExxonMobil, 2015).

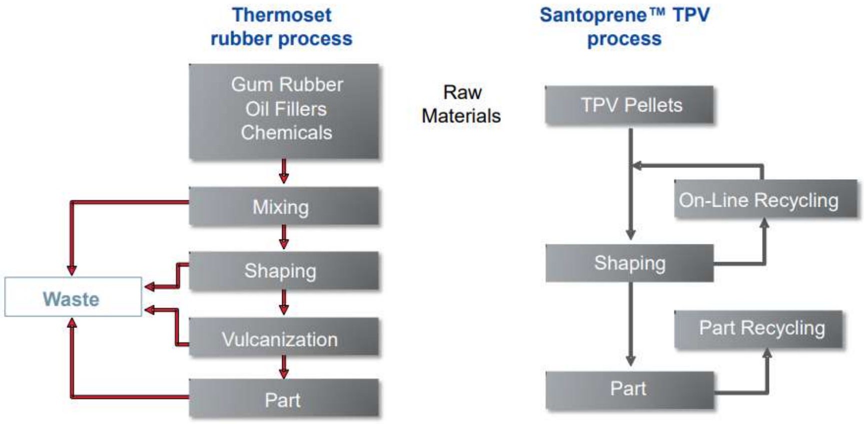

Figure 4 Comparison of EPDM and TPE extrusion processes in weather-strip production TPV is a kind of TPE, Santoprene: one of TPV brand

1.2. EPDM based Rubber Compound

EPDM-based rubber compound is the main elastomer used in automotive sealing applications due to its advantageous properties such as excellent resistance to ozone, thermal and weather aging performance with its saturated polymer backbone structure and wide hardness range. They exhibit high elastic properties under compression, good dynamic fatigue resistance, and excellent abrasion resistance (Mao et al., 2008). It provides a cheap compounding feature due to its high filler and processing oil capability and low density (Karaağaç et al., 2013).

Of the world's rubber consumption, EPDM is the fastest growing elastomer among synthetic rubbers. It was introduced in the USA in 1963 (Sutanto et al., 2006). Non-tire rubber products in the vehicle, namely weather-strips, hoses, vibration insulators, and miscellaneous parts, are mainly composed of EPDM.

EPDM-based compound rubber used in weather-strips includes EPDM polymer matrix, mineral oil, white fillers, carbon black, antioxidants, various accelerators and process aids. Based on the application and demand of the profile, the compound design is developed and the required material properties are obtained with the adjusted formulation.

1.3. Thermoplastic Elastomer (TPE)

1.3.1. History

In the 1960s, research on thermoplastic elastomers (TPE) was initiated, and the first TPE was introduced with the commercialization of polyurethane thermoplastic elastomers (TPE-U) by B.F. Goodrich, Mobay, and Upjohn in the USA and by Bayer A.G. and Elastogran in Europe.

In 1966, Shell marketed the first styrene-diene block copolymers as Kraton, which is an anionic block copolymerization of styrene with butadiene (S-B-S) and styrene with isoprene (S-I-S). In 1972, Shell developed it by adding S-EB-S copolymer (TPE-S) and commercialized it as Kraton G, which is produced via hydrogenation of the polybutadiene center block that eliminates the double bonds and improves oxidation and ozone resistance.

In 1960, thermoplastic polyolefin blends (TPOs) were developed and the first patent was recorded for EPM and a more than 50% polypropylene blend. In 1974, partially dynamically vulcanized EPM or EPDM (ethylene propylene diene monomer rubber) by using peroxide curing and polypropylene blends was patented.

In the 1970s and 1980s, extensive research was carried out on Thermoplastic Vulcanizates (TPVs), which are mechanically mixed combinations of an elastomer and a thermoplastic by Monsento Company. Santoprene, a blend of EPDM and PP, was the first commercial brand, released in 1981. Geolast is a blend of NBR and PP released in 1985. Then, different types of thermoplastic elastomers were introduced and developed. During the 1990s and 2000s, many companies developed new products. Thermoplastic elastomers have improved, such as functionalized styrenic TPEs, thermoplastic fluoroelastomers, improved TPVs, and so on (Drobny, 2007).

1.3.2. Definition

Thermoplastic elastomers (TPE) are a type of polymeric material or blend that integrates thermoplasticity with rubber-like characteristics. They may be melt processed as thermoplastic polymers with typical plastic processing methods, including injection molding, blow molding, and extrusion, but they develop their ultimate rubber-like features immediately after cooling. (Sengers, 2005; Segupta, 2004).

The two-phase structure of materials provides superior properties: the soft phase, an elastomer, gives elasticity and flexibility, while the hard phase, a thermoplastic polymer, which is semi-cyristalline or has a high glass transition temperature (Tg), gives strength to the material and represents the physical crosslinking for the elastomer part (Sengers,2005).

Thermoplastic elastomers have thermoreversible networks, and these physical cross-links are not permanent in general and may disappear with swelling or temperature rise (Drobny, 2007). On the other hand, the cross-links of thermoset rubbers are chemical. This occurs by a slow, irreversible curing process, and once the rubber has been cured, it cannot reproduce anymore (Drobny, 2007; Sengers, 2005). Moreover, in termoplastic elastomers, the transition from a processible melt to a solid rubber-like characteristic is rapid, reversible, and occurs during the cooling phase (Holden, 1987).

A shematic representation of the thermoplastic elastomer group in polymers is given in Figure 5.

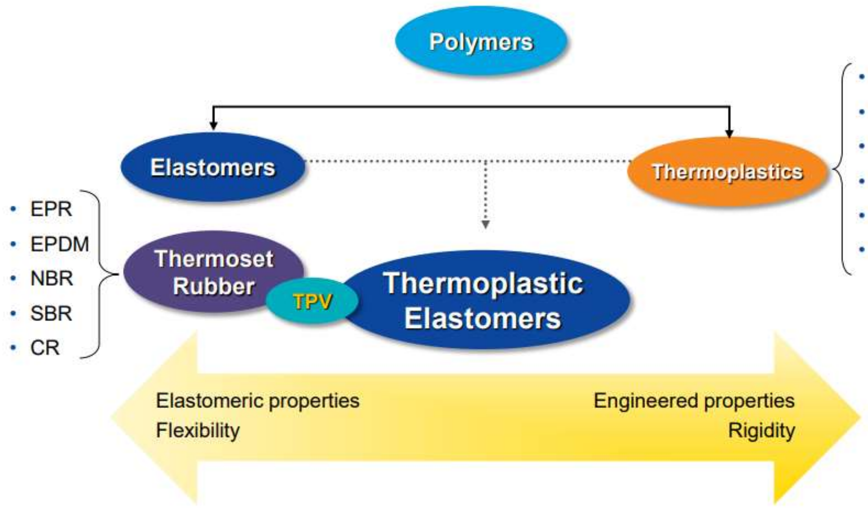

Figure 5 Polymer overview (ExxonMobil, 2015)

Since most thermoplastic elastomers have two separate systems, each phase constitutes their major properties and shows their specific glass transition temperature (Tg) or crystalline melting temperature (Tm). These temperatures give the points at which the physical properties of the elastomer transition and define the material service range of the material (Holden, 1987; Drobny, 2007). The flexural modulus of thermoplastic elastomer over these wide range of temperatures is illustrated in Figure 6 (Drobny, 2007). As it is seen, the lower service temperature, which is below the Tg of the soft rubber phase, the polymer becomes stiff and brittle. Above the upper service temperature, which is higher than the Tm of the hard thermoplastic phase, the polymer softens or melts and becomes a viscous fluid (Holden, 1987; Drobny, 2007).

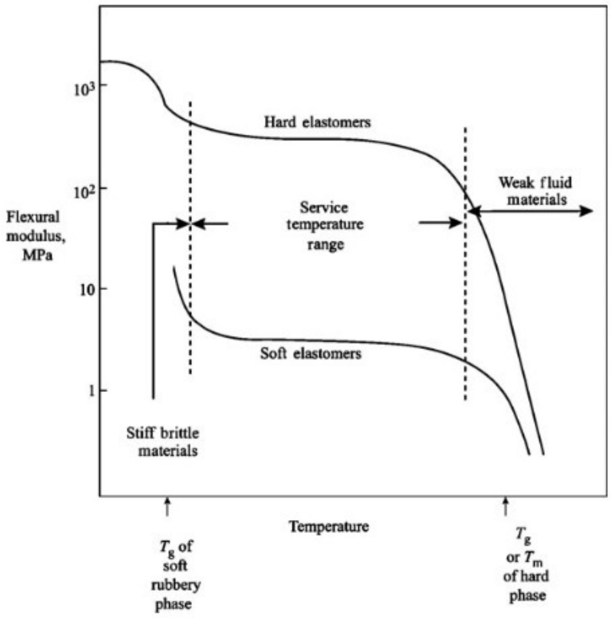

Figure 6 Stiffness of TPEs at different temperatures (Drobny, 2007)

1.3.3. Classification

In TPE classification part, different TPE types are illustrated in a schematic representation. The properties of the most commonly used TPEs in sealing systems are compared to those of each other and thermoset rubber. Since the study was conducted with styrenic-based thermoplastic elastomer (TPS) material (SEBS/PP blend), it is more detailed. Other types of TPE materials are kept out of the study. TPE can be categorized depending on the connection between the soft and the hard phases as polymer-elastomer blends, block copolymers, or ionomers. Figure 7 depicts the TPE classification of polymer-elastomer blends and block copolymers (Sengers, 2005).

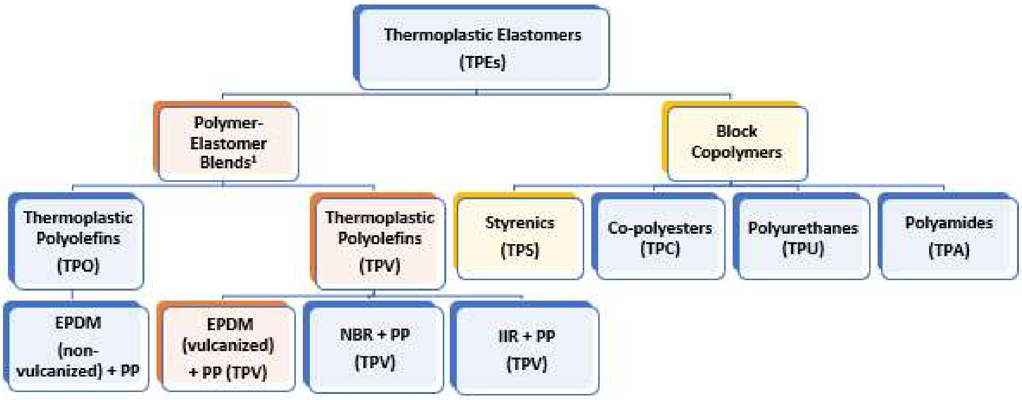

Figure 7 Thermoplastic elastomers classification (ExxonMobil, 2015)

In automotive sealing system production, polymer elastomer blends are preferred, which are indicated with different colors in Figure 7. Vulcanized EPDM based TPV materials are the most widely preferred types. In addition to TPV, block copolymer TPS is used mostly as a blend of SEBS and PP, since SEBS is never utilized as a pure material (Segupta, 2004).

In Table 1, the glass transition and crystalline melt temperatures of TPEs generally used in sealing profiles are listed.

Table 1 Glass transition and crystalline melt temperatures of some TPEs

TPE Type	**Soft, Rubbery Phase, Tg, °C**	**Hard Phase, Tg or Tm,°C**
S-EB-S + PP (TPS)	-55	95 (Tg) and 165 (Tm)
EPDM + PP (TPV)	-60	165 (Tm)

Polymer-elastomer blends can be produced by melt mixing of an elastomer with a thermoplastic polymer. Two structures are obtained by the lack of miscibility of the polymer and elastomer (Drobny, 2007). In the thermoplastic phase, polyolefins, in particular polypropylene (PP) and polyethylene (PE), are by far the most commonly used. However, other thermoplastics can also be used to prepare TPV and TPS blends. The general ingredients are listed in Table 2. All of the ingredients are compounded by using a twin-screw extruder.

Table 2 Comparison of TPV and TPS blends (ExxonMobil, 2015)

Type	**TPV**	**TPS Blends**
Elastomer Phase	EPDM,NBR,IIR..	SBS,SEBS,SEPS
Thermoplastic Phase	PP	PP
Oil	includes	includes

Filler	includes	includes
X-linking system	includes	-
Others	Additives to target spesific properties like color,gloss..	
Antioxidants	-	includes

In Table 3, the main properties of thermoset EPDM based rubber compound and thermoplastic elastomer TPV and TPS blends which are prefered for weather-strip production are compared. As it is seen, EPDM rubber is produced through chemical reaction and cannot be re-processed after the vulcanization process. But, it has excellent compression set, weathering, ozone, and aging resistance that are critical for weather-strips. TPV and TPS materials are produced through a physical blend. Despite performance differences due to material formulation and manufacturer, they can be good competitors for automotive sealing applications.

Table 3 Comparison of EPDM rubber, TPV and TPS blend (ExxonMobil, 2015; MCPP, 2019)

	EPDM/Rubber	TPV (EPDM) fully cured	TPS Blends (SEBS/PP)
Composition	chemical blends; creates chemical bonds make the rubber non-reprocessable	two phases: dynamically vulcanized EPDM in continuous PP thermoplastics phase	physical blend of PP, SBC, OIL and filler
Recyclability	No	Yes	Yes
Density	~1.2	0.89 - 0.98	0.90 - 1.2
Typical Hardness, Shore	40A-90A	35A-50D	5A-55D
Typical Service Temperature, °C	-40/+135	-60/+135	-50/+110
Processability	Poor	Good	Good
Compression Set	Excellent	Good	Good

1.3.3.1. Styrenic Based TPE / TPS (SEBS/ PP Blend)

Styrenic based TPE (TPS) is classified into block copolymer types of TPE materials, which have two types of monomers in the same polymer chain (Figure 8.) SEBS (polystyrene-block-polyethylene-co-butene-block-polystyrene) blends is a triblock copolymer with an elastomeric block of poly (ethylene-co-butylene) (EB) between two polystyrene (PS) end-blocks. The PS end-blocks are the hard phase of the polymer, acting as physical cross-links for the EB elastomeric phase (Holden, G., 2009). Although SEBS is already a TPE itself, it is never used as pure due to its hard processability and high cost for the final product (Drobny, 2007).

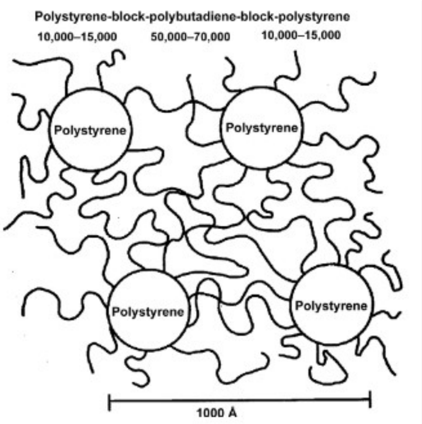

Figure 8 Schematic of a styrene butadiene styrene block copolymer (Drobny, 2007)

The saturated backbone in SEBS is the increased temperature and UV stability of the polymer. They are designed to meet the required processing behavior as well as the required mechanical and physical properties. They can be blended with other polymers and compounded with fillers, plasticizers (e.g., oils), processing aids, resins, colorants, and other compounding ingredients (Drobny, 2007). Generally, this blend is prepared with mostly PP material to improve the properties of compounds. Polypropylene gives the compound better processability as SEBS has a higher melt viscosity, which makes it difficult to process. When the compounds are processed under high shear and then quickly cooled, the polypropylene and the SEBS/oil mixture form two co-continuous phases as shown in Figure 9. The continuous polypropylene phase significantly improves both the solvent resistance and the upper service temperature of these compounds since they are insoluble at ambient temperature and have a relatively high crystalline melting point of about 165 °C (Sengupta, 2004).

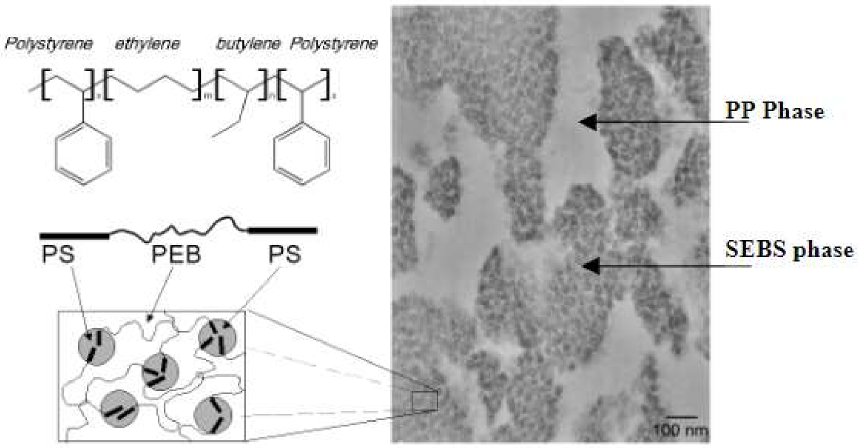

Figure 9 Morphology of TPS blends (SEBS/PP) (Sengers, 2005)

In Table 4, ingredients inside the TPS blends and their effects on the formulation are listed. As it is seen, oils in the formulation reduce the UV resistance while improving the processability and cost reduction. It is critical to get well-mixed and compounded materials to sustain the material's durability performance in the long term. Polypropylene increases the material hardness and gives the material strength while also functioning as a physical crosslink for the elastomer. It provides resistance to high temperatures and ozone and decreases the material cost.

Table 4 Ingredients Effects on TPE-S (SEBS/PP blend) (Drobny, 2007; Walker, BM.,1988)

Ingredients	Oils	PS[1]	PE[2]	PP[3]	EVA	Fillers
Hardness	decreases	increases	increases	increases	increases slightly	increases slightly
Processability	improves	improves	variable	variable	variable	variable
Ozone Resistance	no change	increases slightly	increases	increases	increases	no change
Cost	decreases	decreases	decreases	decreases	decreases	decreases
Others	decreases UV resist.	-	often satin finish	improves high-temp. properties	-	often improves high-temp. properties

[1]: Polystyrene, [2]: Polyethylene, [3]: Polypropylene

1.4. Bonding Mechanism

By ASTM, adhesion is described as the state in which two surfaces are held together by interfacial forces that may be valence forces, interlocking forces, or both (Islam, 2008). This means that two adhered materials have interfacial intermolecular interactions in the contacting area. If the forces existed between molecules and atoms, adhesion would be interpreted with theirs effects at the surfaces and within the interphases (Pocius, 2012). To adhere two materials, it is necessary to generate adhesion forces across the interface, whose magnitude and nature are important. Surface tension is a direct measure of interatomic and intermolecular forces. It is difficult to describe adhesion in simple terms as it is a multi-disciplinary topic, which includes surface chemistry, rheology, polymer chemistry, physics, mechanics of materials, and fracture analysis (Baldan, 2012; Qin and Schreiber, 1999).

Adhesion mechanisms at the interface are explained with different models in the literature: (i) mechanical interlocking, (ii) adsorption theory, (iii) diffusion theory, (iv) electronic theory or electrostatic theory, (v) chemical bonding theory (Baldan, 2012; Maeva et.al.,2004; Van Leeden, 2002; Fourche, 1995; Yang et.al., 2021). Some of the related bonding models/theories are explained briefly as follows;

Mechanical Interlocking: One of the earliest adhesion theories was introduced in 1925. This theory proposes that the main reason for the adhesion is the mechanical keying of the material due to the irregularities of the adhered surface (Figure 10). That’s why the substrate surface roughness, porosity, and wettability are critical factors to obtaining sufficient adhesion. This macroscopic level mechanical (physical) interlocking adhesion occurred when the polymer melt flows into the irregularities of the substance. After the materials solidify, a mechanical locking is generated (Baldan, 2012; Bex et.al., 2018).

