RUBBER EXTRUSION PARAMETER OPTIMIZATION

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TIIVISTELMÄ

Opinnäytetyön tilannut yritys tarjoaa erilaisia lastinkäsittelylaitteita ja -ratkaisuja asiakkailleen. Opinnäytetyö tehtiin yrityksen merenkulkuun ja erityisesti kuivarahtiin erikoistuneeseen yksikköön, jonka yksi tuoteryhmä on alihankintana valmistetut lastiluukuntiivisteet rahtilaivoihin. Opinnäytetyössä haettiin optimaalisia ajoparametreja uuden lineaarisen lastiluukuntiivistetuotteen suulakepuristusta varten. Työssä tarkasteltiin ruuvinopeutta, kumimassan lämpötilaa ja ulostulevan profiilin pintalämpötilaa. Kyseiset ajoparametrit ovat vain tälle yhdelle tietyn muodon ja koon omaavalle tiivisteelle kun se valmistetaan yhdellä tietyllä kumisekoitusreseptillä, suulakkeella ja kylmäsyöttö suulakepuristimella. Yrityksen lopullinen tavoite on saada tämä lineaarinen tiivistetuote hallittuun massatuotantoon. Tämän opinnäytetyön teoriaosa käsittelee kumia materiaalina ja sisältää lyhyen yleiskatsauksen kumituotteen suunnitteluun, valmistukseen, eri työstötekniikkoihin ja kumin testaukseen. Näitä aiheita on käsitelty lastiluukun kumitiivistetuotannon näkökulmasta ja tätä opinnäytetyötä tullaan käyttämään uusien suunnittelijoiden perehdytysmateriaalina.

Optimaalisten ajoparametrien löytämiseksi suoritettiin nykyisen työohjeen ohjearvojen perusteella niistä alitettuja ja ylitettyjä koeajoja 13 kappaletta. Tiedot koeajoista kerättiin manuaalisesti ja niitä käsiteltiin Excel -taulukkolaskentaohjelmalla. Suulakepuristimen koeajoparametrien arviointi perustui niiden tuottamien tulosten vertailuun tuotteen teknisessä piirustuksessa olevien mittatoleranssien ja standardipuristumakäyrän välillä.

Saatujen tulosten perusteella nykyisen työohjeen ruuvinopeus, kumisekoituksen paine ja lämpötila voivat kaikki olla hieman nykyistä korkeampia. Kaikista kriittisimmäksi ajoparametriksi tämän tuotteen osalta muodostui kumisekoituksen lämpötila suulakepuristimen päässä. Ylärajoja ei saavutettu ajoparametrien kanssa, mutta alarajoista saatiin enemmän tietoa. Yksi tuotteen teknisen piirustuksen apumitoista kannattaisi myös lisätä kriittisiin mittoihin antamalla sille mittatoleranssiraja. Tässä työssä tehtyjen laajojen ajoparametriyhdistelmien jälkeen on helpompi tarkastella jotakin tiettyä parametria ja sen vaikutusta tiivistetuotannon laatuun tarkemmin. On suositeltavaa toistaa työssä löydetyt ajoparametrit kolmesti pitkien ajoaikojen kanssa, jotta voidaan lopullisesti varmistua opinnäytetyön tuloksista.

ABSTRACT

Tampereen ammattikorkeakoulu
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PAULIINA PELTOLA:
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The company which ordered this final thesis is providing a wide range of cargo handling equipment and solutions. This final thesis was carried out for the marine division and especially to the department which designs dry cargo related solutions. This thesis is a study for the optimal parameters for cold-feed rubber extrusion with one new hatch cover packing profile for bulk vessels. Optimal parameters are for this specific profile shape and size with one specific compound recipe, die and extruder. Final aim for the company is to get this linear profile into controlled mass production. This final thesis is going to be used as training material for new designers. The theory deals with rubber as a material and it consists of short general review into rubber product manufacturing. Designing of rubber product is reviewed as well as different machining and test methods, from the point of view of hatch cover packing.

Experimental extrusions were carried out with parameters above and below from the present working instructions for this seal product. Data from these totally 13 different combination of experimental extrusion parameters, were collected manually. From each extrusion 3 duplicate samples were taken. From them, dimensions before and after vulcanization, hardness, surface quality and compression curves were studied. The data was processed with Excel spreadsheet. The results were referred to the dimension tolerances and standard compression curve of the technical drawing for this packing product.