Figure 10 Mechanical interlocking between two substrates with surface irregularities (Awaja et.al, 2009; Van Leeden, 2002)

Absorption theory: The most accepted one is the absorption theory, which states that the bonding of the materials occurs because of established intermolecular interatomic forces at the interface after contact. This theory, which is also named as the thermodynamic theory, includes wettability, rheological, and chemical adhesion models that are, however, sometimes considered different models (Baldan, 2012; Sharpe and Schonhorn, 1964; Yang et.al, 2021). The forces between the materials are can be as follows;

- Primary bonds such as covalent, ionic and metallic bonds
- Donor-acceptor interactions
- Secondary bonds such as van der Waals force, Hydrogen bonds (Baldan, 2012, Maeva et.al.,2004, Yang et.al, 2021);

Diffusion theory: The theory explains the adhesion between two polymer materials, generated by the interdiffusion of the macromolecules as shown in Figure 11 (Baldan, 2012; Yang et.al, 2021). For this theory, both materials must be polymers that are miscible and compatible with each other (Grundmeier and Stratmann, 2005).

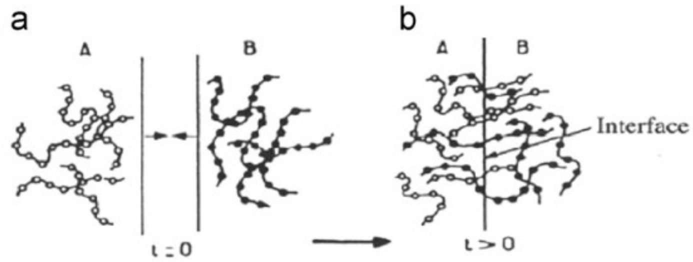

Figure 11 Diffusion theory of adhesion (Fourche, 1995)

The bonding of two polymers is a complex phenomenon where the material pairs come together under a specified temperature and pressure, and then the molecules begin to diffuse from one side at the interface and bond after a period of time. When two different polymers interact at the interface, the degree of bonding is obtained by the entanglement between the molecules at the interface (Islam et.al., 2010).

In a TPE and thermoplastic adhesion process (Figure 12), the TPE material melt transmits heat to the cool thermoplastic and increases the polymer mobility (softening/melting). With the help of shear force and injection process conditions, TPE polymer chains diffuse into the substrate interphase and mix and entangle with its molecules (diffusion and entanglement). Then, the interface cools down and solidifies to fix the morphology and generate a strong adhesion (solidification) (Teknor Apex, 2021). A higher degree of entanglement means a stronger interface in the solid state (Six et al., 2019).

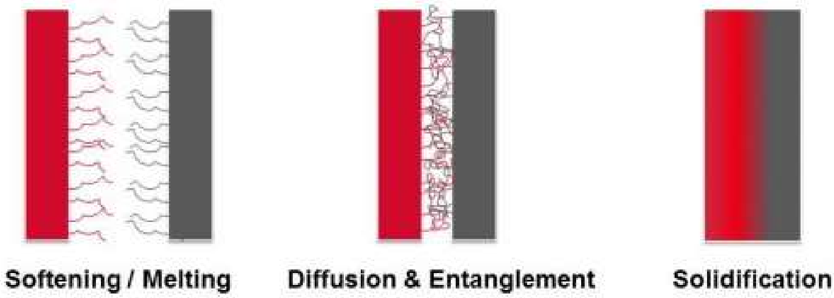

Figure 12 Diffusion mechanism for a TPE-thermoplastic material adhesion (Teknor Apex, 2021)

For each bonding mechanisms, intimate contact between the materials are essential (Bex et.al., 2018). This is only achieved if good wetting features obtained between the polymer melt and rubber substrate in EPDM-TPE material bonding. In addition, EPDM samples used in this study were cut and prepared by the same researcher with the same tool during the experiment. Because it is important to diminish the surface roughness deviation as much as possible for an effective analysis. If the EPDM component has undercuts or drafts, it would be difficult to separate the two materials because of the high mechanical interlocking, and that would be misleading for parameter analysis.

A guideline has been prepared by a group of professionals established within the German Rubber Manufacturers Association (WDK) to increase the adhesion quality of the EPDM-TPE hybrid applications used in automotive weather-strips. This guide focuses on the usage of thermoplastic elastomers (TPE) in the end cap and corner molding parts of EPDM body sealing profiles. The purpose is to recommend structural design, process parameters, and testing to ensure successful manufacturing with these two materials. Some of the recommendations offered in the guideline are listed as follows (wdk, 2020):

- Design

Wall thicknesses should be between 1 and 3 mm, with a maximum of 3 mm. Extruded EPDM profile and TPE corner molding thickness differences should be minimized, and TPE injection should preferably be done on punched and cut EPDM surfaces as shown in Figure 13-A. Bonding surfaces should be increased. An option is shown in Figure 13-B. If possible, the tapered areas of the extruded profile lips should not be sharply pointed to minimize stress concentrations at the lip ends, as given in Figure 13-C. A stopper and expansions should be used in non-visible areas in the critical areas to increase surface area in Figure 13-D. Overfilling of some areas again to boost the surface area and bonding performance as shown in Figure 13-E. Injection tapes in the form of small strips and puzzle patterns in the non-visible areas could be an another option to enhance the surface area as illustrated in Figure 13-F (wdk, 2020):

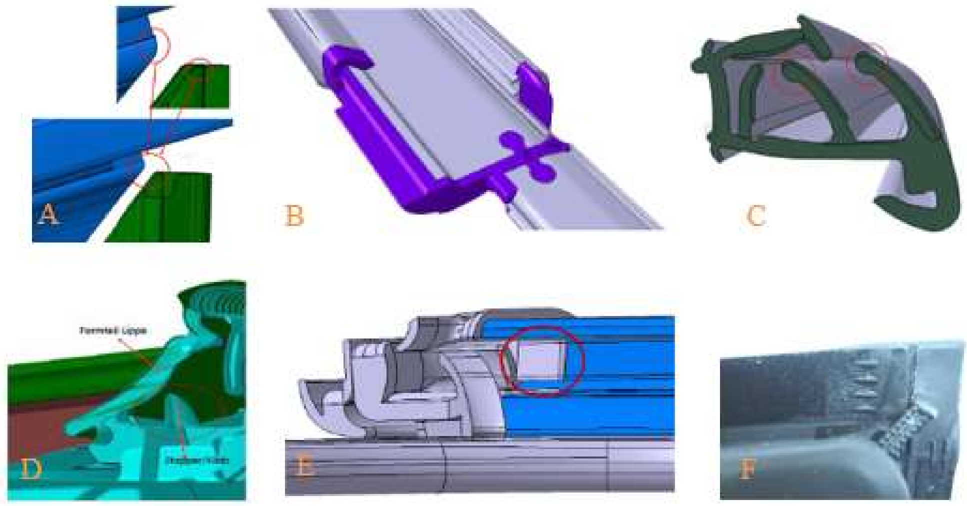

Figure 13 Some recommendations for EPDM-TPE hybrid applications in weather-strip (wdk, 2020)

A- Punching with angle trimming, B- increase mold area, C-expansion of EPDM profile lips, D-Expansions or stoppers, E-reinforcement with overfilling, F- Injection strip inserts

- Process

Extruded profiles should be manufactured within a few hours of the injection molding to avoid any contamination, passivation of the surface, and surface roughness reduction due to relaxation. Any lubricants should not be used, and trimming burrs should be eliminated, and the cross-section tolerances should be low. Generally, vertical injection molding machines are preferred in the injection molding process, and process parameters should be adjusted according to the material as recommended by its supplier. Some recommendations to avoid possible bonding problems between the EPDM profile and TPE molded part are listed as follows (wdk, 2020):

- Good ventilation: air inclusions should not be between the extruded profile and the molded part.
- Sufficient melting and mold temperatures
- A fast filling phase is preferable.

- No impurities on the connection surfaces. Lubricants should not be used to enable easier insertion of extrudates into the mold.
- Profile cutting operations should be done before processing and not exceed 24 hours to avoid contamination, blooming, etc.

For better performance of the weather-strip bonding area, some expectations from TPE materials are:

- High adhesion strength for better demolding
- High bond elongation at break for assembly
- UV – stabilized
- Easy to process, low viscosity (Allod, 2019)

1.5. Injection Molding Process

Injection molding offers higher production cycles for manufacturing with thermoplastics. As a thermoplastic elastomer can be processed like a thermoplastic, it provides advantages for automotive sealing systems (weather-strip) manufacturing, such as high production rates, easy processing, low cycles, low labor costs, and repeatable quality. In fact, the main process is extrusion molding in weather-strip production. In the finishing operations after the extrusion process, the extruded profiles/parts are cut and bonded with each other by injection molding to get the final design for a particular application. The extruded profiles and the bonding area are shown on a glass run channel example in Figure 14. From P1 to P8 profiles shown in the figure are extruded parts that have different designs and specific requirements, and they could be produced by using EPDM rubber compound or thermoplastic elastomer. From M1 to M5 areas are the injection molding parts, or corner moldings, that could also be produced by using EPDM rubber compound or thermoplastic elastomer. This thesis focuses on the bonding performances of the EPDM compound rubber extruded parts and the thermoplastic elastomer injection molding parts called hybrid applications.

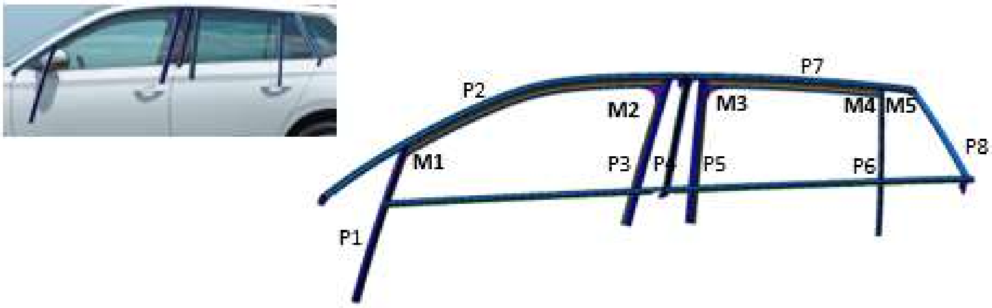

Figure 14 An example of hybrid weather-strips (Glass Run Channel)
P: EPDM extruded profile, M: TPE injection corner molding

For an EPDM extruded profile, the advantages of EPDM and TPE corner molding are listed in Table 5. As it is expected, EPDM profile and EPDM corner moldings will have a higher bonding strength than TPE corner moldings and lower shrinkage. However, choosing TPE corner moldings provides benefits for environmental protection with their recyclability and weight reduction advantages. They also have shorter cycle times. Some auxiliary materials may deteriorate during the EPDM corner molding process since EPDM requires vulcanization at high temperatures. This is not a risk for the TPE injection molding processes, which are performed at lower mold temperatures.

Table 5 Advantages of EPDM and TPE corner moldings for EPDM extruded profiles (Allod, 2019)

EPDM corner molding	TPE corner molding
high mechanical strength	increase recycable material usage
use of isopropanol as a lubricant for part insertion is not critical	no burning of the flock (an auxiliary material used in profile)
less shrinkage	fast cycle times

Injection molding is a widely used manufacturing process for thermoplastic and thermoset polymers. For a successful process, the parts to be produced must be designed carefully, the injection mold must be well designed taking into account the material and process considerations, and the injection molding machine properties must be considered (Lal and Vasudevan, 2013). For good processing with injection molding, the melt distribution, injection gate, venting, and demolding also need special attention (Allod, 2019).

An injection molding machine (Figure 15) includes a clamping side and an injection side. The clamping side provides the ability to open and close the mold and eject the products. On the injection side, TPE material melts at a specified heat and transfers the material into a mold. During the process, the molten material accumulates in front of the screw while the screw rotates at a specified speed (rpm). After molten material is introduced into the mold, the injection machine controls the screw ram speed, injection speed, or injection pressure (Elastron, 2021). The injection pressure is a complex function of melt, mold, and injection speed since it varies across the cavities and feeding (Drobny, 2007). In this study, the injection pressure is adjusted to the maximum that the machine allows, and the injection speed is selected as variable. Injection pressure is recorded for each run during the experiments.

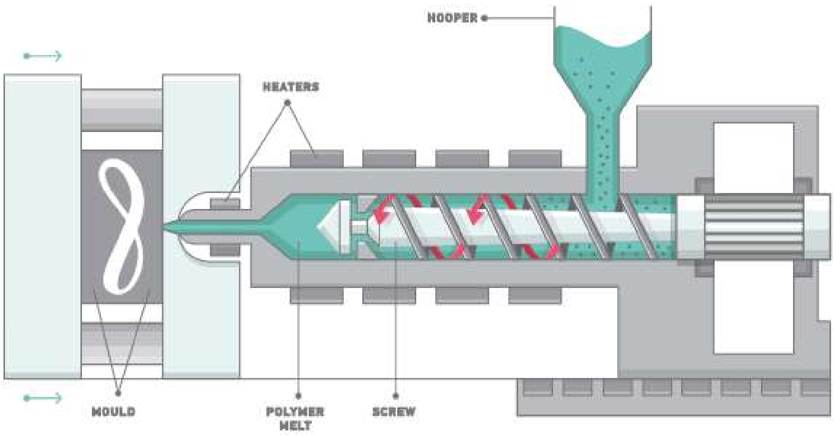

Figure 15 A vertical injection molding machine (Elastron, 2021)

An injection molding cycle is illustrated in Figure 16. In the filling phase of the process, the molten material must be filled into the mold as fast as possible. As the flow characteristic of the material depends on the melt temperature, speed, and shear rate, proper adjustment is critical to avoid possible quality problems. Melt temperature must be set according to the material's technical data sheet to avoid degrading during the process. In the packing phase, as the material gets into the cavity, it starts to cool, causing shrinkage. Material is injected to eliminate the shrinkage, and injection speed and pressure decrease in this phase. In the holding phase, a certain amount of pressure is applied until the gate completely freezes off. New material entry should be avoided into the mold in the cooling phase. At a stable mold temperature with a well-designed cooling system, the part is solidified (Elastron, 2021).

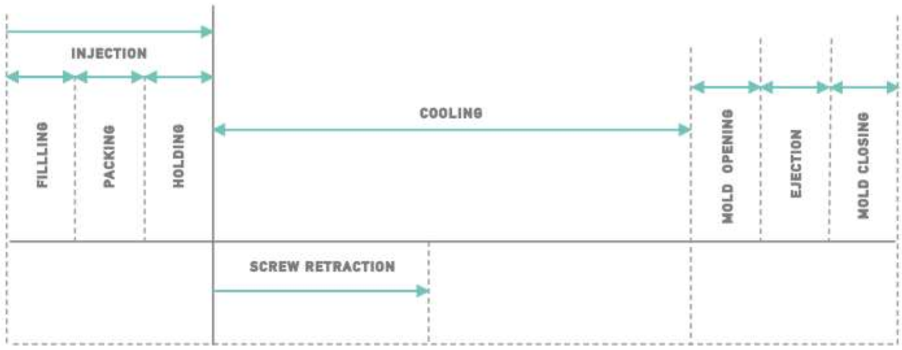

Figure 16 Injection molding cycle (Elastron, 2021)

Some recommendations for injection molding of TPE materials by MCPP Company, which is one of the TPE producers preferred in automotive sealing system production are given:

- Mold temperature: 20°C- 50°C for usual, 40°C- 80°C for visible parts
- Holding time: It can be adjusted between 4 and 15 seconds, and increasing holding time rather than holding pressure should be preferred to resolve visual issues (MCPP, 2019).
- Injection temperatures: It differs from the TPE material type and requires adjustment according to the material data sheet so as not to degrade the material during the process.

1.6. Design on Experiment

Design of Experiments (DOE) is a statistical methodology that provides cost and time effective planning, execution of experiments, and analysis and evaluation of results. It can be used for process and system development, improvement, and optimization (Durakovic, 2017).

Ronald A. Fisher's agricultural research in the 1920s was the start of this methodology. Thanks to this approach, he decreases the number of experiments required to determine the significant effects and allows for the study and evaluation of a large number of variables more economically (Dowlatshahi, 2003). Then many researchers worked on this approach and added different methods. DOE was widely used as a research method in the late 1960s and 1970s. In the 1990s and later, it has sharply increased with software development in different scientific areas (Durakovic, 2017).

The main approach in DOE is that statical analyses of the scientific experiments are performed in a systematic way to find out the input variables (Xs) and investigate their impacts on the response variable (Y). It can be applied to a system, product, or process (Durakovic, 2017). It is also used for physical processes and computer simulation models (Durakovic, 2017; Garud et. al., 2017).

An example of the process or system for design an experiment study is represented in Figure 17. We usually draw the process to find out a combination of each input parameter, including noise (uncontrollable) factors such as environmental effects and outputs that can have more observable responses. The inputs and outputs can be quantitative (colored blue in Figure 17) or qualitative.

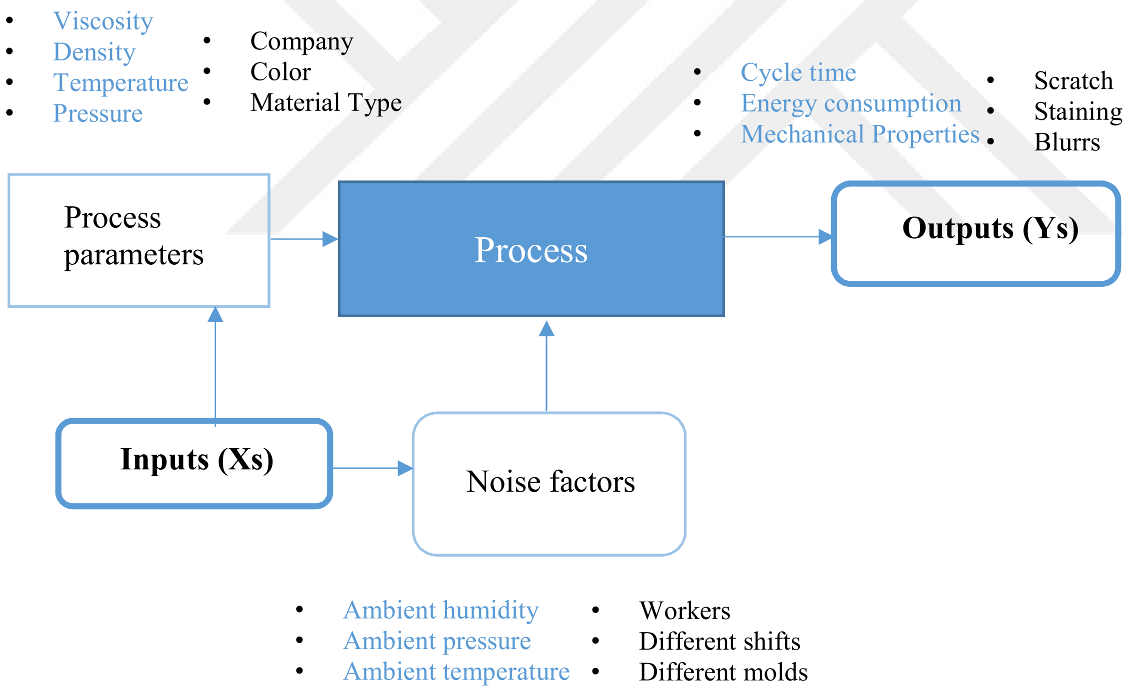

Figure 17 An example flowchart for design of experiment study (SPAC, 2021)

Steps and guidelines for planning and performing DOE are given as below:

- Identify the problem/requirement.
- Identify the response variable — a measurable output.
- Select the factors and levels — a fishbone diagram can be used to identify all the factors and choose those that will be studied. Additionally, the

number of replications is determined. That means how many times the design matrix is repeated.

- Identify the experiment design matrix — plan of the experiments, number of test determinations. A screening design including extra variables may be useful to obtain significant ones. The steps given in Figure 18 could be followed to choose a convenient design.
- Perform the experiment in accordance with the design matrix.
- Statistical analysis using suitable software such as Minitab, Design-Expert, SPSS, etc.
- Validation of the findings (Durakovic, 2017).

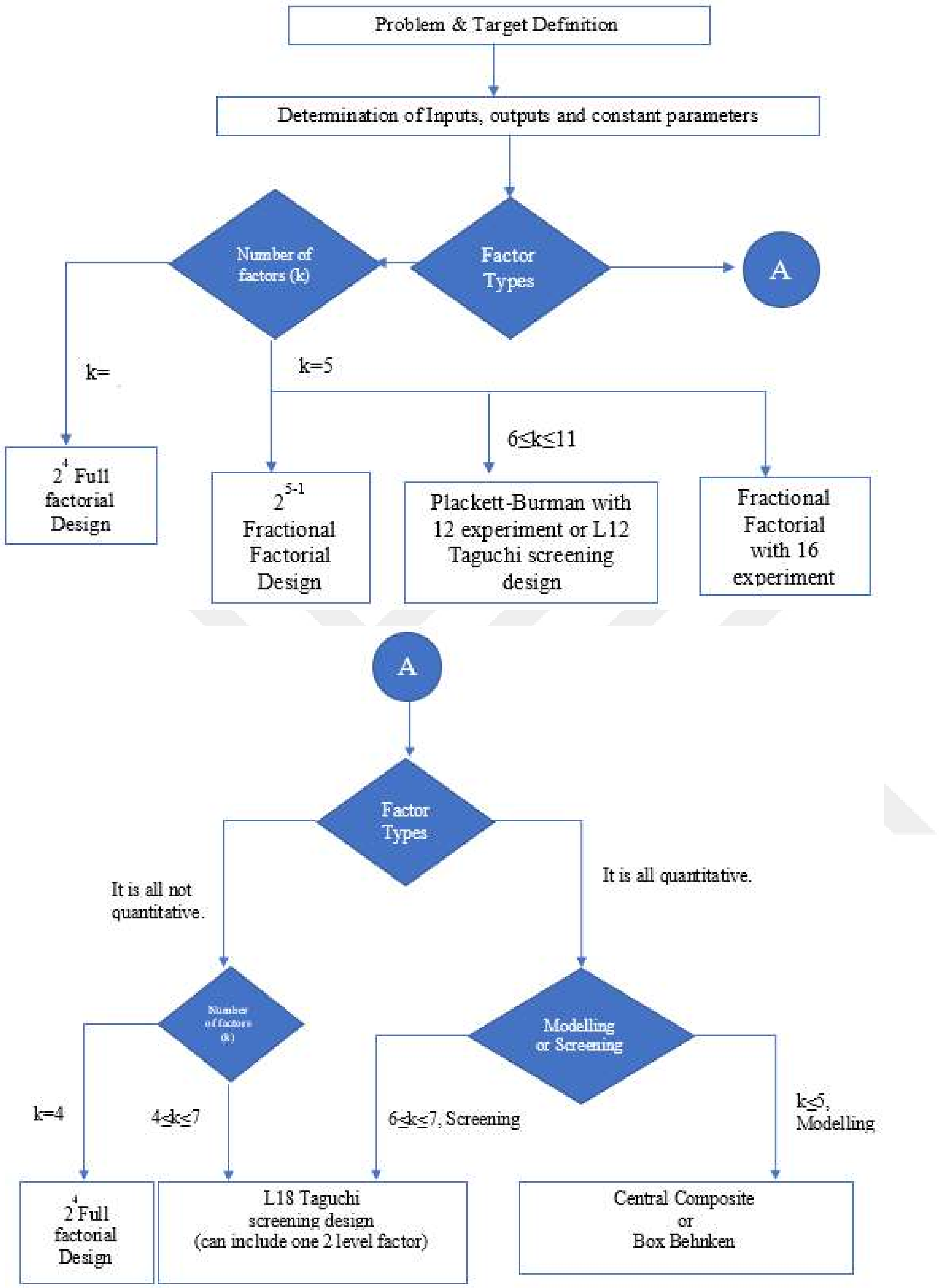

Figure 18 Selection of design of experiment plan (SPAC, 2021)

In factorial designs, one, two, or more factors can be investigated. Experiments with one factor are often analysed using a t-test or ANOVA (Durakovic, 2017). The number of experiments might be too high with multiple factors (A, B,...K) with two levels, which can be fractional designed as Full

Factorial Design 2^k or Fractional Factorial Design 2^{k-p}. Three or four center points can be added as a zero-level in which all variables are adjusted at their midvalue. The advantages of center points are listed as follows:

- reduction the probability of missing non-linear relationships in the intervals' middle.
- Determination of the confidence intervals with the help of repetition (Lundstedt et al.,1998).

A full factorial design can be selected if the number of factors is low and resources are available. The design of an experiment (DOE) is planned with 2^k, in which 2 represents the number of levels and k represents the number of factors. This means each factor has two levels ("low" and "high"). For instance, the number of combinations for 2 variables is 2^2, while for 3 variables it is 2^3, and so on (Lundstedt et al., 1998).

A fractional factorial design can be selected if the number of factors is increased and sources are limited. It is considered in a fractional factorial design that usually only a low number of main effects and lower-order interactions are effective. Higher order interactions are considered as not significant for the response. It is designed with 2^{k-1}, where 2 denotes the number of levels and $^{k-1}$ denotes the number of factors. For instance, with 3 variables, it is 2^{3-1}= 4 treatment combinations, and so on (Lundstedt et al.,1998).

2. LITERATURE SURVEY

Many studies have been performed on the bonding performances of different materials and the relationships between process parameters and bonding strengths, but the majority of these studies have focused on thermoplastics to thermoplastics or thermoplastics to thermoset materials produced by using mostly 2K injection molding. Such research often includes an empirical design of experiments toward optimal processing parameters for a certain material combination. Furthermore, many researchers investigated injection processes using design of experiments methods in order to understand the relationship with some quality problems such as shrinkage, warphage, and so on.

Bex et al. have many publications on two-component injection molding of thermoplastics with thermoset rubber. They worked with EPDM-HDPE and NBR-ABS material pairs and showed the influence of 2K injection molding process parameters on the adhesive strength with the help of a design of experiment method. Their factors were mold temperature at the interface, injection speed and temperature, holding pressure, and initial roughness of the thermoplastic part. According to the research, the mold temperature at the interface is the most influential parameter, as demonstrated in this thesis. And they found that the holding pressure only has importance when it is too low or there is insufficient holding time. Other parameters have no significant influence (Bex et al.,2018).

Another study by Six. et al. suggests that increasing the mold temperature at the interface of thermoset rubber and thermoplast increases bonding strength. They vulcanized the rubber part first in a 2K injection molding, then bonded with a termoplastic. When they increased the molding temperature for better cycle times, they found that the adhesion strength decreased at a specific temperature due to gas bubbles at the interface that occurred during the vulcanization process (Six et al., 2019). In this thesis, vulcanized EPDM rubber is bonded with thermoplastic elastomer, which is inserted into the mold at the ambient temperature. That’s why this could not be taken as a risk for the mold temperature parameter.

Bex G. et al. worked also on the compability of thermoplastic/thermoset rubber used in two-component injection molding with wetting measurements and reported that at high temperatures, EPDM rubber is best wetted by polypropylene and polyethylene, while nitrile rubber by polycarbonate. They demonstrated that it was only possible to achieve physical bonding between the EPDM rubber and PP or PE and between NBR and PC (Bex et al., 2017).

There are also studies with various types of thermoplastics and elastomers that have been carried out to determine the adhesive strength as a function of process conditions. For instance, A. Islam et al. examined bonding in overmolding for 16 material combinations in their studies and investigated some process parameters in molded interconnect devices (MIDs) on polymer-polymer bonding performances, which are melt and mold temperature, injection speed, injection pressure, holding pressure, holding time, and cooling time. This study was performed on acrylonitrile butadiene styrene (ABS) in combination with polycarbonate (PC). It was found that the injection and mold temperature are vital factors influencing the bonding strength in two-shot molded parts. They needed to be set high enough to allow the melting of two materials together. Other parameters such as injection speed, pressure, and holding pressure had smaller effects on the bond strength. Holding and cooling time have no positive effect on the bonding, but have a negative effect when set to an insufficient value. Additionally, interfacial roughness has a dramatic effect on the adhesion since it promotes the mechanical interlocking of the melt into the interface (Islam et al., 2010).

Verma G. submitted a master's thesis on the bond strength of thermoplastic elastomers to various co-extruded thermoplastics. He focused on determining the compability of the different samples and proposing a unique method for estimating the compability and bonding strength of them. He indicated that it is significantly related to the compability of the materials and the similarity of their molecular structures and polarities. When the bonding strengths increase with the increased compability, the impact strength also increases (Verma, 1996).

M.R. Persson et al. were able to analyze the adhesion between polyamide-12 with 0 to 50 wt% glass fibers (PA12-GF) and TPE modified for adhesion to polyamides. It was reported that bonding increased with increasing TPE injection speed and melt temperatures, while it decreased with increasing glass fiber fraction in the PA12-GF. However, it was not directly related to the glass fiber fraction present in the interface. They reported that it seemed to be an influence of the PA12 (polymer) microstructure effected by fiber fraction and that the flow character of the material changed the microstructure in the skin and material interfaces (Persson et al., 2020).

Carella A.R. et al. analysed TPE polymer pairs sequentially injected into a mold in a range of mold and injected melt temperatures and packing pressure in order to find optimal bonding conditions. They also correlated the calculated interface temperature and packing pressure for bonding. They figured out that there are restrictions on melt and mold temperatures and holding pressure parameters to prevent degradation of the materials and dimensional stability. They concluded the study as first mold and melt temperatures may be selected to adjust the interface temperatures, and then the packing pressure may be found with a set of experiments. After that, the peeling tests were performed to find the optimum process parameters. These findings may be adapted for different geometries with extrapolation. Additionally, they reported that melt temperatures may be decreased with suitable combinations of mold temperature and packing pressure to avoid warpage and/or degradation (Carella et al., 2002).

Calaon M. et al. investigated the influence of packing time and pressure parameters on injection molding of polypropylene nanostructured surfaces with a combined distance from the gate. They showed that the packing pressure and the distance from the gate location have a significant impact on the PP roughness, while holding time has the minimum (Calaon et al., 2012). Those parameters that affect the surface roughness may also influence the bonding strength.

Krumal M. et al. explained the effects of the process parameters and quality of the flow pathway surface on the thermoplastic elastomer melt flow. They observed that injection pressure and rate have an influence on the flow length of TPE materials, while surface roughness of the injection mold cavity or runners is not significant (Krumal et al., 2010).

Han S.R. et al. demonstrated the relationship between injection molding process parameters and mechanical properties and shrinkage of TPE material. They investigated the melt and mold temperatures, injection and holding pressure parameters. They found that injection temperature and injection pressure affect the tensile strength and shrinkage of the TPEs. When the morphology of TPE materials is scanned by using SEM, it is seen that as melt temperature increases, the rubber particles inside the TPE get smaller and more dispersed. This increases the material's tensile strength. Additionally, they reported that all process parameters influence the material hardness (Han et al., 2006).

3. EXPERIMENTAL STUDY

In this study, the design of experiment (DOE) method is used to investigate the effects of injection molding process parameters on EPDM-TPE bonding performance, and optimum parameters (solution set) are determined to enhance the bonding performance for used EPDM-TPE pairs and mold designs. For this purpose, two types of design experiments were performed. In these studies, the experiments were conducted according to the design matrix generated for selected injection process parameters. Then the mechanical test results (tensile strength) measured on the samples of each experiment run were assessed using a statistical software to find out the relation between the parameters on the materials' bonding performance and set solutions were determined with the optimizer tool in the same software. The mechanical test results were then re-evaluated on ten samples produced with those process parameters, and the findings were validated. The optimum (set solution) process parameters determined were also used to manufacture a real weather-strip profile.

This section describes the materials and equipments used in the experiments, as well as the methods that were followed. The experimental setup and procedures, testing of the samples, and statistical analysis of the results are expressed. This section also includes the preliminary studies for the design of experiments plan and experiment design matrices.

3.1. MATERIAL

In the study, styrenic-based thermoplastic elastomer (TPE-S or SEBS-TPS) and EPDM-based rubber compound sample were used. Additionally, isopropylalcohol (IPA) was selected as a cleaning agent for the EPDM sample edges before the experiment to eliminate any kind of contamination or dust on the bonding area.

3.1.1. Styrene-Based Thermoplastic Elastomer (TPE-S)

Styrene-based thermoplastic elastomer (SEBS-TPS) is supplied by ALLOD Werkstoff GmbH & Co. KG company. It is a blend of SEBS and PP materials that has 65 Shr A hardness, high flow and good EPDM bonding characteristics. It is a preferred material in the automotive industry for these kinds of EPDM-TPE hybrid applications. The material properties are demonstrated in Table 6, and the shear viscosity curve is illustrated in Figure 19.

Table 6 TPE material properties (Allod,2021)

Property	Test Method	Unit	Value
Density	DIN EN ISO 1183-1	g/cm³	0,99-1,03
Hardness (3s)	DIN EN ISO 868	Shore A	63-73
Hardness (15s)	DIN EN ISO 868	Shore A	64-72
Tensile strength at break flow direction	DIN 53 504	N/mm²	6,4-9,4
Elongation at break flow direction	DIN 53 504	%	640-940

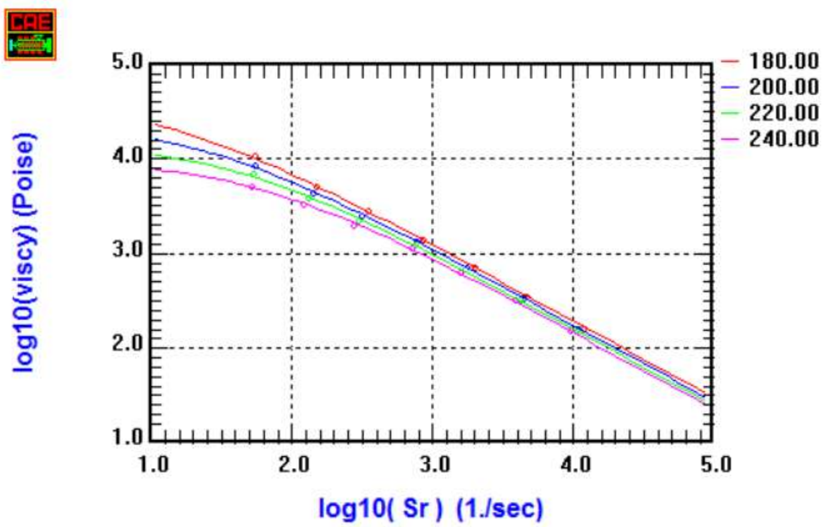

Figure 19 TPE-S material shear viscosity curve (Moldex 3D Molding Inovation, 2013)

3.1.2. EPDM based rubber compund

An EPDM-based rubber compound, named "C523" was produced in the Standard Profil Laboratory. It can be used as a lip part material for glass run channel profiles that has 65 ShrA hardness, 70±5 MU viscosity (Mooney ML (1+4) at 100 °C) and 6±5 min scorch time (Mooney Scorch (1+20) at 121°C t05).

3.2. EQUIPMENTS

This section contains the equipments and mold used to produce TPE-EPDM bonded samples in the experiments and testing phase. The EPDM compound was prepared by using a mixer. A hydraulic press was used to make the EPDM samples with a 2 mm thickness. In the experiments, a vertical injection molding machine was used to prepare the samples consisting of EPDM and TPE materials with the wdk 2701 mold. Universal mechanical test equipment was used to examine the bonding strengths of the samples in testing stage. A Scanning Electron Microscope (SEM) was used to evaluate the interface morphologies of the split areas.

3.2.1. Injection moulding machine

A vertical injection molding machine, produced by LWB Steinl Machinery, which is the provider of injection machines for elastomer and thermoplastic materials, was used during the study. It is the VC Class type shown in Figure 20, which has 38 tonnes clamping force, an RS-injection unit with a rotating and axially moving screw and a hot runner system.

The screw rotating axially to the rear allows the compound to be conveyed to the front of the screw tip during plasticizing. With the help of a servo valve, this screw movement is controlled under pressure and speed. The injection unit has self-optimizing controllers during heating and individually regulated heating strips (LWB Steinl Machinery, 2021).

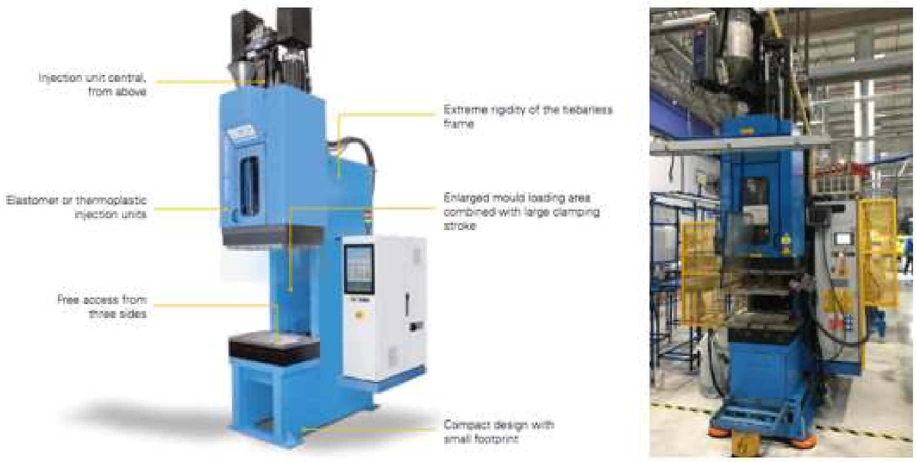

Figure 20 Injection molding machine used in the experiments

3.2.2. Injection Mold

The wdk 2701 mold design shown in Figure 21 was used in the study, which was generated to test EPDM and TPE material bonding performances by a corresponding working group under wdk (German Rubber Manufacturers Association). The mold is designed to assess the adhesion in both parallel and transverse directions of injection by taking into consideration the TPE materials' anisotropic behavior. The mold with the wdk 2701 design was also shown in Figure 22. One of the mold's entrances was closed, and just one side of the mold was used during the experiment to reduce volume differences between the two sides. As it is seen in Figure, a 100mm x 50mm x 2mm EPDM compound sample was inserted into the mold and TPE material was injected from the top of the mold, named "filmanguss". Finally, EPDM and TPE bonded samples were produced with a 2 mm x 100 mm x 150 mm dimension.