These results suggest that the current ranges of present working instruction can be updated into higher values, what comes to the screw speed, head compound pressure and temperature. The head compound temperature was found to be the most critical one from these three parameters under study. In the technical drawing of this packing product, one dimension tolerance can be changed from additional to critical one by giving it a tolerance. Further research is required to confirm these now founded extrusion parameters by conducting extrusion according to the new extrusion parameter ranges three times with longer extrusion times.

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Key words: extrusion, hatch cover, packing, rubber, seal.

INDEX

1   INTRODUCTION

This final thesis is studying one rubber product machining technique extrusion from the point of view what is relevant in the present hatch cover packing manufacturing of the company. This study is concentrating only into a one specific linear hatch cover packing product while hatch cover packing corners are made with molding technique. This linear seal profile is manufactured with cold-feed extruder which has one feed-screw. The parameters to be optimized are the screw speed of extruder, the extrusion head compound temperature and the surface temperature of output seal profile.

This final thesis is based on to the present extrusion parameters of the working instruction. There was no specific parameter or direction to be taken, only confirm that the present parameters are the best ones. To gain this information there were conducted experimental extrusions above and below these present values. Totally 13 different combinations of extrusion parameters were extruded and three duplicate samples were taken from each combination. Three duplicate samples were taken from all of the extrudates, starting from band-end closest to the extruder, at intervals of 70 cm. Before and after vulcanization four different dimensions were measured from these totally 39 duplicate samples. Hardness was measured on Shore A –scale from every duplicate sample. Compression curves were measured, while sample was in metal holder, which imitates the rubber channel, where the packing is located in hatch cover. Finally the detail dimensions of profiles were measured. Dimensions after vulcanization and compression curves were compared with the actual extrusion parameters to find the relations between them.

Major part of products which are designed in the dry cargo has something to do with metals and especially steel. Rubber materials are minority part of the designing, but crucial part of the weathertight hatch cover. It is important for designers also have basic knowledge of rubber material besides of metals. This final thesis theory is reweaving essential parts of rubber product manufacturing. In the experimental part of this final thesis which is confidential, there is dealt the present hatch cover packing manufacturing in more details. Rubber as a material is very different when compared it to other materials. In this final thesis theory there are several examples of its uniqueness. When one wants to use wood material choice can be made between

different trees like pine or mahjong. In some cases used wood material can also be combinations of few different trees. When one wants to use rubber material choice can also be made between different rubbers like natural rubber or chloroprene rubber but there are not available just a chloroprene rubber but several different chloroprene rubbers with different chemical compositions. In chapter 3.2 is told more about rubber compounding and choices one has to make when using this material.

2   RUBBER AND RUBBER PACKINGS

Rubbers and plastics are consisting of short molecule chain units called monomers. When these units are linked to each other polymer is formed. In polymer there are certain frequencies for one or more monomers to be appearing in it. Polymer is a rubber when its main chain is flexible in the temperature it is used, its individual chains can be cross-linked to each other and its main chains has not got any weak links (example O-O) (Kothandaraman 2008, 1–2). This cross-linking of rubber is achieved by vulcanization (see chapter 3.4) which plastics do not need.

2.1   Short review into the history of rubber

In 1521 was the first written word about the rubber balls although first rubber plants are known to exist from over 50 million years. These balls were made of natural rubber latex of the *Hevea brasieliensis* rubber trees, caoutchouc. No-one knows when the latex of rubber plant was found useful the first time. Rubber plants only grow in the area which is inside of 15 degrees, on both ways, from the equator. Europeans were very suspicious about the new magical material but some of them used it in order to help different diseases. (Palo-oja & Willberg 1998, 17–72.)

Synthetic rubber was created after hard demands of rubber raw material which could not be satisfied in the end of the 1800 –century because Brazil owned 80 % of the worlds rubber raw material resources. Demanding only increased after the air filled rubber tire was invented and the motorization spread fast. At the beginning of the 1900 -century the pressure just kept arising to find another source of rubber raw material beside of the natural rubber. The first one, who patented the synthetic rubber manufacturing method, was a German chemist Fritz Hofmann in 1909. During the wars rubber was one of the most important raw materials for the war equipments and every country tried to be self-supported. Natural rubber again came to be more used than synthetic rubber because synthetic rubbers did not have any better features or the costs were too high to achieve those. (Palo-oja & Willberg 1998, 17–72.)