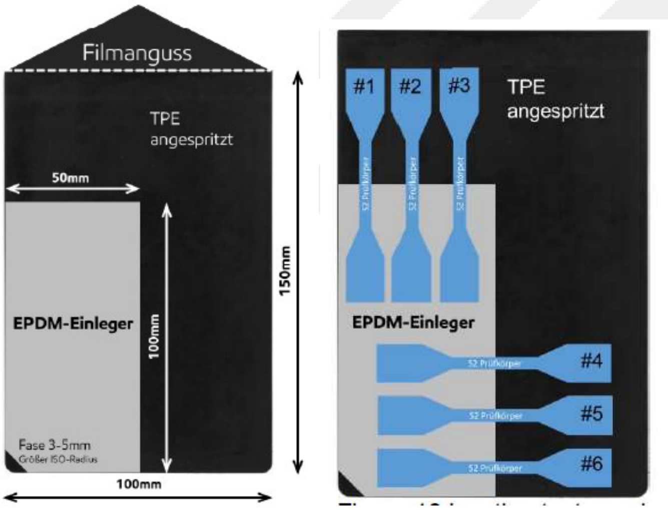

Figure 21 wdk 2701 mold design (wdk, 2021)

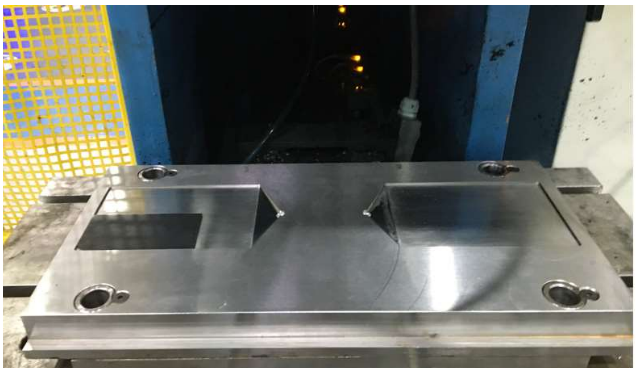

Figure 22 Injection mold used in the experiments

3.2.3. Temperature Controller

A temperature controller named with its brand, "Reguloplas", shown in Figure 23, was adapted to the injection molding machine to set and control the mold temperature. Using this device, it was attempted to keep the temperature within acceptable tolerance limits during the trials, which were defined at 5 °C. However, the mold temperature increased as it was used.

Figure 23 Temperature controller

3.2.4. Dryer

Before the experiments, TPE materials were dried at 80 °C for 4 hours by using a dryer to remove humidity that could disrupt the bonding.

3.2.5. Universal Mechanical Testing Machine

In mechanical testing to assess the bonding performance of two materials, a 10 kN Zwick Roell Universal Testing Machine was used, given in Figure 24. Specimens were cut according to ISO 37 Type S2 in the flow and across direction shown in Figure 25. Sample 1, 2 and 3 results were recorded as flow direction and samples 4, 5, and 6 were as across direction. And then the tensile strength and the elongation at break were measured.

The applied pre-load was 1N and the test speed was 200 mm/min as given in the wdk guideline. Each sample width of the bonding area was measured before the test using the Mitutoyo caliper indicated in Figure 26. The thickness of EPDM-TPE samples varied between 2-2,5 mm, and the width was 4 mm.

Figure 24 Universal mechanical testing machine

Figure 25 Two component test samples (EPDM-TPE)

A: flow direction B: across direction

Figure 26 Thickness measurement device - Caliper

3.2.6. Statistical Analysis Software

In the analysis phase, the tensile strength (MPa) and elongation at break (%) results were analyzed by using Minitab 17 which were obtained in flow direction for 1st study and flow and across directions for 2nd study. During the evaluation, the effects of the factors and their interactions on the bonding were investigated. Furthermore, the highest and lowest bonding performances were found. Optimum parameters for the materials and mold design, named as the set solution, were also defined with the optimization tool in Minitab. The relationship between the injection pressure and process parameters was also reported.

3.2.7. Scanning Electron Microscope (SEM)

Scanning Electron Microscope Analysis was carried out using the Thermo Scientific Apreo S. The analysis was performed after the second design of the experiment study. Under the miscoscope, the interfaces of the samples showing the highest and lowest bonding performances were examined. The differences between the surface morphology of the EPDM and TPE split areas were monitored.

3.3. METHOD

The design of an experimental method was used for the experiment plan since it is a productive methodology that helps save costs and time. For effective analysis, the following steps were carried out during the experiments:

- After specifically defining the scope of the study, factors were identified with a fishbone diagram. Then their levels were determined. Outputs and uncontrolled parameters were defined. *(See 3.3.1 Preliminary Investigation Section)*
- The design of experiment matrix was generated. *(See 3.3.2. Design of Experiment Plan Section for 1st and 2nd DOE Studies)*
- The experiments were performed according to design matrices and the data collection. *(See 3.4 Experimental Steps Section)*
- Mechanical testing was performed on the produced two component test samples. The factors were statically analyzed to evaluate significant and insignificant ones, process parameters' effects on the bonding test results, and optimization study for used materials and mold design.

- The process parameters found using Minitab were corrected on ten samples through a validation study.

In this thesis, two designs of experiments were studied and performed. After evaluation of the 1st DOE Study statically, it was decided to show different factors' effects on the bonding performance. That's why, the 2nd DOE Study was generated as a further investigation.

In the experimental part of the thesis, the study was planned and carried out in the order given in Figure 27.

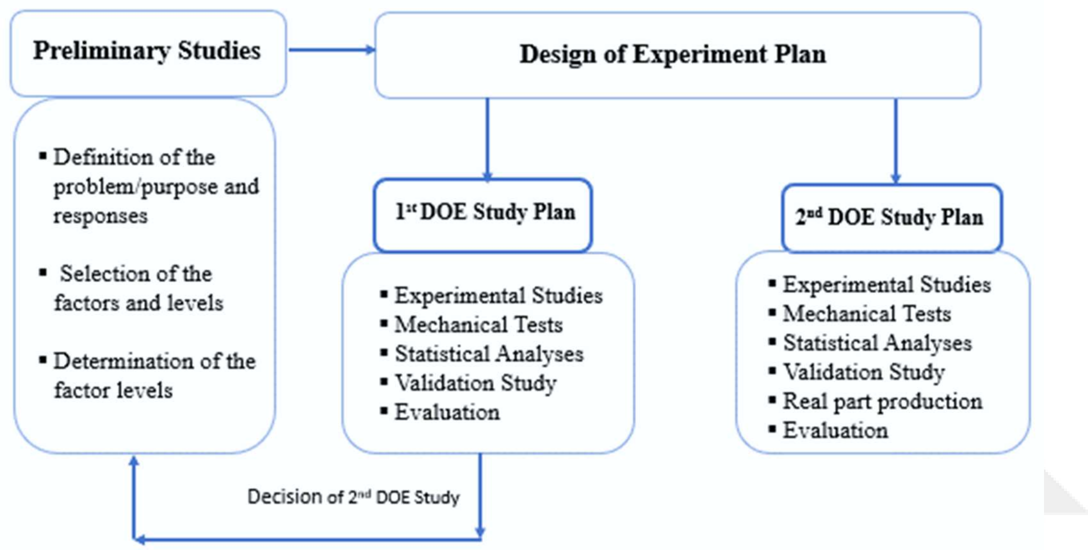

Figure 27 Flowchart of the method followed during the study

3.3.1. Preliminary Investigation

This section includes the problem/purpose definition, selection of the factors and their levels, responses (outputs), and uncontrolled parameters.

3.3.1.1. Definition of the problem/purpose and responses

The main purpose of the study was to investigate the injection molding process parameters on EPDM-TPE bonding and enhance this bonding performance. Thus, tensile strength and elongation at break were determined as responses (outputs) of the study. The main output was tensile strength, which was directly linked to the bonding of TPE and EPDM materials. Because higher bonding energy is proportional to higher tensile strength. In addition to this, higher elongation at break is also essential, as it indicates fewer breakage risks while handling the weatherseal after the process.

3.3.1.2. Selection of the factors and levels

The bonding performance of TPE and EPDM materials can be affected by a variety of parameters in the injection molding process. The Fishbone diagram in Figure 28 shows some potential factors for selecting the process parameters as variables for study.

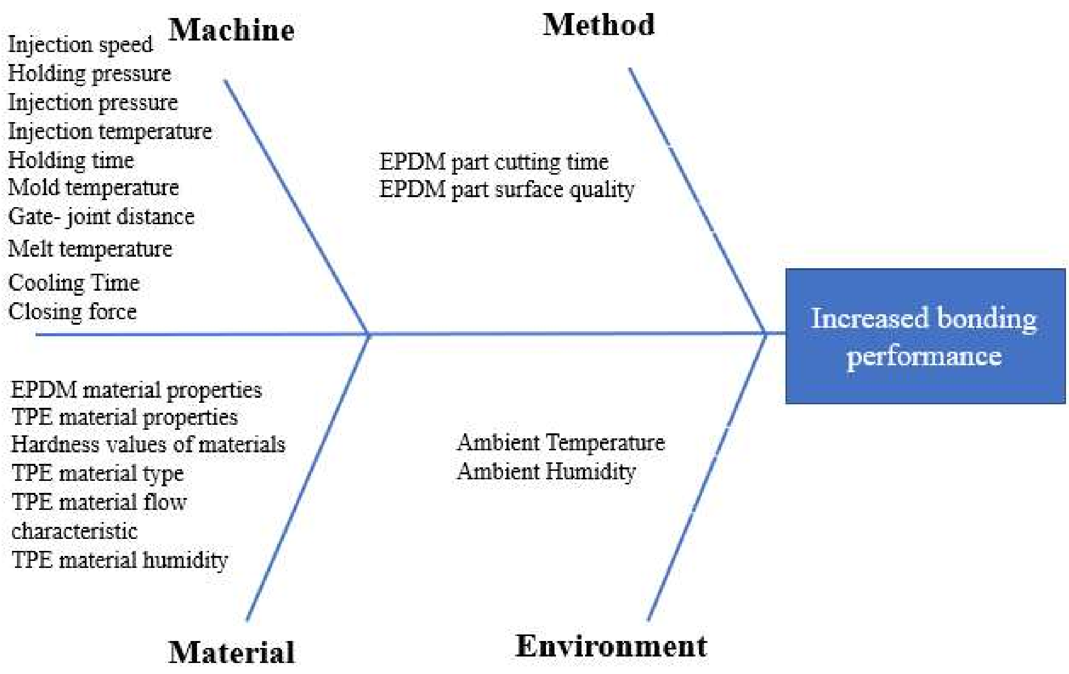

Figure 28 Fishbone diagram of potential factors on EPDM-TPE bonding performance

Seven process parameters whose highest scores were considered the main factors, such as injection speed, mold and melt temperatures, holding pressure, distance between the gate and joint, and holding and cooling time.

According to the evaluation of the fishbone diagram in Figure 28, the injection speed, injection temperature, holding pressure, holding time, mold temperature, and gate-joint distance were selected for the 1st DOE study. After this 1st screening DOE study, injection speed, injection temperature, holding pressure, cooling time, and mold temperature parameters were chosen for the 2nd DOE study as listed in Table 7.

Table 7 Selected variables for 1st and 2nd DOE study

1st DOE Study Factors		2nd DOE Study Factors	
Factor	Name	Factor	Name
A	injection speed – cm3/sec	A	injection speed – cm3/sec
B	holding pressure – bar	B	holding pressure – bar
C	gate-joint distance – mm	C	mold temperature – °C
D	mold temperature – °C	D	injection temperature – °C
E	injection temperature – °C	E	cooling time – s
F	holding time – s		

The parameters of injection speed, injection temperature, gate and joint distance, and mold temperature were selected after considering their effects on the crystallization process inside the mold, which may be linked to adhesion. Furthermore, injection speed and temperature influence the material's viscosity. It was known that holding pressure, which is the secondary pressure, and holding time are important on the shrinkage of the part and it was decided to see if they had an effect on the bonding performance or not. In the second DOE, cooling time was added as a variable, while holding time was removed since it was found there was not a single effect on the bonding itself.

The TPE material type, material production batch, EPDM sample preparation procedure, and part geometry were kept constant during the experiments.

Further to that, since filling time is directly related to injection speed and injection pressure, it was not taken as a parameter.

During the trials, injection pressure was set to its maximum value (1800 bar) to transform the machine into a controlled-with-injection-speed machine, and injection pressure and injection time parameters were recorded during the experiments.

EPDM sample preparation is one of the critical for the study which directly affects the interface rougness and, as a consequence, the bonding performance. That’s why the samples were cut at the same time (just before the experiments) by the same person and the edges of the section were cleaned using IPA to eliminate any contamination, dust, or impurities at the EPDM interface.

Ambient temperature and humidity were uncontrolled parameters of the study.

3.3.1.3. Determination of factor levels

Levels of the factors were determined after discussion with TPE supplier.

The low values defined for each variable correspond to the minus (-) sign in the experiment design matrix, and the high values represent the (+) signs. The center levels are also added to the design, which means that the low and high values are shown as zero (0) points in the matrix.

For 1st DOE study, the factor and their levels are given in Table 8.

Table 8 1st DOE factors and levels

Factor	Name	Low level (-)	Center level (0)	High level (+)
A	injection speed – cm3/sec	25	62,5	100
B	holding pressure – bar	100	200	300
C	gate-joint distance – mm	50	75	100
D	mold temperature – °C	40	50	60
E	injection temperature – °C	200	230	260
F	holding time – s	2	3,5	5

After evaluation of the 1st DOE study statically (see Section 4.1), new levels were determined for the new factors in the 2nd DOE study, as given in Table 9.

Table 9 2nd DOE factors and levels

Factor	Name	Low level (-)	Center level (0)	High level (+)
A	injection speed – cm3/sec	25	62,5	100
B	holding pressure – bar	50	100	150
C	mold temperature – °C	25	42.5	60
D	injection temperature – °C	200	230	260
E	cooling time – s	15	27,5	40

3.3.2. Design of Experiment Plan

Table 10 shows the design plans of the 1st and 2nd DOE studies followed during the experiments. The design matrices are detailed in following parts.

Table 10 Design of experiment plans

	1st DOE Study	2nd DOE Study
Design type	Fractional Factorial Design	Fractional factorial Design
Factors	6	5
Design	2^{6-1} + 3 center points	2^{5-1} + 3 center points
Number of experiments	35	19
Blocks	1	1
Centre points	3	3
Main Output	Tensile Strength	Tensile Strength

Output 2	Elongation at break	Elongation at break

3.3.2.1. 1st DOE study plan

The 1st DOE Plan given in Table 11 was created with a fractional factorial design of six varying factors. 35 experiment runs, including one replicate, one block, and three center points, were performed to observe the effect of the factors and the effect of the interactions of the factors on the responses.

The parameters of gate and joint distance are adjusted by cutting the EPDM insert. A schematic image is illustrated in Figure 29. In this study, only flow direction tensile strength test results were analyzed, and so, the across direction of TPE melt was kept out of scope.

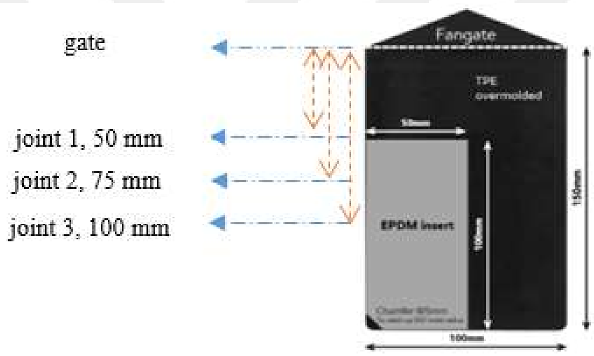

Figure 29 Images of levels of gate-joint distance variable

Table 11 1st DOE study experimental plan

Std Ord.	Run Ord.	Center Pt	Blocks	injection speed (cm^3/sn) A	holding pressure (bar) B	gate-joint distance (mm) C	mold temp. (°C) D	injection temp. (°C) E	holding time (sec) F
1	4	1	1	25	100	100	40	200	2
2	28	1	1	100	100	100	40	200	5
3	17	1	1	25	300	100	40	200	5
4	23	1	1	100	300	100	40	200	2
5	14	1	1	25	100	50	40	200	5
6	35	1	1	100	100	50	40	200	2
7	2	1	1	25	300	50	40	200	2
8	31	1	1	100	300	50	40	200	5
9	18	1	1	25	100	100	60	200	5
10	3	1	1	100	100	100	60	200	2
11	9	1	1	25	300	100	60	200	2
12	21	1	1	100	300	100	60	200	5
13	10	1	1	25	100	50	60	200	2
14	16	1	1	100	100	50	60	200	5
15	1	1	1	25	300	50	60	200	5
16	25	1	1	100	300	50	60	200	2
17	8	1	1	25	100	100	40	260	5

18	29	1	1	100	100	100	40	260	2
19	7	1	1	25	300	100	40	260	2
20	20	1	1	100	300	100	40	260	5
21	34	1	1	25	100	50	40	260	2
22	33	1	1	100	100	50	40	260	5
23	27	1	1	25	300	50	40	260	5
24	24	1	1	100	300	50	40	260	2
25	22	1	1	25	100	100	60	260	2
26	11	1	1	100	100	100	60	260	5
27	5	1	1	25	300	100	60	260	5
28	26	1	1	100	300	100	60	260	2
29	6	1	1	25	100	50	60	260	5
30	32	1	1	100	100	50	60	260	2
31	30	1	1	25	300	50	60	260	2
32	13	1	1	100	300	50	60	260	5
33	15	0	1	62,5	200	75	50	230	3,5
34	12	0	1	62,5	200	75	50	230	3,5
35	19	0	1	62,5	200	75	50	230	3,5

3.3.2.2. 2nd DOE study plan

The 2nd DOE Plan was determined to be studied after the first screening design findings. As it is given in Table 12, the fractional factorial design of five varying factors was determined using the parameters of injection speed, injection and mold temperature, holding pressure, and cooling time. It included 19 experiment runs, including one replicate, one block, and three center points.

In this plan, gate and joint distance parameters were eliminated to analyze the bonding performance differences in the flow direction and across the direction of the TPE melt. The holding time parameter was replaced with the cooling time, which is also assumed to have an effect on the bonding performance. According to the findings of the initial DOE research, the holding pressure boundary limitations were revised. Mold temperature limits were extended to simulate real production conditions.

The injection speed, holding pressure, mold temperature, injection temperature, and cooling time are controlled inputs that are adjusted at each sample production according to the experimental set-up shown in Table 12. The cycle time and injection pressures were also noted during the experiment.

Table 12 2nd DOE study experimental plan

Std Order	Run Order	Center Points	Blocks	injection speed (cm^3/sn) A	holding pressure (bar) B	mold temperature (°C) C	injection temperature (°C) D	cooling time (sec) E
1	1	1	1	25	50	25	200	40

2	2	1	1	100	50	25	200	15
3	3	1	1	25	150	25	200	15
4	4	1	1	100	150	25	200	40
5	5	1	1	25	50	60	200	15
6	6	1	1	100	50	60	200	40
7	7	1	1	25	150	60	200	40
8	8	1	1	100	150	60	200	15
9	9	1	1	25	50	25	260	15
10	10	1	1	100	50	25	260	40
11	11	1	1	25	150	25	260	40
12	12	1	1	100	150	25	260	15
13	13	1	1	25	50	60	260	40
14	14	1	1	100	50	60	260	15
15	15	1	1	25	150	60	260	15
16	16	1	1	100	150	60	260	40
17	17	0	1	62	100	42,5	230	27
18	18	0	1	62	100	42,5	230	27
19	19	0	1	62	100	42,5	230	27

3.4. EXPERIMENTAL STEPS

The same procedure was followed in the experimental steps of the 1st and 2nd DOE studies despite the differences in the variables and their levels. In accordance with the number of variables, in the first screening study, 35 experimental runs were performed according to Table 11 in Section 3.3.2.1 In the second study, performed with 19 experimental runs according to plan in Table 12 given in Section 3.3.2.2

Two-component test specimens were prepared by injection moulding considering the following experimental plan:

1. After the generated Design of Experiments (DOE) plan was with the selected parameters, injection molding process parameters were set according to the defined experiment runs. (Table 11 & Table 12)
2. As indicated in Figure 30, a cold EPDM insert cleaned with IPA was replaced in the wdk 2701 mold.

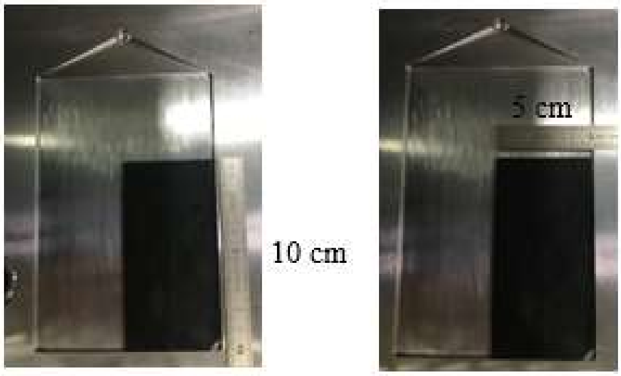

Figure 30 EPDM insert replaced in the mold before the injection process

3. Two component test samples with 100mm x 150mm x 2mm dimensions were produced in which the TPE was injected onto an EPDM insert in the mold and taken after each run. The samples produced in the second study are illustrated in Figure 31.

4. Injection pressure and injection time parameters were also recorded during the experiments.

5. Samples were collected to perform mechanical tests such as tensile strength and elongation at break after each experiment run.

6. Mechanical tests were performed with using Universal Mechanical Testing Machine and the results are investigated using Minitab 17, statistical analysis software.

7. The findings were validated on ten samples produced after the analysis.

Furthermore, at the end of this thesis study, the set solutions were tested on the real profile design to see if the bonding performances met the customer expectations.

Figure 31 Samples produced during the experiments in 2nd DOE study

4. RESULTS AND DISCUSSION

In this thesis, the design of an experiment method was selected as a methodology. It is an effective approach used in industry to investigate the significant and insignificant variables in the responses.

In this section, the two designs of experiment studies performed with selected injection molding parameters were evaluated on the statistically analyzed mechanical test results. The investigation of the process parameters' effects on the EPDM-TPE bonding performances, best, worst, and optimum (solution set) process conditions for used materials and mold design was discussed. The outputs of the design of experiments on repetability studies was explained, and finally, the validation of the solution set determined to enhance the bonding performance of the materials was discussed.

4.1. 1st DOE Experiments

4.1.1. Mechanical Test Results

This section gives the mechanical test results of the first screening design. Table 13 shows the tensile strength and elongation at break test results in flow direction for each experiment run. From the first observation, it is seen that process parameters applied at Std Order 1 give the lowest bonding results, which will be examined in detail in the statistical analysis section. In Std Order 25 and 26, the highest bonding performances are obtained.

Table 13 Mechanical test results of 1st DOE experiments

		Tensile Strength (MPa)			**Elongation at Break (%)**		
Std Order	**Run Order**	**TS#1**	**TS#2**	**TS#3**	**EB#1**	**EB#2**	**EB#3**
1	4	1.60	2.27	2.49	52.50	97.59	122.20
2	28	4.20	3.78	2.98	255.32	233.61	160.98
3	17	3.31	3.03	3.27	177.84	145.82	158.10
4	23	3.00	2.88	3.50	163.69	152.13	200.50
5	14	3.81	3.43	3.04	208.34	185.84	148.71
6	35	4.65	5.19	3.27	271.60	301.30	170.73
7	2	3.11	3.11	2.69	140.48	151.88	101.80
8	31	3.05	3.22	3.11	191.48	198.57	190.40
9	18	2.90	3.57	3.55	129.03	209.98	219.30
10	3	3.81	4.33	3.74	216.46	254.51	216.11
11	9	2.78	3.30	1.29	112.53	172.48	30.13
12	21	4.47	4.01	4.42	260.34	218.82	261.92

13	10	3.01	2.88	2.02	146.05	145.34	63.98
14	16	3.99	4.70	3.38	263.82	325.48	209.17
15	1	3.43	3.09	2.77	191.03	162.51	124.88
16	25	3.75	3.75	3.34	233.42	234.32	196.88
17	8	3.46	3.13	4.13	184.48	154.4	240.42
18	29	5.63	5.94	6.18	374.32	395.15	415.13
19	7	4.70	4.07	3.89	305.69	242.73	224.78
20	20	3.73	3.65	4.45	211.84	218.84	265.99
21	34	4.05	4.25	3.74	252.46	250.32	212.69
22	33	4.80	4.68	4.28	331.03	305.86	272.63
23	27	3.15	3.12	2.78	191.73	177.67	132.84
24	24	4.30	3.53	3.55	293.46	227.84	224.4
25	22	6.34	7.38	6.95	454.17	550.55	524.5
26	11	7.02	6.94	6.76	522.46	502.63	495.42
27	5	4.27	4.96	4.52	260.57	321.84	286.92
28	26	5.11	5.18	4.55	341.03	346.13	300.71
29	6	2.59	2.79	3.57	162.65	146.98	216.8
30	32	4.26	4.04	4.19	322.32	332	298.53
31	30	3.39	3.78	4.19	213.86	247.65	284.15
32	13	4.58	4.67	4.03	297.63	319.63	276.36
33	15	3.91	4.21	3.50	260.55	305.88	225.86
34	12	4.51	3.89	3.23	302.48	252.05	183.19
35	19	3.51	3.59	2.83	190.98	198.09	135.28

4.1.2. Statistical Analysis

This section shows the statistical analysis of the mechanical test results listed in the previous section using Minitab 17, a statistical program.

By using backward elimination of terms, a model was carried out to check whether each of the factors and their interactions investigated in the experiment were significant or not. It is defined as having a 95% confidence level and "does not require a hierarchical model". Utilizing P values of the factor and interactions, statistically insignificant factors, that were higher than 0.05, were removed from the model. In Table 14, only significant factors and interactions with lower P values than 0.05 are listed. The model's R^2 value is obtained at 88,07% for flow direction, which is at a confident level. Except for holding time, each parameter has a significant effect on bonding performance, as indicated in the table, and there are also double and triple interactions affecting the bonding.

Table 14 Evaluation of 1st DOE study tensile strength results

1st DOE Statistical Analyses Tensile Strength Results in flow direction					
	DF	Adj SS	Adj MS	F	P
Linear					
A	1	14,710	14,7102	80,30	0,000
B	1	5,927	5,9267	32,35	0,000
C	1	7,753	7,7526	42,32	0,000
D	1	4,646	4,6460	25,36	0,000
E	1	31,491	31,4909	171,90	0,000
2-Way Interaction					
AB	1	2,025	2,0251	11,05	0,001
AF	1	0,813	0,8135	4,44	0,038
BC	1	0,969	0,9690	5,29	0,024
BE	1	2,060	2,0601	11,25	0,001
CD	1	6,299	6,2991	34,38	0,000
CE	1	11,984	11,9844	65,42	0,000
DE	1	1,647	1,6467	8,99	0,004
DF	1	0,967	0,9674	5,28	0,024
EF	1	4,121	4,1214	22,50	0,000
3-Way Interaction					
ABD	1	2,322	2,3222	12,68	0,001
ABF	1	0,992	0,9925	5,42	0,022
ADE	1	0,855	0,8552	4,67	0,034
ADF	1	4,023	4,0225	21,96	0,000
AEF	1	6,987	6,9871	38,14	0,000
Error	83	15,205	0,1832		
Total	104	127,438			

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
0,428014	88,07%	85,05%	80,94%

A: injection speed B: holding pressure C: gate-joint distance D: mold temperature E: injection temperature F: holding time

The regression equation of the model found from the analysis is given as follows in coded units:

*TS_flow = 3,8921 + 0,3914 inj. speed - 0,2485 holding pres. + 0,2842 gate joint distance + 0,2200 mold temp. + 0,5727 inj. temp. - 0,1452 inj. speed*holding pres. + 0,0921 inj. speed *holding time - 0,1005 holding pres.*gate joint distance - 0,1465 holding pres.* inj. temp. + 0,2562 gate joint distance* mold temp. + 0,3533 gate joint distance* inj. temp. + 0,1310 mold temp. * inj. temp. + 0,1004 mold temp. *holding time- 0,2072 inj. temp. *holding time + 0,1555 inj. speed * holding pres.* mold temp. - 0,1017 inj. speed * holding pres.*holding time - 0,0944 inj. speed * mold temp. * inj. temp. + 0,2047 inj. speed * mold temp. *holding time+ 0,2698 inj. speed * inj. temp. *holding time*

Single effect coefficients, bolded in the equation, show that injection temperature has the highest single effect and holding pressure has a negative single effect on the bonding. These single effects are also shown with main effect plots in Figure 32. Injection temperature, injection speed, gate and joint distance, and mold temperature have positive impacts on the bonding performance, whereas holding pressure affects the bonding adversely. There is no single impact of holding time on adhesion. Injection temperature has the major effect, followed by injection speed.

A higher interface temperature supports molecular interdiffusion and entanglement rates at the interface. High injection temperatures also reduce the viscosity of TPE materials, resulting in greater wettability and more intimate contact at the interface, which has a positive impact on the bonding. Besides, injection speed influences the interfacial bonding since, at high values, it increases the melt temperature due to the shear heating and lowers the melt viscosity. Furthermore, injection speed and pressure also increase the mechanical locking between the materials. The mold temperature increases the interfacial temperature of the materials, which results in stronger bonding.

Holding pressure, found as a single negative effect on bonding, must be evaluated separately. If the holding pressure is too high to move the EPDM insert inside the mold, this may affect the bonding performance adversely. Otherwise, it is considered to increase the mechanical interlocking (Islam, 2010). For thermoplastic materials, holding pressure has a negative influence when only it is set too low or the holding time is insufficient (Bex, G., 2018).

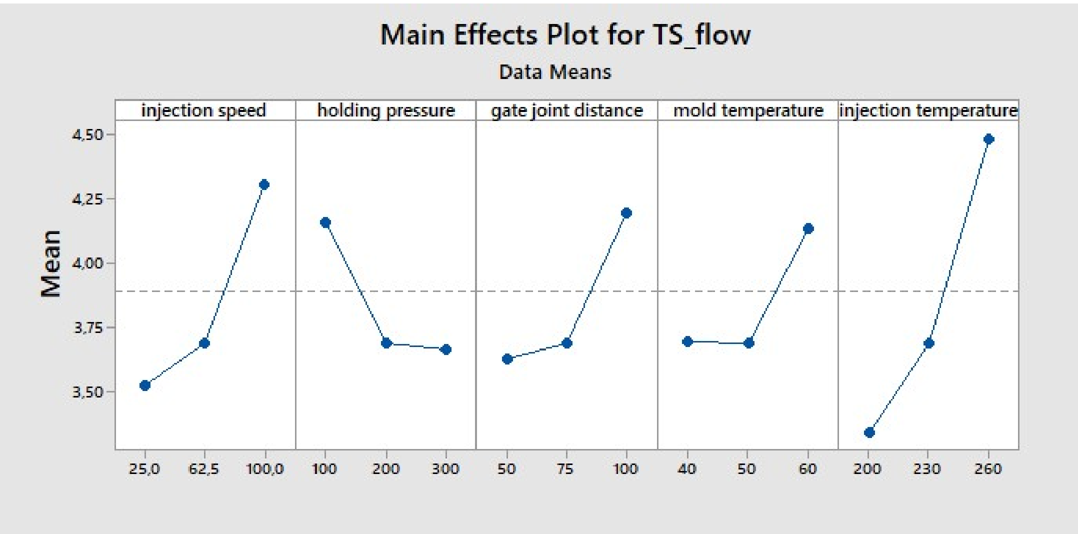

Figure 32 Main effects plot for tensile strength in flow direction

The main effect plot was used to show the effects of process parameters on the elongation at break results. As it is seen in Figure 33, the process parameters have a similar single influence on these two outputs. It is seen that the parameters to be adjusted for better bonding also increase the elongation at break results between two materials.

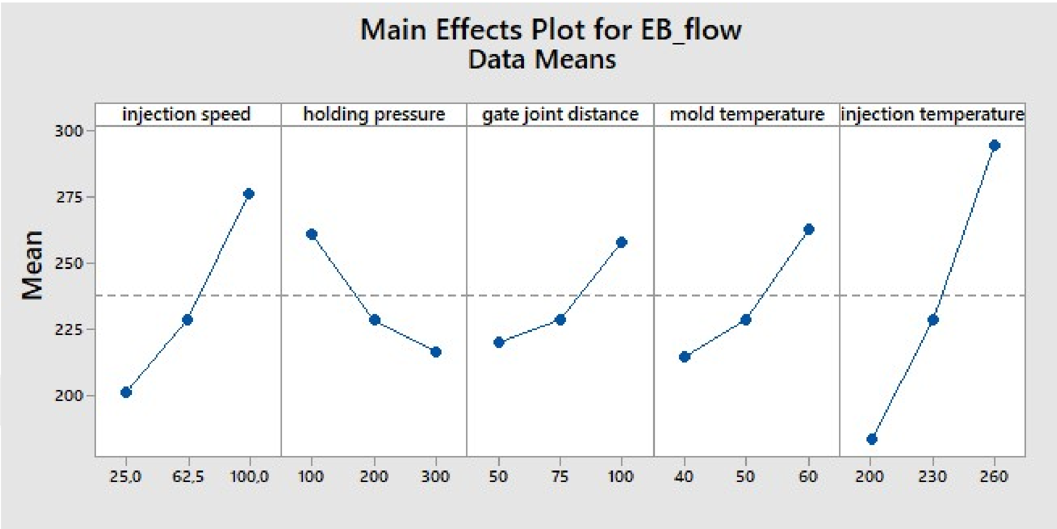

Figure 33 Main effects plot for elongation at break in flow direction

The Pareto charts given in Figure 34 and Figure 35 help to evaluate the effect of each factor and their interactions.

Parameters effects on tensile strength (in flow direction):

<u>The single effects:</u>

- Injection temperature (E) has the highest impact on the bonding performance, followed by injection speed. Additionally, gate and joint distance (C), holding pressure (B) and mold temperature (D) have single effects except for holding time.

<u>Interactions:</u>

- The gate and joint distance & injection temperature (CE) have significant double interactions on the adhesion. Similar to the gate and joint distance & mold temperature (CD) interaction, they both have a synergistic effect on increasing the interface temperature and wettability of the material contact area. According to the analysis, injection temperature and holding time (EF), holding pressure and injection temperature (BE), injection speed and holding pressure (AB), mold temperature and injection temperature (DE), holding pressure and gate and joint distance (BC), mold temperature and holding time (DF), and injection speed and holding time (AF) have also double interactions on bonding strength.

- Injection speed and holding time parameters interact with injection temperature (AEF), mold temperature (ADF), and holding pressure (ABF) in a three-way interaction on bonding performance. Additionally, injection speed and mold temperature have interactions with mold temperature (ABD) and injection temperature (ADE). However, their effects are at such a low level that they do not affect the system dramatically.

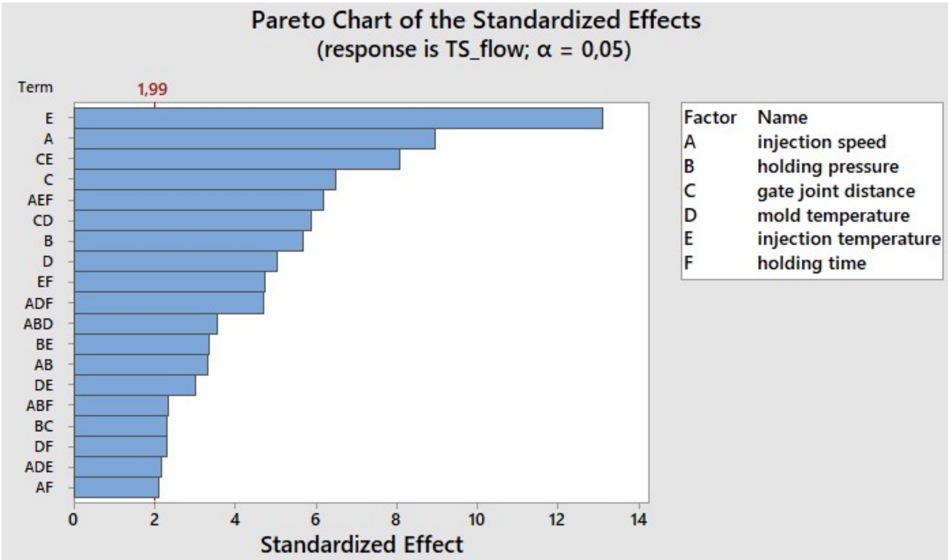

Figure 34 Pareto chart of tensile strength in flow direction

Parameters effects on elongation at break (in flow direction):

The same analysis was also carried out on the elongation at break results, which is not directly related to bonding performance, but it is essential to handle the part without any breakage from the mold after the process. Although the elongation at break results are strongly linked to the TPE material properties the effects of the process parameters are found to be:

The single effects:

- Injection temperature (E) has the greatest impact on elongation results, and injection speed (A) is in the second order as it is seen for tensile strength results. Mold temperature (D), holding pressure (B), and gate and joint distance (C) all have independent effects on elongation at break results.

Interactions:

- As it is seen in Figure 35, the gate and joint distance and injection temperature (CE) have significant interactions on the elongation at break results. Other interactions observed were correlated with the findings in the tensile strength analysis given in Figure 34, but in a different order.
- Except for injection speed, holding time, and injection temperature, each triple interaction detected in tensile strength results has an influence on elongation at breaks.

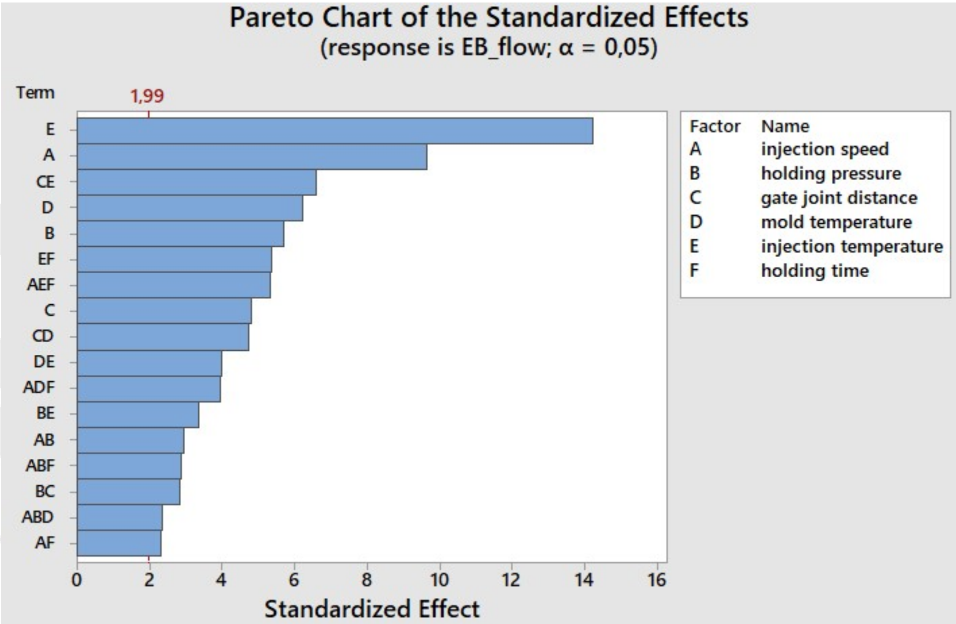

Figure 35 Pareto chart of elongation at break in flow direction

The graphical representations of the double interactions on the tensile strength values are shown in Figure 36. Each point in the interaction plot indicates the mean tensile strength result at different combinations of factor levels. Parallel lines mean that there are no interactions between the factors that are already hidden in the figure. The larger the difference in slope between the lines, the higher the degree of interaction. As a result, as it is seen from the graph, the gate and joint distance and injection temperature interactions are the most effective on the bonding performance.