Wars had a big effect to the rubber industry. In 1933 styrene-butadiene rubber (SBR) was invented by the Germans, ethane-propene rubber (EPM) and ethane-propene-diene rubber (EPDM) was invented by the Italian industry during the years 1958 – 1959. In the early 1980's 70 % of the natural rubber production was in Southeast Asia and only 1 % in Brazil. (Palo-oja & Willberg 1998, 17–72.)

Rubber first came to Finland in the middle of the 1800 –century as goloshes which were luxury products. Rubber parts were also imported inside of different industrial machinery which were bought from foreign countries. Even then, the rubber recipes were highly classified which meant that rubber product workshop establishing was almost impossible in Finland. The first goloshes made in Finland were so poor-quality that it took a long time to convince customers that those Finnish rubber products had as good quality as the imported ones. In 1915 Finnish rubber manufacturer, called Suomen Gummitehdas Osakeyhtiö, had already a wide rubber product range from a golosh to a rubber packing beside of the different kinds of tires and hoses. Another one like that general rubber product plant was not established, on the contrary, workshops were created to specialize into only narrow range of rubber products. (Palo-oja & Willberg 1998, 17–72.)

In the middle of 1920's, due to the lack of natural rubber, Finnish rubber industry begun the usage of secondary rubber raw material. During the wartime the usage of reclaim increased temporarily. Recycling is not developed because of the environmental concerns during the latest years on the contrary it was taken into usage because of the lack of virgin rubber raw material. During the 1960's slowly increasing building and automotive industry the demand for different kind of rubber profile bands encouraged Finnish technical rubber producer to expand their production into rubber profile bands, too. (Palo-oja & Willberg 1998, 17–72.)

2.2   Rubber as a material

The main feature that distinguishes rubber from other materials is its reversible deformation ability (even 1000 %). Rubber has a unique mix of features: small toughness, it is almost perfectly incompressible, it has good wear-resistance, high friction and good resistance to corrosion. Due to these features, rubber has functions

like elasticity, damping, sealing, protection and / or holding together. Toughness is depended from the number of cross-linking sections in rubber material. The rubber will be tougher if number of those sections increases. (Nokia tekninen kumi N.D. 23; Mark & Others 2005, 402, 405.)

The production distribution between natural and synthetic rubber in the world is seen in figure 1 (adapted from International Rubber Study Group 2012, modified). In figure 2 (adapted from Mark, Erman & Eirich 2005, 402, modified) is shown in more details which industries uses the natural rubber.
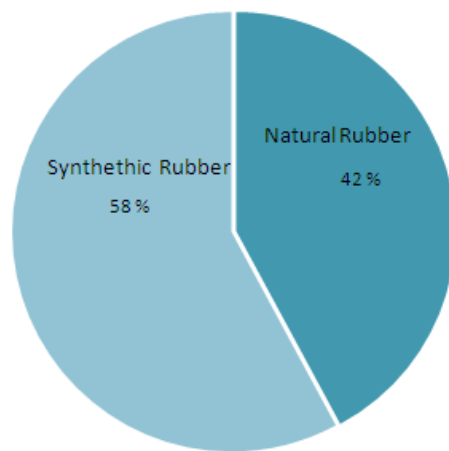

FIGURE 1. World Rubber Production in 2011 (adapted from International Rubber Study Group 2012, modified)
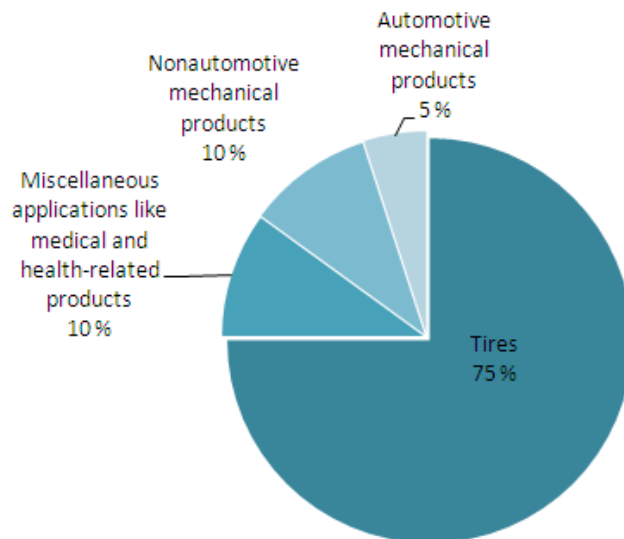
FIGURE 2. Global Natural Rubber Consumption (adapted from Mark & Others 2005, 402, modified)

Rubber is a unique material also in its ageing features, with ageing is meant chemical process caused by oxygen in the air, which results into a loss in physical features. Rubber has a memory meaning that the conditions and events it has undergone during its lifecycle can withstand in it. There are big effects on the quality of rubber in the way it has been stored; has it been in a warehouse where the temperature arises close to +40 °C during summer time, or has it been in very moisture air or has the raw rubber been frozen during the storing. (Metalliteollisuuden Keskusliitto, MET 2001, 153; Väliaho 2012.)