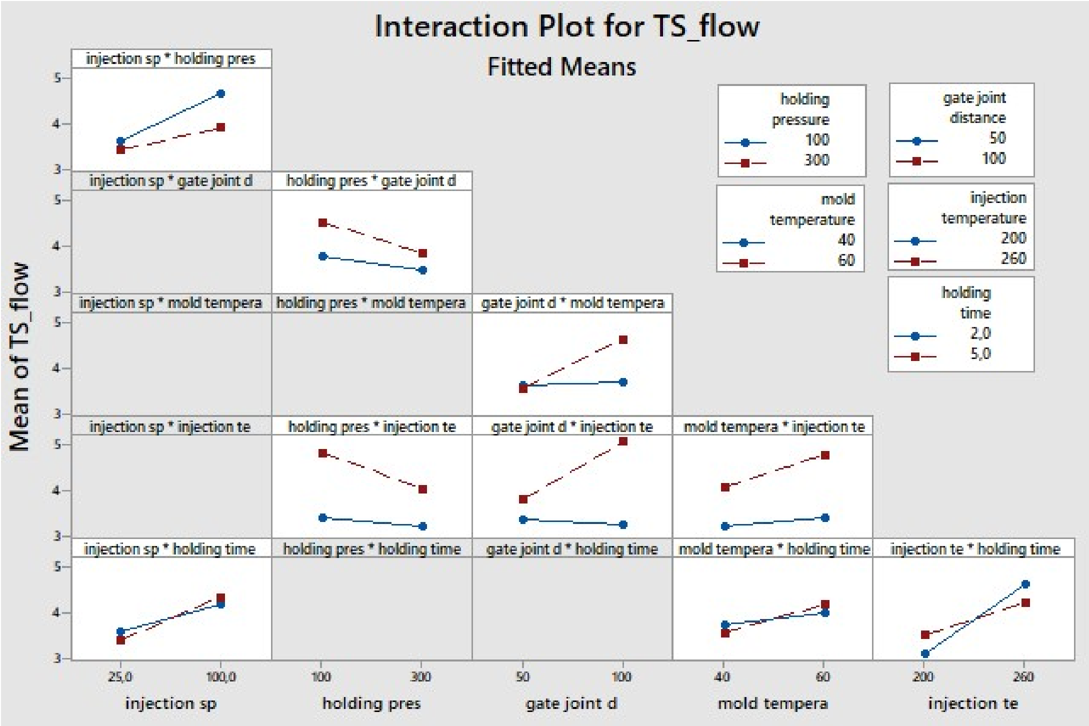

Figure 36 Interaction plot of tensile strength in flow direction

The optimizer tool in Minitab 17 was used to find the best process parameters for EPDM and TPE material bonding performance. As it is seen in Figure 37, maximum tensile strength was achieved with 7.05 MPa in flow direction when the process conditions were set to 100 cm^3/sec injection speed, 100 bar holding pressure, 60 °C mold temperature, 260 °C injection temperature, and 5 sec holding time, which is not a significant single effect. At those parameters, elongation at break results were also found to be 519% in flow direction.

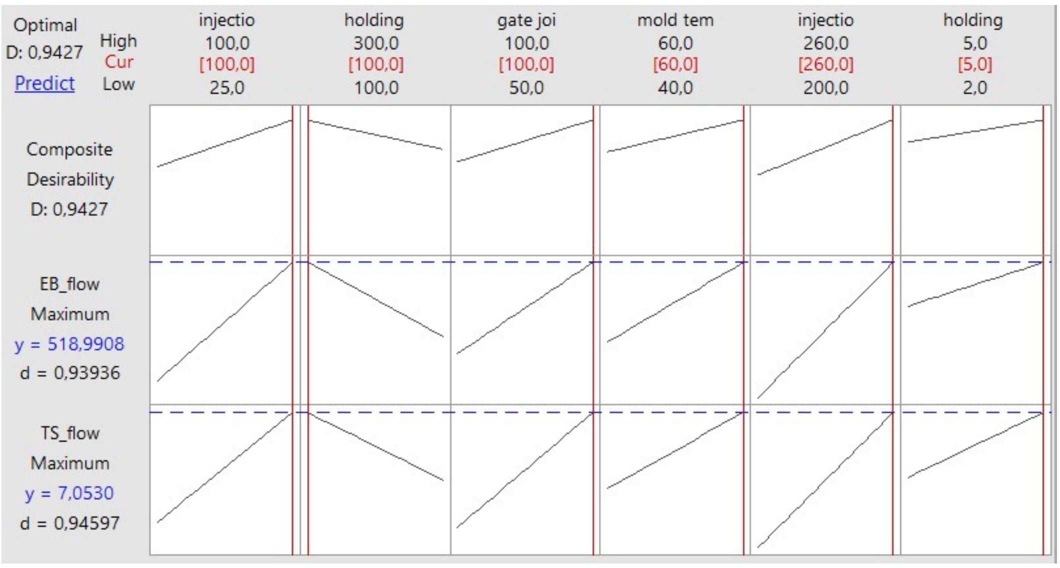

Figure 37 1st DOE study process parameters for the highest bonding

On the other hand, the worst process parameters for EPDM and TPE material bonding performance were also defined to understand the minimum levels of the bonding and confirm the factors' impacts. They are obtained with 2.11 MPa in flow direction when the process conditions are set as 25 cm^3/sec injection speed, 300 bar holding pressure, 40 °C mold temperature, 200 °C injection temperature, and 2 sec holding time, which is not a significant single effect. At those parameters, elongation at break results are also found to be 51% in flow direction (See in Figure 38).

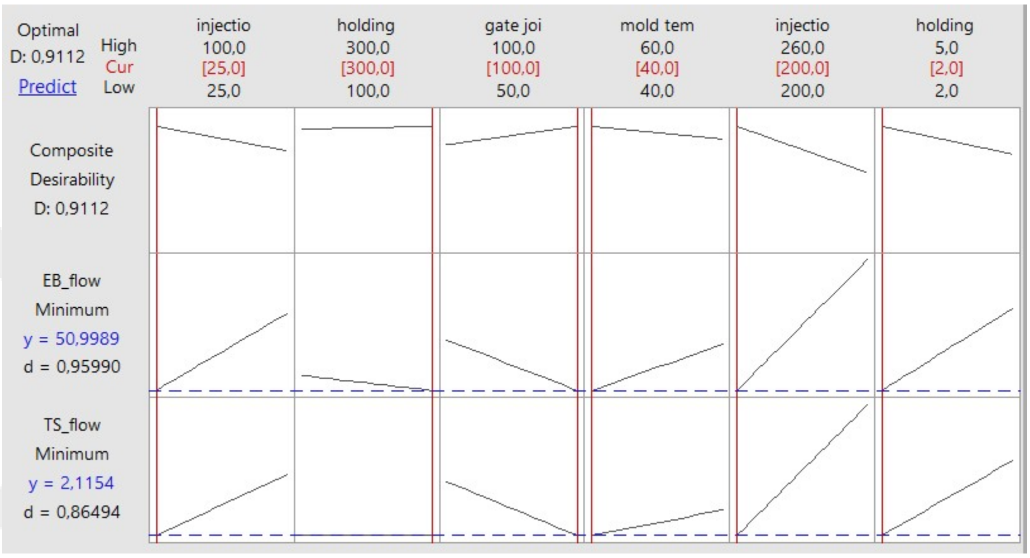

Figure 38 1st DOE study process parameters for the lowest bonding

The styrenic-based TPE-S material used in the study should not be processed above 230 °C so as not to degrerate the material. Therefore, the best process parameters are re-analysed with decreasing the injection temperature 230 °C and found as shown in Figure 39. In this analysis, the gate and joint distance was adjusted to 50 mm. The injection speed was determined as 100 cm^3/sec, the holding pressure as 100 bar, the mold temperature as 60 °C, and the holding time as 5 seconds. The tensile strength was 4.60 MPa, with 312% elongation at break. This was called the solution set of the 1st DOE study (screening design).

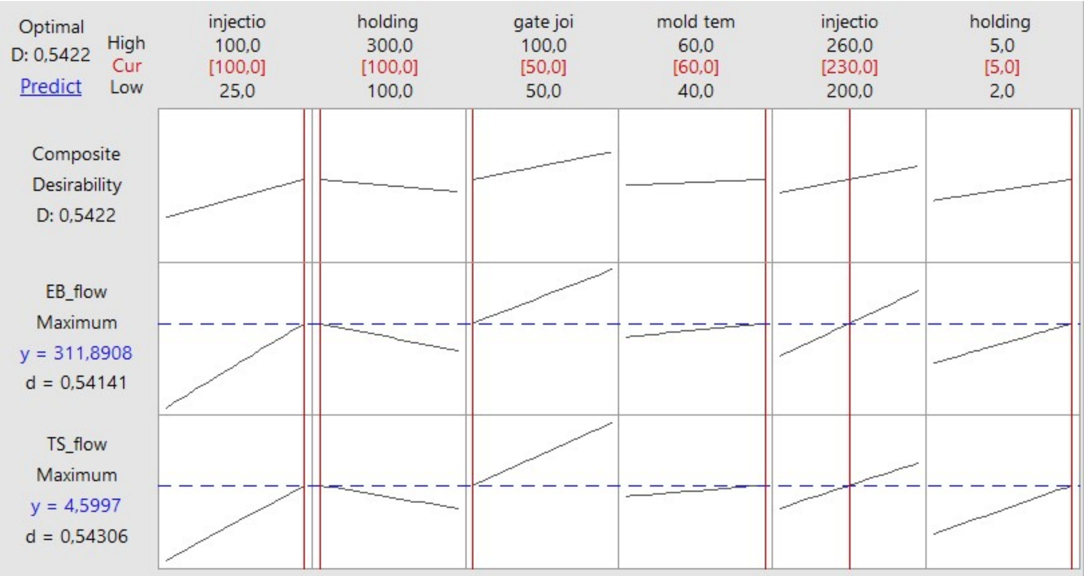

Figure 39 1st DOE study solution set to enhance EPDM-TPE bonding

4.1.3. Validation of 1st DOE Experiments

The process parameters found with statistical analyses in Section 4.1.2 are validated in this part of the study.

Ten samples were produced by using the solution set and worst process conditions given in Table 15. It is seen that tensile strength results are differed between 4.10MPa ± 0.74 for flow direction and 4.04MPa ± 0.65 for across direction. The process parameters obtained in the first DOE Study with the help of the optimizer tool in Minitab 17 were confirmed with the results illustrated in Figure 40 and Figure 41.

Table 15 Validation of 1st DOE study

Parameters		Best		Worst	
Injection speed – cm3/sec		100		25	
Holding pressure – bar		100		100	
Gate-joint distance – mm		50		50	
Mold temperature – °C		60		40	
Injection temperature – °C		230		200	
Cooling time – sec		28		28	
Holding time – sec		5		5	
Mechanical Test Results		mean	max.	mean	max.
Tensile Strength – MPa Main Output	flow	4.10 ± 0.74	5.41	2.90 ± 0.35	2.10
	across	4.04 ± 0.65	5.20	3.02 ± 0.38	2.28
Elongation at break - % Output 2	flow	304 ± 107	535	192 ± 42	95
	across	367 ± 107	591	237 ± 60	80

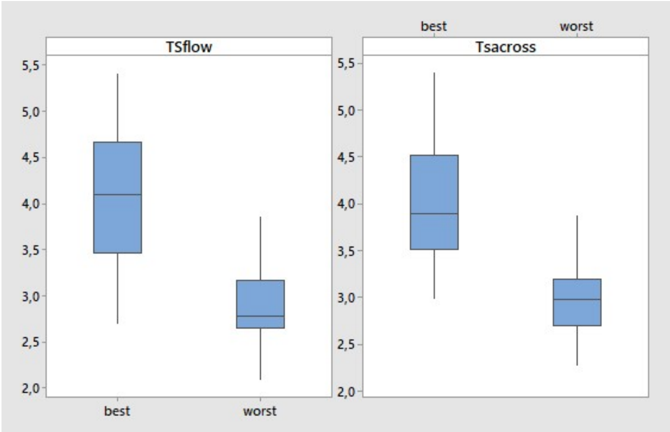

Figure 40 Tensile strength results of 1st DOE validation analysis

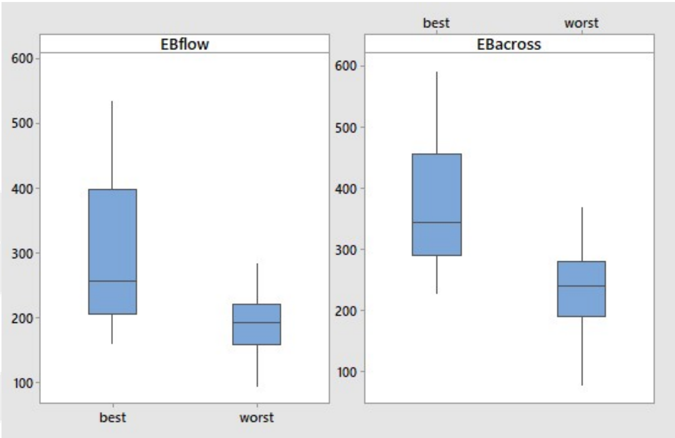

Figure 41 Elongation at break results of 1st DOE validation analysis

4.2. 2nd DOE Experiments

4.2.1. Mechanical Test Results

In 2nd design of experiment study, the bonding performances differences in the flow and across directions could be examined since the gate-joint distance variable was removed from the design. A cooling time parameter has also been added to replace the holding time parameter, which has no single effect on bonding. Table 16 lists the mechanical test results of each experiment run, which were performed on the S2 type specimens in the flow and across directions. According to the results, Std Order 17 experiment run, which represents the center points, the split between the EPDM and TPE parts was not in the joining area but on the TPE side. That means the highest bonding performance was achieved at those process parameters. The lowest bonding performance was observed at Std Order 3. However, in the second DOE study, the tensile strength results (bonding strengths) were higher than those obtained in 1st DOE study.

Table 16 Mechanical test results of 2nd DOE experiments

	Tensile Strength (MPa)						Elongation at break (%)					
	flow direction			across direction			flow direction			across direction		
Std Order	**TS#1**	**TS#2**	**TS#3**	**TS#4**	**TS#5**	**TS#6**	**EB#1**	**EB#2**	**EB#3**	**EB#4**	**EB#5**	**EB#6**
1	4.08	3.84	3.12	3.71	4.00	3.75	251.5	284.4	276.4	400,0	406.7	435.1
2	5,18	4.43	3.89	3.30	3.33	3.54	574.9	403.8	367.8	329.5	346.8	330.1
3	3.70	3.79	3.35	3.34	3.41	2.96	370.4	417	365.5	314.1	368.9	320.7
4	3.77	4.25	4.07	3.66	3.36	3.46	34.7	363.4	419.3	350.4	306.9	360.5
5	4.84	3.91	3.52	5.11	4.86	5.69	488.1	403.5	251.4	440.6	449.9	445.8
6	4.51	4.22	4.93	6.02	6.95	6.77	371.8	332.5	355.4	531.6	607.7	626.5
7	4.26	4.14	3.72	5.18	5.02	4.28	373.3	342.8	302.7	437.0	411.6	378.5
8	5.34	5.66	4.26	5.87	5.51	5.55	514.5	464.2	402.1	531.1	509.5	544.7
9	3.67	3.52	4.40	5.41	5.77	5.34	326.6	328.1	433.5	544.8	556.1	470.9
10	5.42	4.35	4.96	6.15	5.01	5.27	480.2	286.9	357.8	625.0	388.2	577.7
11	3.97	3.48	3.29	4.40	4.57	4.04	330.9	324.1	269.9	418.6	382.4	384.0
12	5.37	6.04	6.34	6.61	5.70	5.70	533.9	526.6	471.3	529.7	437.5	428.6
13	6.08	6.92	6.42	6.34	7.69	6.37	472.4	593.8	562.8	505.0	610.9	533.6
14	6.33	4.19	5.25	6.58	7.36	6.18	596.0	364.0	468.6	509.1	720.5	509.0
15	4.69	5.97	4.88	5.74	6.15	5.41	381.1	495.7	412.1	464.2	561.9	348.0
16	4.93	4.88	5.38	7.56	7.19	7.51	397.9	465.8	401.7	547.2	505.0	515.9
17	5.25	5.57	4.00	7.80	7.30	6.33	442.9	432.4	367.6	680.4	672.2	564.9
18	4.86	4.65	4.42	6.14	5.48	5.48	429.2	379.3	409.9	507.5	430.6	468.9
19	3.49	4.70	3.08	6.65	5.57	5.33	322.7	386.8	285.4	538.7	455.5	408.7

4.2.2. Statistical Analysis

This section shows the statistical analysis of the mechanical test results of the second DOE study using Minitab 17 as it was performed for the first one.

By using backward elimination of terms, a model was created to check whether new factors and their interactions are significant or not. Again, only significant factors and interactions with lower P values than 0.05 are shown in Table 17. Tensile strength test results were statistically analyzed for 2nd DOE in both directions. The model's R2 values are obtained as 60,91% for flow direction and 84,43% for across direction, that are lower than the first screening design for flow direction.

Table 17 Evaluation of 2nd DOE study tensile strength results

2nd DOE Analyses Tensile Strength Results in flow & across direction										
	Flow direction					**Across direction**				
	DF	Adj SS	Adj MS	F	P	DF	Adj SS	Adj MS	F	P
Model	6	28,9180	4,8197	12,99	0,000	8	81,024	10,128	32,53	0,000

Linear											
A	1	4,3140	4,3140	11,62	0,001	A	1	5,070	5,070	16,28	0,000
C	1	5,9855	5,9855	16,13	0,000	B	1	1,442	1,442	4,63	0,036
D	1	8,2917	8,2917	22,34	0,000	C	1	35,192	35,19	113,0	0,000
						D	1	26,137	26,13	83,94	0,000
2-Way Interaction											
AC	1	3,701	3,701	9,97	0,003	AB	1	2,412	2,412	7,75	0,008
AE	1	1,956	1,956	5,27	0,026	CD	1	1,643	1,642	5,28	0,026
BE	1	4,668	4,668	12,58	0,001	CE	1	2,042	2,041	6,56	0,014
Error	50	18,556	0,371				48	14,94	0,311		
Total	56	47,474					56	95,97			

Model Summary							
S	R-sq	R-sq(adj)	R-sq(pred)	S	R-sq	R-sq(adj)	R-sq(pred)
0,609200	60,91%	56,22%	50,49%	0,558023	84,43%	81,83%	78,69%

A: injection speed B: holding pressure C: mold temperature D: injection temperature E: cooling time

Regression equations of the models for flow and across directions are given as follows in coded units:

*TS_flow = 4,5882 + 0,2998 inj speed + 0,3531 mold temp + 0,4156 inj. temp - 0,2777 inj speed*mold temp - 0,2019 inj speed*cooling time - 0,3119 holding pressure*cooling time*

*TS_across = 5,2642 + 0,3250 inj speed - 0,1733 holding pressure + 0,8562 mold temp + 0,7379 inj. temp + 0,2242 inj speed*holding pressure - 0,1850 mold temp*inj. temp + 0,2062 mold temp*cooling time + 0,967 Ct Pt*

As it is seen in the first study, injection speed, mold temperature, and injection temperature have positive single effects on the bonding performance in flow direction. In addition to this, the holding pressure has a negative effect in the across direction. The findings of the first screening design of experiments were confirmed in this second study. As it was mentioned in Section 4.1.2, high injection temperature, injection speed, and mold temperature increase the wettability of the materials and increase the bonding at the interface. Injection temperature has a major effect on the TPE material viscosity. Holding pressure may cause the EPDM insert to move, thereby reducing the intimate contact area of the parts in the across direction.