Rubber does not have such a positive image from the environmental point of view because synthetic rubber is made from crude oil the same way as plastics are. The usage of plastics is in larger volumes than the usage of rubbers. This is the reason why plastics re-usage is generally more studied which also has led to that it is partly easier to carry out. As seen in the figure 3 (adapted from Mark, J. & Others 2005, 404–405, modified), the biggest consumer of the synthetic rubbers is the tire industry which uses about 60 % of the global synthetic rubber. (Nokia tekninen kumi N.D. 23; Mark & Others 2005, 402, 405.)
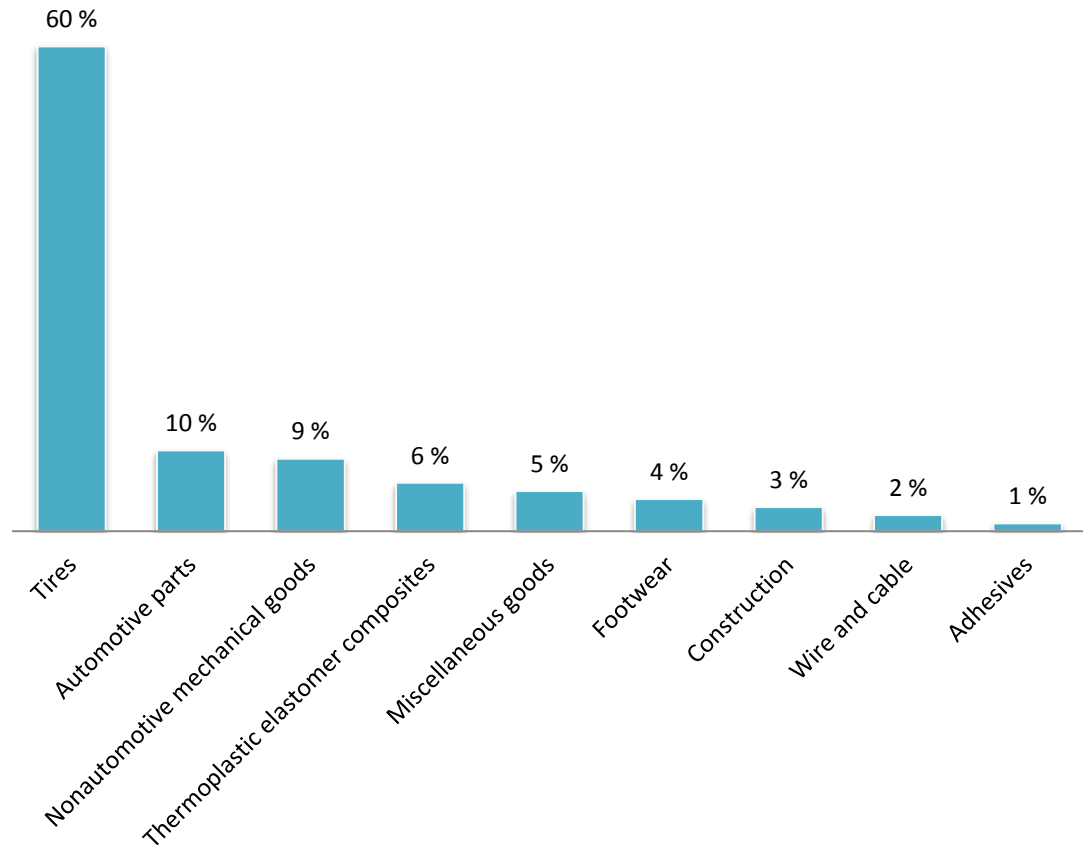
FIGURE 3. Global Synthetic Rubber Consumption (adapted from Mark & Others 2005, 404–405, modified)
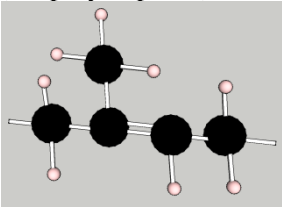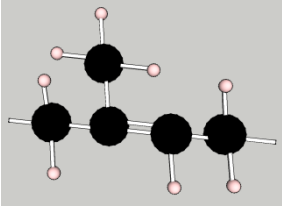
2.2.1 Rubber types and rubber grades
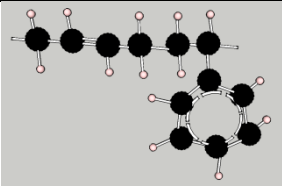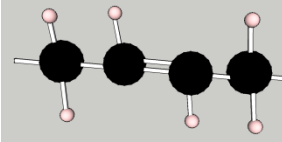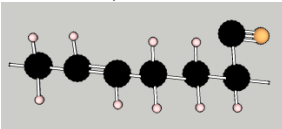
There exist several different types of synthetic rubber besides natural rubber. Both, natural and synthetic, rubbers are divided further to different grades with several different ways. For example, natural rubber is available in three basic grades: technically specified, visually inspected rubber and specialty rubbers. There are six basic types of technically specified natural rubber: L, CV, 5, 10, 20, and 50. These grades have specific features, example, in dirt and ash content and with Mooney viscosity. Same thing is with the synthetic rubbers they are divided further into different grades and the characteristics of those grades can have dramatic differences between each other. This leads into a situation where purchasing of raw-materials have to be extremely professional and accurate.