The factor analyses performed on the tensile strengths in flow and across direction are shown in Figures 42 and 43 and evaluated as follows:

For flow direction (Figure 42):

- Injection temperature (D) has the highest impact on the bonding performance as it is found in the first screening design. Mold temperature (C) has a higher impact than injection speed. This means that the higher the temperature at the interface, the greater the bonding strength between the materials. Injection speed also affects the temperature and the TPE material rheology. It was observed that holding pressure and cooling time have no single effect on the bonding performance in the flow direction. However, cooling time has an interaction with holding pressure and injection speed. It should be adjusted high enough according to the part design to allow crystallization for strong adhesion at the interface.

- Moreover, a synergic effect of the injection speed and mold temperature on the bonding performance was obtained from the analyses.

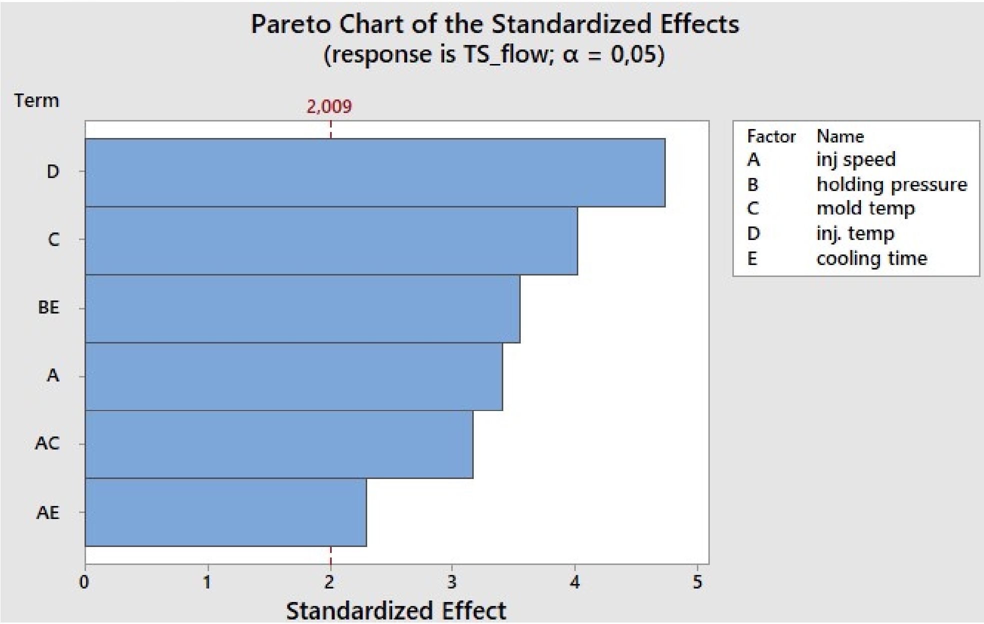

Figure 42 Pareto chart of tensile strength in flow direction

For across direction (Figure 43):

- Mold temperature impact was found to have the highest level of bonding as most of the researchers reported in their studies that it is a critical parameter for the injection molding process (Kadam, S.D., 2012). Injection temperature and injection speed variables followed it, and holding pressure was found to be an effective parameter. As it was interpreted before, the negative effect of the holding pressure may result from the EPDM insert oriantation. This parameter is required to be set sufficiently to not disrupt the insert position.

- Mold temperature also has a synergic effect with cooling time and injection temperature. If the mold temperature is raised to enhance the bonding performance, it will require more time to cool the part during the injection process. This also increases the process cycle time and, thus, the cost.
- Injection speed and holding pressure has double interactions as same in flow direction.

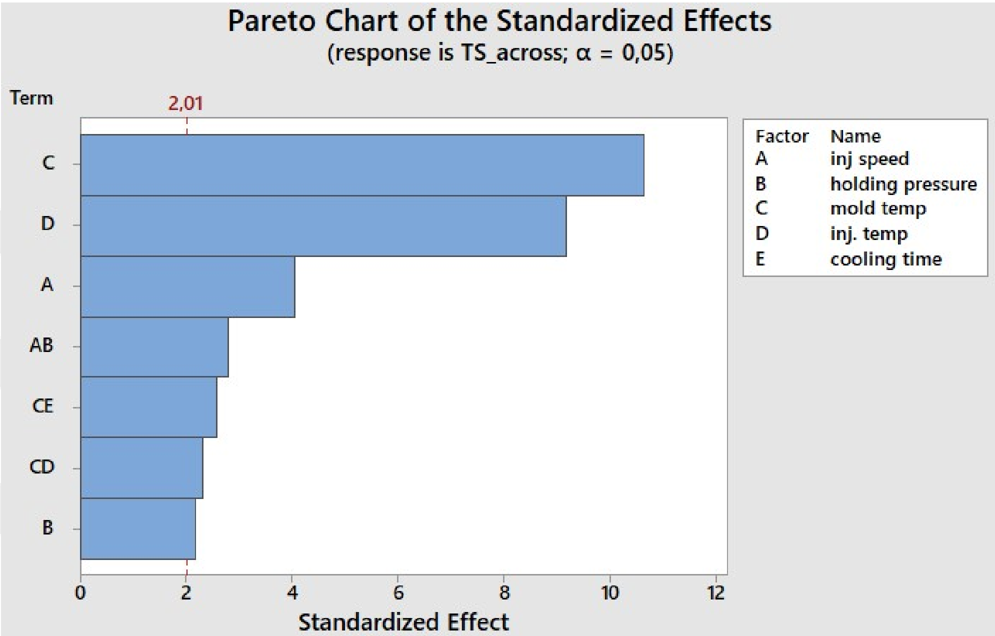

Figure 43 Pareto chart of tensile strength in across direction

The counter plot in Figure 44 shows that as the mold temperature and injection temperature, which have the greatest impact on bonding performance, increase, the tensile strength results increase as well. When you set the injection temperature at 230 °C and the mold temperature at 60 °C, the temsile strength results could rise to 4.8-5.0 MPa when the injection speed is 62,5 cm3/sec, the holding pressure is 100 bar and the cooling time is 27,5 sec. (at center points).

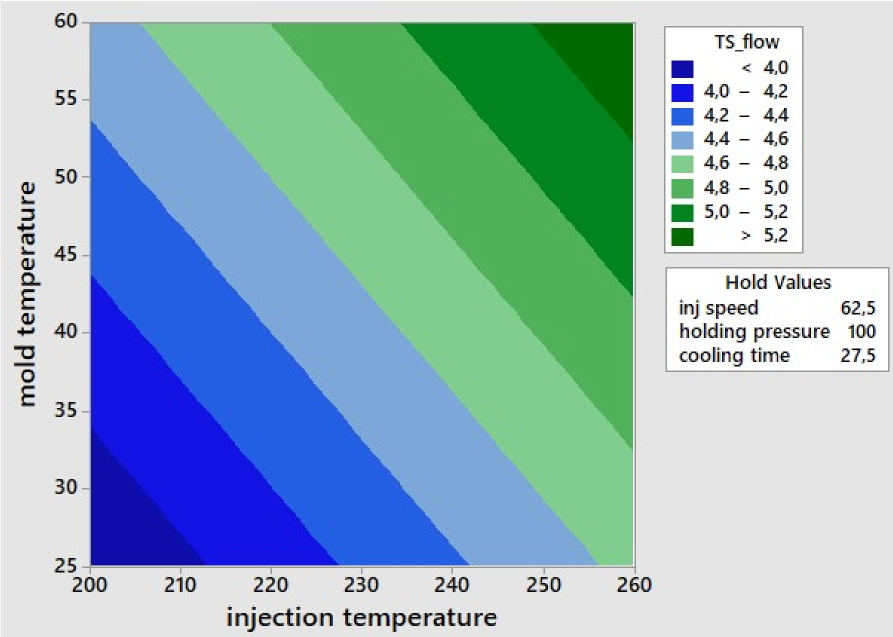

Figure 44 Counter plot of tensile strength (mold temp. vs injection temp.)

Injection pressure recorded during the experiments was also evaluated on Counter Plot, Figure 45. This shows that it increases with injection speed and decreases with injection temperature due to the TPE material flow behaviour.

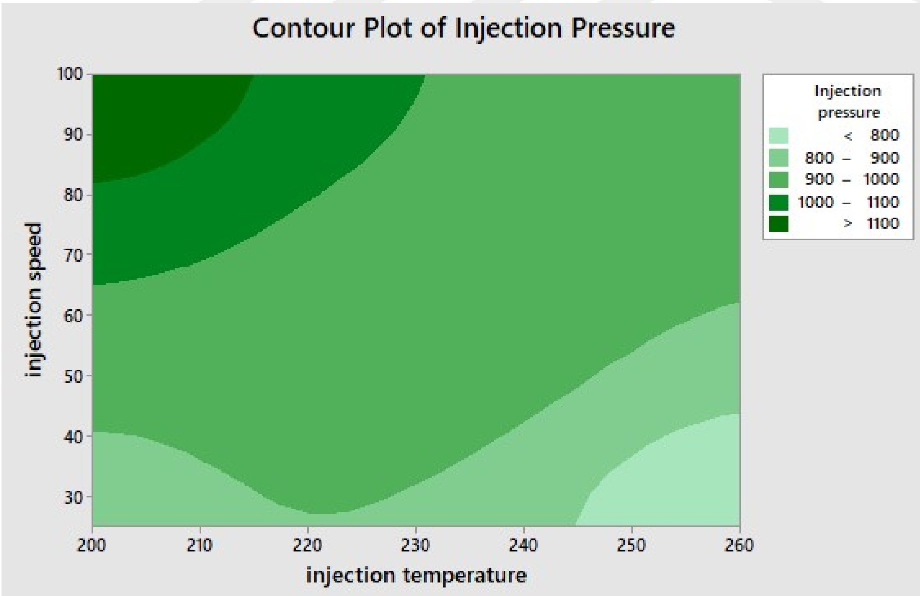

Figure 45 Counter plot of injection pressure (injection speed vs injection temp.)

As it is seen in Figure 46, the maximum tensile strength results are achieved with 5.89 MPa in the flow direction and 6.84 MPa in across direction when the process conditions are set as 100 cm3/sec injection speed, 150 bar holding pressure, 60 °C mold temperature, 260 °C injection temperature, and 15 sec cooling time, which is not a significant single effect. At those parameters, the elongation at break is found to be 491% in the flow direction and 560% in the across direction.

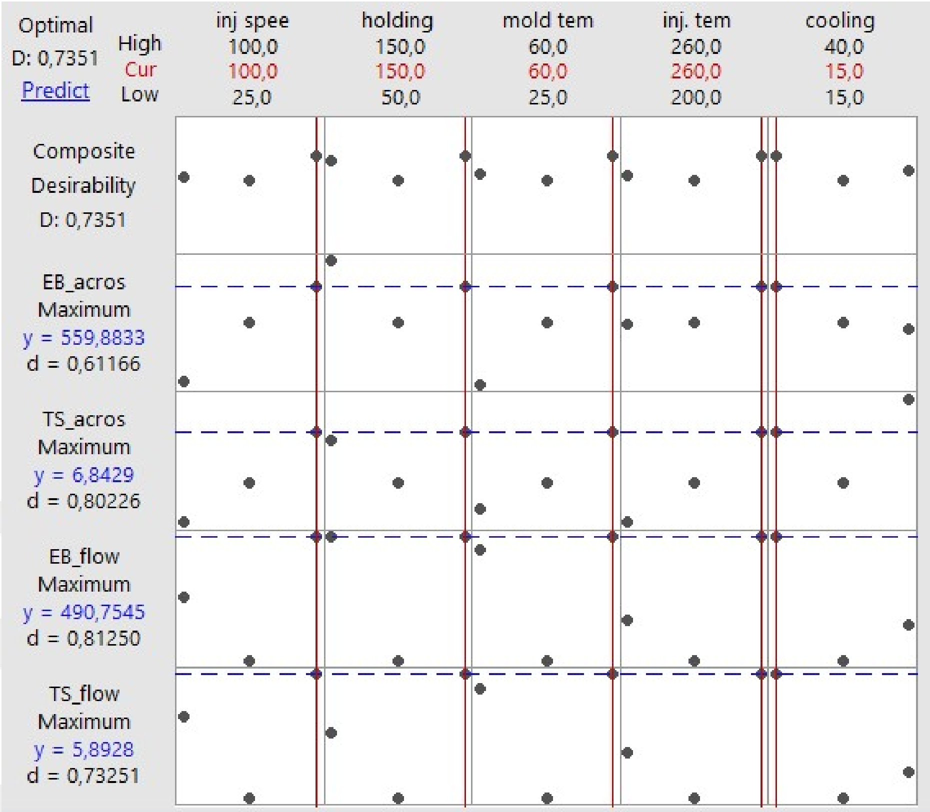

Figure 46 2nd DOE study process parameter for highest bonding performance

Besides, the process parameters for the lowest EPDM and TPE material bonding performance are also defined to confirm the factors' impact. As shown in Figure 47, they are obtained with 3.13 MPa in the flow direction and 2.55 MPa in across direction when the process conditions are set as 25 cm^3/sec injection speed, 150 bar holding pressure, 25 °C mold temperature, 200 °C injection temperature, and 40 sec cooling time, which is not a significant single effect. Elongation at break is found to be 296% in the flow direction and 303% in the across direction at those parameters. The observed results confirm that process parameters are critical for bonding performance apart from material compability.

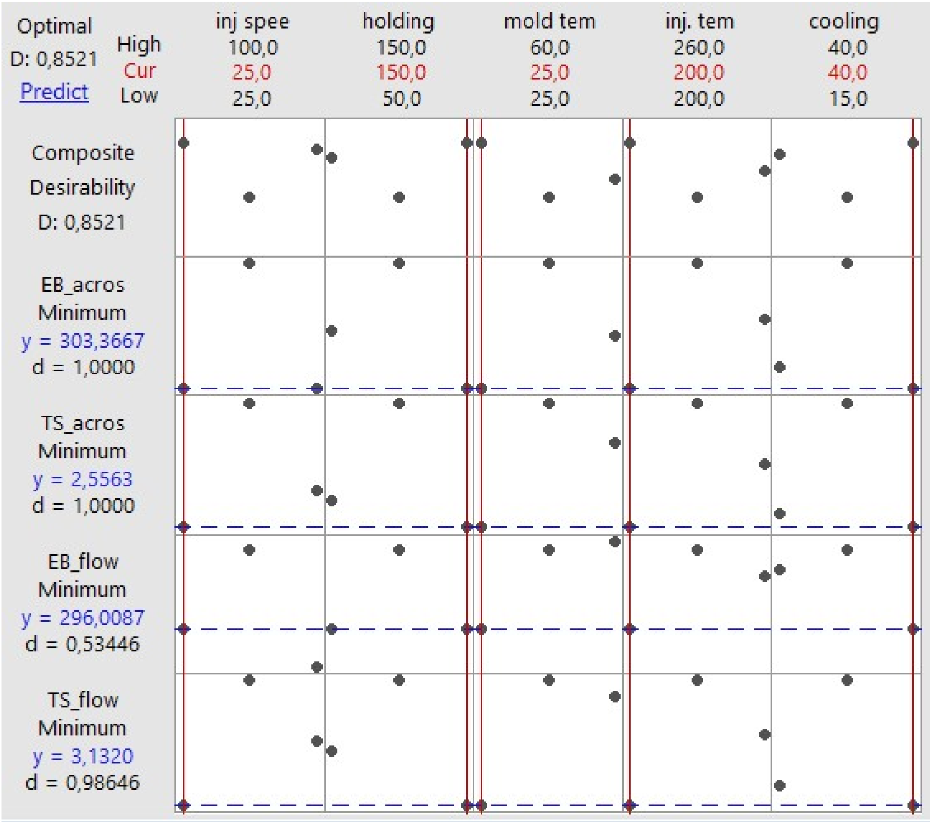

Figure 47 2nd DOE study process parameter for lowest bonding performance

Due to the fact that the styrene based TPE-S material should not be processed over 230 °C to prevent its degradation during production, optimum process parameters are altered for this temperature as seen in Figure 48. The set solution was found at the center of the process variables at 62,5 cm^3/sec injection speed, 100 bar holding pressure, 42,5 °C mold temperature, 230 °C injection temperature, and 27,5 sec cooling time. At those parameters, the tensile strength and elongation at break are 4.58 MPa and 394% in the flow direction, and 6.23 MPa and 525% in the cross direction, respectively. The observed results are also higher than the target responses, which had been determined as 3.5 MPa for tensile strength and 350% elongation at break at the beginning of the study.

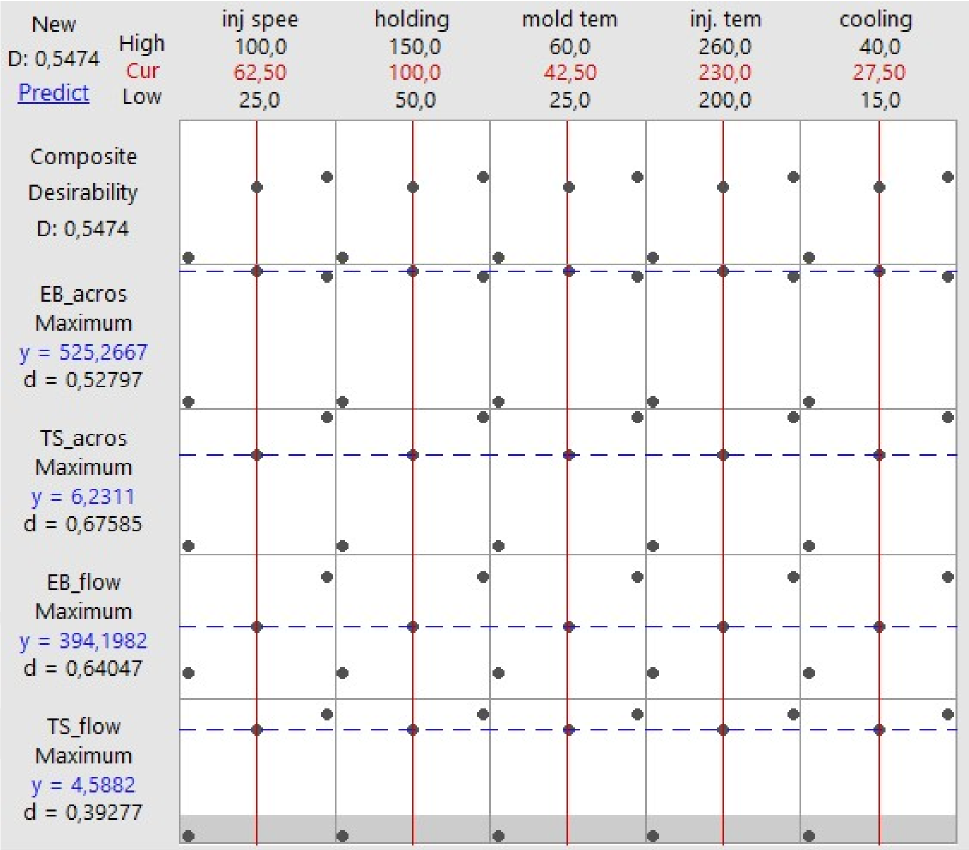

Figure 48 2nd DOE study solution set to enhance EPDM-TPE bonding

As it is also seen from Figure 48, higher tensile strength results are obtained with the new levels and cooling time variable introduced to the design in the second study. Another point to consider is that the tensile strength results are higher in the across direction than those in the flow direction. This could be due to the mold design, as TPE melt reaches the EPDM substrate in the across direction last and stops. This could increase the intimate contact and wettability of the parts tested in the across direction.