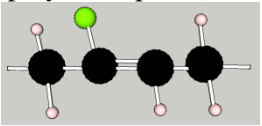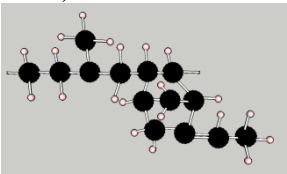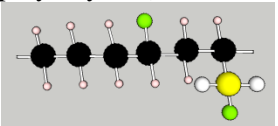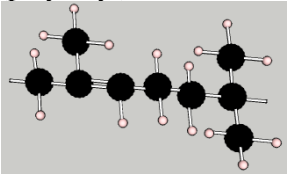
As an example of the simplicity of the term 'rubber' here are presented the following review into one rubber and its grades. One of the synthetic rubbers is polyethylene diene rubber (EPDM). When purchasing EPDM one has to choose from a wide range of different kinds of EPDMs. This elastomer has different kinds of features depending on the diene, for example, ethyliedene norbornene (ENB) is ten times more expensive than dicyclo pentadiene (DCPD). DCPD is cheap but its methine hydrogen may affect the cure efficiency. On the other hand 1, 4 hexadiene (HD) has the best ozone and heat resistance and it also gives ease for recycling the EPDM. EPDM usually has $4 - 5$ % content of diene which can be increased to $8 - 10$ % if faster cure is needed. Ethylene content in EPDM can vary from 45 to 75 % and when it increases it betters the extrusion with lower die swell and better shape retention but impairs the ease of mixing. (Mark & Others 2005, 402–405; Kothandaraman 2008, 54.)
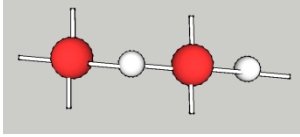
Table 1 is presenting the main features of natural rubber and few common synthetic rubbers. There are also figures of the monomer for most of the elastomers in table 1. Operating temperature range for each elastomer varies a lot between different literature sources, these temperature ranges in the table 1 are the most careful ones.

TABLE 1. Few Rubber Types (Nokia tekninen kumi N. D. 11, 36, 48–49, 51; Dick 2004, 239; Mark & Others 2005, 404; Kothandaraman 2008, 11, 35, 42, 44, 49–51, 53, 55, 57, 59, 62, 143; Lipasti 2008, 15, 17, Attachement Kumityyppien ominaisuuksia – table; Laurila 2011, 47, 53, 59, 61, 64–65, 67; figures: Pauliina Peltola 2012)

Elastomer		Features and examples of products	Long-term operating temperature range [°C]
NR	Natural rubber (cis-polyisoprene)	Nonpolar High tensile and tear strength without fillers Fast cure rate due to the carbon double bonds Pure microstructure which means content of cis-formed molecule is 100 % Excellent resilience Good cold resistance As a elastomer renewable natural resource Cannot withstand oils Poor weather and ozone resistance Limited lifetime in high temperatures and oxidative environments Products: tires, shoes, seals, hoses	From -22 to 55
IR	Isoprene rubber (cis-polyisoprene) So-called fake natural rubber	Features like NR Microstructure consists of different isoprene molecules unlike NR Does not get hard during storage Poor residual compression Poor weather and ozone resistance Cannot withstand oils Quite expensive Products: tires, shoes, seals, hoses	From -55 to +70
SBR	Styrene-butadiene rubber (polystyrene/butadiene)	Nonpolar Cheap When styrene content arise	From -20 to +70

		processability and tensile strength will increase but on the other hand temperature features and resilience will decrease at the same time (styrene content 23 – 25 % is the best) Excellent resilience Excellent residual compression features Resistance to acids Good ageing resistance Poor weather and ozone resistance Cannot withstand oils Largest volume synthetic rubber due to the tire industry Products: hoses, conveyor belts	
BR	Butadiene rubber (polybutadiene)	Used only in rubber mixes Fast cure rate due to the carbon double bonds Excellent resistant to freezing Good resilience Poor mechanical properties Poor processability Poor weather and ozone resistance Cannot withstand oils Products: tires	From -70 to + 80
NBR	Nitrile rubber (polyacrylonitrile-butadiene)	Polar Excellent residual compression Resistant to hot water Good resistance to oils Reinforcing fillers is a must for getting good strength properties Poor ozone and weather resistance Products: oil refining related products	From -10 to +70
CO, ECO	Epichlorohydrin rubber (polyethylene oxide, polyepichlorohydrin)	Excellent weather and ozone resistance Good residual compression Good resistance to oils ECO is quite expensive Products: oil refining related products	From -10 to +80
ACM	Acrylic rubber (polyacrylate)	Excellent weather and ozone resistance Good resistance to oils Poor water and gas resistance Poor resilience Poor acid and base resistance Products: motor seals and hoses	From -25 to +150

CR	Chloroprene rubber (polychloroprene)	Polar High tensile and tear strength without fillers Self-extinguishing (halogen included) Good weather and ozone resistance Better oil resistance than NR but only to splash oil Crystallization feature restricts use at low temperatures Quite expensive Products: weatherproof seals, conveyor and vee belts	From -20 to +70
EPM, EPDM	(polyethylene-propylene) (polyethylene-propylene diene) (ethylidenenorbornene trimer)	Nonpolar Excellent electrical, heat, ozone, weather and light resistance, suitable for out-doors Good chemical, wear and heat resistance Can be extended with large amount of oils which leads to lower costs, although elastomer itself is not the cheapest one Slow cure rate Poor gas and oil resistance Poor strength properties Poor glue-ability and self-adhesion Products: seals (aviation, highway joints, petroleum), cable coverings, profile bands	From -30 to +80
CM, CSM	Chlorinated ethylene rubber (chloro-polyethylene) Chlorosulfonated ethylene rubber (chloro-sulfonyl-polyethylene)	Excellent heat, ozone and weather resistance Good chemical resistance CSM has excellent wear resistance and color preservability Products: chemical hoses, rubber blankets	From -20 to +80
IIR	Butylrubber (polybutyl)	Nonpolar Excellent heat resistance Excellent gas tightness Good weather and ozone resistance Resistant to oxidative chemicals Resistance to acids Slow cure rate Low resilience Difficult to process Cannot withstand oils	From -10 to +80

		Poor resistance to freezing Products: tire tubes, cables, seals, steam hoses, balloons	
Q	Silicone rubber (polysiloxane)	Excellent heat and cold resistance Good ozone resistance Poor resistance to steam Poor wear resistance Cannot withstand oils Poor resilience and gas tightness Poor resistance to acids and bases Products: special seals, cable covering	From -50 to +200
FPM	Fluorine rubber (polyheksafluorineprope ne/ vinyldienefluoride)	Excellent heat and chemical resistance Excellent weather and ozone resistance Good oil and fat resistance Good resistance to oils Better acid than base resistance Low resilience Products: special oil resistant seals and hoses for high temperatures	From -20 to +175

The line between plastics and rubbers is getting more and more inaccurate in the future. New materials are being developed and these two materials are mixed-up together. Rubber and plastic are evolving towards polymer technology which includes elastomers and polymers. (Nokia tekninen kumi N.D. 18.)