4.2.3. SEM Analysis

The surface morhologies of the materials' split areas were investigated using a scanning electron microscope. The aim was to monitor the EPDM and TPE surfaces after the tensile strength test and understand if there were differences on the surfaces or not. Figure 49 depicts the morhological of TPE-EPDM surfaces with varying bonding strengths: A part has a bonding strength of 6.65 MPa, while B part has 3.71 MPa.

From SEM images, it was observed that there were more rough surfaces and cativities on the A part, which gave the high bonding strength results. Although this analysis does not represent the entire portion, it demonstrates the differences in morphologies between the TPE sides of the high and low-bonded parts.

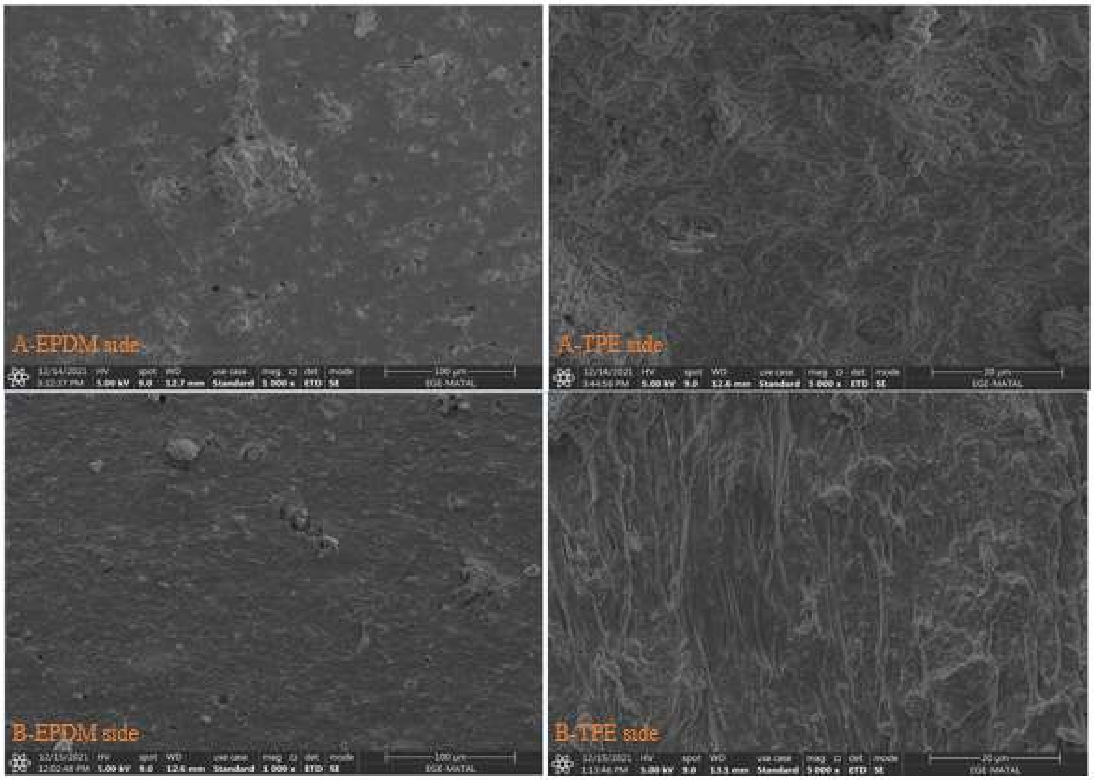

Figure 49 SEM images of EPDM and TPE parts after tensile test

A: Part has high bonding (6,65 MPa) (set solution), B: Part has low bonding (3,71 MPa)

4.2.4. Validation Study of 2nd DOE Experiments

The process parameters found as a set solution in the second study were validated on ten samples produced at those parameters. Table 18 shows the mean and maximum values of tensile strength and elongation at break results of these samples as 4.12 ± 0.58 in flow direction and 5.13 MPa ± 1.09 in across direction. Figure 50 and Figure 51 also illustrate the distribution of tensile strength and elongation at break results in flow and across direction.

Table 18 Validation of 2nd DOE study

Parameters		Best	
Injection speed – cm3/sec		63	
Holding pressure – bar		100	
Gate-joint distance – mm		50	
Mold temperature – °C		43	
Injection temperature – °C		230	
Cooling time – sec		28	
Holding time – sec		5	
Mechanical Test Results		mean	max.
Tensile Strength – MPa Main Output	flow	4.12 ± 0.58	5.66
	across	5.13 ± 1.09	6.98
Elongation at break - % Output 2	flow	356 ± 73,9	514
	across	475 ± 95,9	626

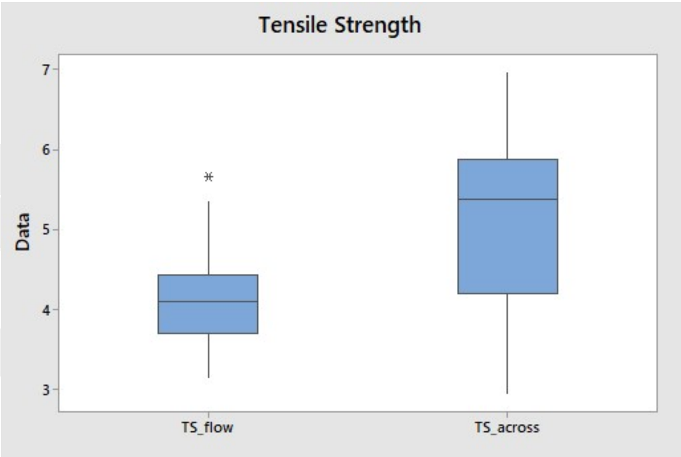

Figure 50 Tensile strength of 2nd DOE validation analysis

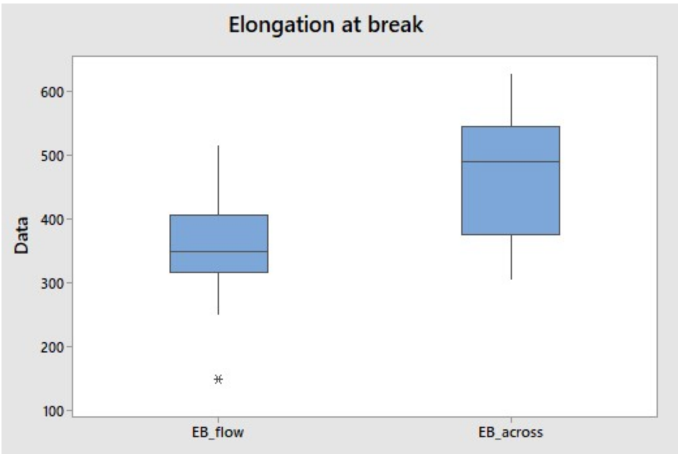

Figure 51 Elongation at break of 2nd DOE validation analysis

4.2.5. Verification Study on Real Part

The solution set process parameters were used to produce an automotive sealing profile. The application was performed on a glass run channel profile that includes an EPDM extruded profile and TPE corner molding. The lip parts of the extruded profile had the same EPDM rubber compound as used in the study, and the corner moldings were made of the same TPE material, which has 65 ShrA hardness. The injection speed parameter had to be adjusted to 58 cm3/sec due to the related injection machine constants. Maximum and mean bonding forces measured on ten profiles are given in Table 19. Additionally, in Figures 52, the bonding forces with deviations and required specification value is illustrated. As it is seen, this verified the process parameters meet the bonding performance of the customer specification 185N (one of the corner molding areas in the GRC profile). As a conclusion, the set solution obtained in the 2nd DOE study also gives better results in a real weather-strip profile application.

Table 19 Bonding force results on a real sealing profile

Parameters		Best	
Injection speed – cm3/sec		62.5 - 58	
Holding pressure – bar		100	
Gate-joint distance – mm		50	
Mold temperature – °C		42.5	
Injection temperature – °C		230	
Cooling time – sec		28	
Holding time – sec		5	
Mechanical Test Results	Customer Spec.	mean	max.
Bonding Force	185 N	242.8 N	265N

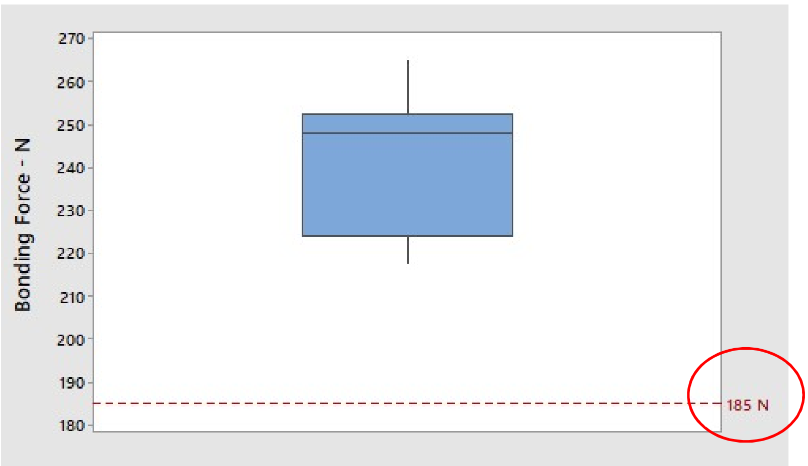

Figure 52 Bonding forces on a real sealing part

185 N: customer specification for one of corner molding area in GRC

4.3. Comparison of the Results

In this section, process parameters determined to enhance bonding performances for this EPDM-based compound and TPE material bonded using the wdk 2701 mold design are summarized in in Table 20. The parameters are listed as for the highest, lowest bonding strengths and the optimum (solution set) one found statically with Minitab software in the first and second design of experiments.

As shown in the table, the optimum process parameters named "solution set" have been obtained with maximum injection speed, mold temperature, and holding time and minimum holding pressure when the injection temperature was set at 230 °C and the gate-joint distance at 50 mm (to get the results in both directions) for the first design of experiment. And then, the parameters were revised and concluded in the second design of the experiment as mean levels of each factor, which are indicated in blue in the table.

Table 20 Summary of process parameters

1st DOE Study				**2nd DOE Study**			
Fractional Factorial Design				Fractional Factorial Design			
Six variables				Five variables			
R^2 88,07% for flow direction				R^2 60,91% for flow direction R^2 84,43% for across direction			
Parameters	**High**	**Low**	**Solution set**		**High**	**Low**	**Solution set**
A Injection speed – cm^3/sec	100	25	100	A Injection speed cm^3/sec	100	25	62.5
B Holding pressure – bar	100	300	100	B Holding pressure – bar	150	150	100
C Gate-joint distance – mm	100	100	50	C Mold temperature – °C	60	25	42.5
D Mold temperature – °C	60	40	60	D Injection temperature – °C	260	200	230
E Injection temperature – °C	260	200	230	E Cooling time - sec	15	40	28
F Holding time – sec	5	2	5				

The mechanical test results performed on the samples produced with those parameters are listed in Table 21. Tensile strength, which represents the bonding strength, was increased at the revised "solution set" in the second design of the experiment, which is highlighted in blue in the table.

Table 21 Outputs obtained from statistical analysis

Statistical Analysis Outputs		1st DOE Study			2nd DOE Study		
		High	Low	Solution Set	High	Low	Solution Set
Tensile Strength – Mpa	flow	7.05	2.11	4.60	5.89	3.13	4.58
	across	-	-	-	6.84	2.53	6.23
Elongation at break -%	flow	519	51	312	491	296	394
	across	-	-	-	560	303	525

The defined "set of solution" process parameters were validated with ten sample productions. The statistical analysis of the set solution was correlated. Table 22 shows the results of their mechanical tests. It is seen that the standard deviation of across-direction tensile strength rises while it decreases in flow direction.

Table 20 Validation study results

Validation Study Outputs		1st DOE Study	2nd DOE Study
		Solution Set	Solution Set
Tensile Strength – Mpa	flow	4.10 ± 0.74	4.12 ± 0.58
	across	4.04 ± 0.65	5.13 ± 1,09
Elongation at break -%	flow	304 ± 107	356 ± 74
	across	367 ± 107	475 ± 96

As a conclusion, "solution set" parameters were considered as the optimum solution for these materials and mold design as follows: when the injection temperature was set to 230 °C, the center injection speed was 62,5 cm3/sec, the center holding pressure was 100 bar, the center mold temperature was 42.5 °C, the holding time was 5 seconds, and the cooling time was 28 seconds. Tensile strength and elongation at break results at these parameters differ by 4.12 ± 0.58 MPa and 356 ± 74% in the flow direction and 5.13 ± 1,09 and 475 ± 96% in the across direction, respectively.

5. CONCLUSION

In this master thesis, the influence of the process parameters on the bonding strength between thermoplastic elastomer and EPDM-based thermoset rubber was investigated for the injection molding process. Additionally, the process parameters that give the highest and lowest bonding performance were analyzed and solution set (optimum) parameters were determined for the TPE and EPDM materials, which have a 65 Shr A hardness and a wdk 2701 mold design.

For this purpose two design of experiment study have been performed:

(i) fractional factorial design with 35 experiment runs with 6 variables; A: injection speed, B: holding pressure, C: gate-joint distance, D: mold temperature, E: injection temperature, F: holding time.

(ii) fractional factorial design with 19 experiment runs with 5 variables; A: injection speed, B: holding pressure, C: mold temperature, D: injection temperature, E: cooling time.

The bonding performance of EPDM-based compound and syrenic-based TPE material has been investigated statistically, and the results were controlled on ten samples produced with the obtained process parameters. The main controlled output was tensile strength, which was linked to the bonding strength of the material. Besides, the elongation at break results were also evaluated, which is important during the assembly of the weatherstrips after the injection molding process. The EPDM and TPE surfaces have been analyzed by scanning electron microscopy to observe the morphologies after mechanical testing. It was performed for the process parameters that give the highest and lowest bonding performances in the second design of the experiment study. At the end of the study, a real weather-strip profile was produced with the set solution process parameters determined statistically and validated with repetability analysis. It was observed that the bonding forces to split the profiles produced with those parameters meet the customer expectations.

The conclusion of the design of experiment studies was explained into two categories:

Influence of the process parameters on EPDM-TPE bonding strength:

It was observed from the experiments that intimate contact between the cold EPDM subsrate and TPE melt, which is related to the good wetting properties of the materials, is essential for bonding.

The most important factor in the bonding strength was found to be the temperature at the interface. The parameters such as mold temperature, injection temperature, and injection speed, which directly affect the interface temperature, have significant effects on the bonding performance. This result was demonstrated by the pareto charts: the injection temperature was the most effective factor in the flow direction results of each study, followed by the injection speed and mold temperature, and the mold temperature was the most effective factor in the across direction of the second study, followed by the injection temperature and injection speed. On a contour plot, the bonding strengths exhibited a continuous increase as an increasing function of injection and mold temperatures. Therefore, it was concluded that the bonding performance could be enhanced by working at as high temperatures as possible. Besides, injection speed influences the TPE material temperature due to shearing. Injection temperature and speed have an effect on the decrease of TPE material viscosity. This means that TPE material easily diffuses into the EPDM subtrate due to its lower viscosity at high temperatures and speeds. The hot TPE melt with a lower viscosity increases the wettability of the materials at the interface and thus the bonding performance.

Higher mold temperatures also support the intimate contact between the materials since the TPE melt co-crystalizes later and has much more time to diffuse into the EPDM substrate. That’s why it is important to set the mold temperature high enough to create sufficient bonding.

As it is mentioned in the literature, the requirements for optimum polymer chain diffusion are: high wettability of the TPE melt on the substrate surface and low TPE viscosity to penetrate into the voids and the substrate roughness (Packham, D., E., 2005). All these parameters are compatible with each other to enhance the bonding, and each of them is important for polymer mobility, chain diffusion into the EPDM interphase, and entaglement for stronger bonding.

Holding pressure, which was found as a negative single-effect variable in the study, should be adjusted high enough to allow the TPE to easily flow into the EPDM substrate cavities while not move the EPDM substance in the mold, which is critical for good intimate contact between the materials and strong bonding.

It is important to remember that the process temperatures and holding pressure variables should also be controlled to avoid degrading the TPE material and prevent part quality failures such as warpage, spots, dimensional changes, and so on.

The holding time and cooling time do not have a direct positive effect on the bonding. It is required to adjust them to give enough time for crystalization of the materials and fix the morhology for strong adhesion.

The factor of mold gate and joining distance, which is referred to as the distance between the mold entrance and the EPDM-TPE contact area, does not give reliable results in the study. This is one of the reasons for generating the second design. From the second study, it was understood that the bonding strength in the across direction was higher than in the flow direction. This may be because the flow does not stop in the contact area of the flow direction parts and continues throughout the mold due to the mold design. And, the TPE melt meets the parts in the across direction last and stops. This may provide a more stable and high-contact area and improve the bonding for parts in the across direction.

Process parameters determined to enhance bonding performances:

As a second aim of the study, injection molding process parameters were determined for this EPDM-based compound and TPE material bonded using the wdk 2701 mold design. The parameters found in the first and second design of experiment studies were summarized in Section 4.3. And as a conclusion of two design of experiment studies, "solution set" parameters were considered as follows: when the injection temperature was set to 230 °C, 62,5 cm3/sec injection speed, 100 bar holding pressure, 42.5 °C mold temperature, 5 seconds holding time and 28 second cooling time. At those center levels, tensile strength and elongation at break results were obtained as 4.12 ± 0.58 MPa and 356 ± 74% in the flow direction and 5.13 ± 1,09 and 475 ± 96% in the across direction, respectively.

The defined "set of solution" process parameters were validated on a two-component sample sheet, and then real weather-strip profile production. It was seen that the bonding performance of the real weather-strip profile had fulfilled the customer's expectations at those process parameters.

In Scanning Electron Microscope (SEM) analyses, more porous structure were obtained on the EPDM and TPE surfaces of the parts produced using the "solution set" process parameters.

Finally, this study demonstrates to us which/how the process parameters are essential to improve the bonding performance. The findings will serve as a guide to solve potential bonding issues between EPDM-TPE materials. Furthermore, wdk 2701 mold and set solution process parameters will be utilized to compare and evaluate various TPE and EPDM materials' bonding performances to generate an alternative materials database for weather-strip production.

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