3   RUBBER PRODUCT MANUFACTURING

Basis for any rubber product are demands for performance, quality, environment and cost. Performance demands come from the customer and the rubber product should answer to these with good quality features, like durability and good appearance. Not forgetting surety that the quality will be consistent and products will be uniform. More and more environmental demands are affecting the manufacturing and end-use features, including disposal. (Mark & Others 2005, 453.)

3.1   Rubber product designing

Rubber designing is considered to be more challenging than designing products from other materials. Rubber compound is unpredictable and small changes in the rubber compound will have effects which can be sometimes not logical, at first hand. Designing rubber products is said to be 'black-art'. Basis of the design work is functional product, suitable lifetime and the possible additions, like fibers, structural stiffeners or coatings. Elastomer is just a part of the rubber product but it should be chosen correctly to answer to the chemical and physical demands of the products end-use environment. Additives and fillers can only support the features of that elastomer. (Nokia tekninen kumi N.D. 48, 52, 58; Metalliteollisuuden Keskusliitto, MET 2001, 129)

Mechanical product shape optimizing will increase the rubber products lifetime. Processing possibilities will often cut down the design alternatives which seem good on the paper. Better rubber designing aims to avoid local strain maximums in the rubber product and tries to distribute the strain evenly throughout the product. Long-term deformations should be small, no deformation over 30 %. The viscoelastic nature of rubber and big deformations sets challenges into the designing stage. Rubber material also undergo shrinkage during the machining approximately $1 - 4$ %. (Nokia tekninen kumi N.D. 48, 52, 58; Metalliteollisuuden Keskusliitto, MET 2001, 129)

The physical end-use environment of a product and synergism of chemical factors will not either help the design work. Service life is also hard to evaluate because of the

features mentioned above. There are also installation and maintenance point of views to be considered. In practice, designing rubber products are married to testing the best early stage prototypes as finished products. This differs from other material designing because with rubbers it is done already in early stage more by practical work than theoretically. Rubber prototype products are tested in imitated working environment using accelerated ageing in higher temperatures than the real working environment has. Though, there are signs indicating that accelerated heat ageing tests will lead to overestimating the natural ageing effects (Brown, Butler & Hawley 2001a, 21).

In packing designing there are features like lubricating film, pressure and pressure shocks to be taken under consideration. Especially with rubber packing the effect of substances are important to be tested: is there any swelling or shrinking of the rubber, when it is in contact with them. The structural demands of packing design begin from the profile shape and possible air channels that give more elasticity to the final product. Thermal durability of the final packing product should also be tested to find out the lowest and highest operating temperatures. (Nokia tekninen kumi N.D. 48, 52, 58; Metalliteollisuuden Keskusliitto, MET 2001, 129.)

Usually the elastomer chosen for the product is compromise between the several wanted features. For example, good oil resistance demands polar elastomers, which means the molecule chains interactions are large-scaled and resistance to freezing is due to that, poor. Another example is, when good strength properties are achieved with weak polysulfic networking but this means that heat stability and residual compression will be poor. (Nokia tekninen kumi N.D. 48, 52, 58; Metalliteollisuuden Keskusliitto, MET 2001, 129.)

3.1.1 Hatch cover packing designing

Hatch cover packing designing, same as every other rubber application, demands comprehensive knowledge and approach from the designer, not only rubber knowledge but more specific the demands of the end-use environment. Hatch cover seal is the final piece of the complicated and wide jigsaw puzzle. This rubber product is a vital component of the final product which is the weathertight hatch cover. Packing itself is a

volume product which means the cost-effectiveness is the base of design and it limits the raw-material choices.

There are available designing equations for a few simple geometries when rubber pads are in compression. None of these can cover fully the packing designing and finite element analysis is the only usable tool in packing designing, because of these products complex nature. By complex nature is meant the profile shape and end-use environment of hatch cover packing with its several different forces and movements. Finite element analysis is only a tool and the results still depends from the skills of the analyst, if he or she can benefit from this accurate, versatile and comprehensive method. It can be very roughly said that finite element analysis is based on meshing the rubber product. It is dividing it into small parts which can be studied more carefully as independent units. Böl & Reese (2005, 25) have created a finite element simulation for elastomeric polymers, which is based on physical chain statistic. In this simulation the only user-defined parameter is the ratio of the number of chains per reference volume. Simulation already consists of number of chain segments, number of chains per reference volume and the parameter which depends on the valance and the rotation angle of the chains. This way local strains and stresses in the microstructure of a rubber product are found and can be taken account in the design process. Figure 4 is showing an example of rubber-boot meshed in finite element analysis (adapted from Böl & Reese 2005, 21–22).
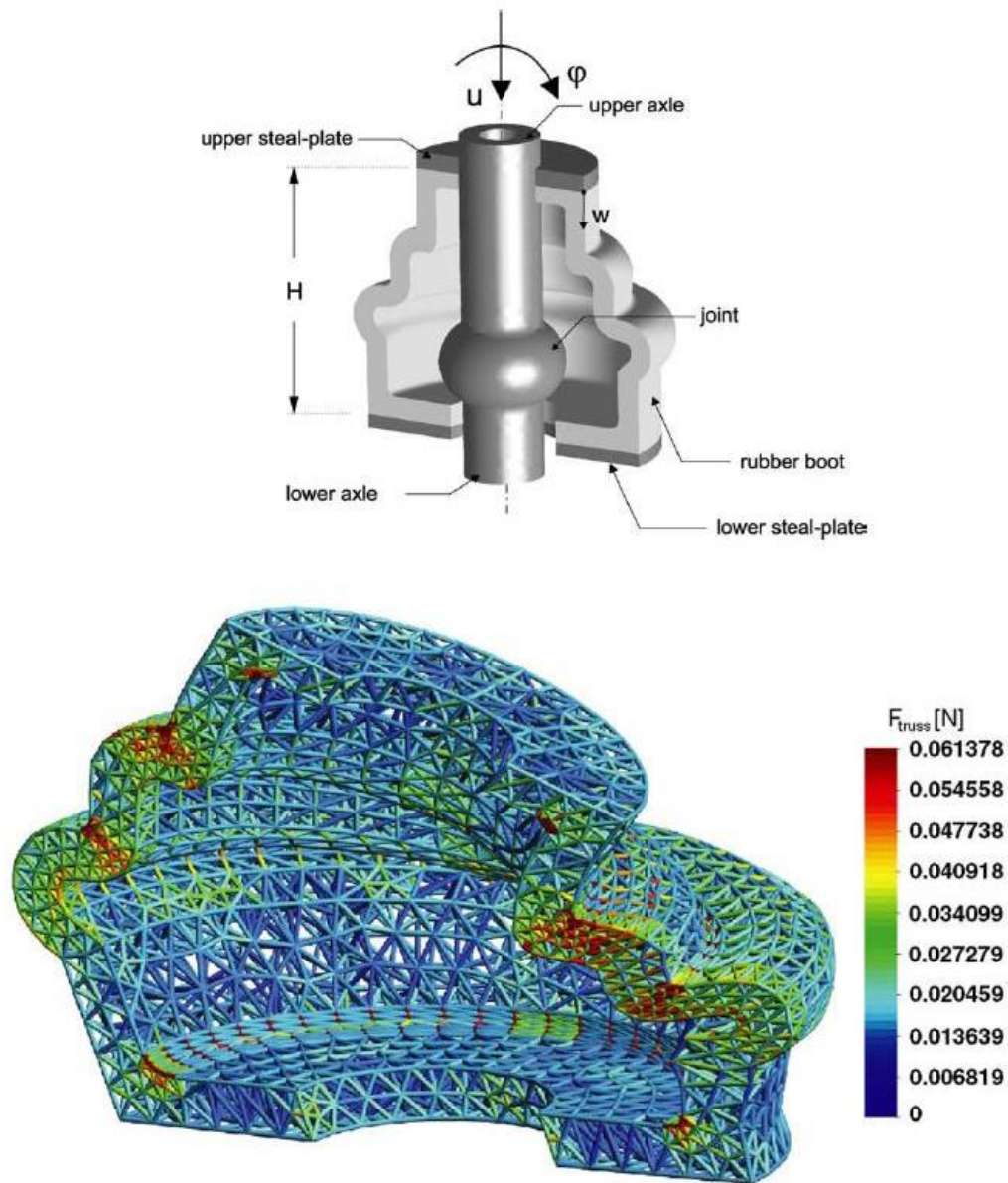
FIGURE 4. Finite Element Analysis of Rubber-boot (adapted from Böl & Reese 2005, 21–22)

3.2 Rubber compounding

Compounding term means what to mix together while mixing term tells how to mix. Rubber is always a forced mixed compound of different substances. The reason for this complicated mix is that no elastomer can work alone because of the lack of vital features demanded from rubber product. These features are not achieved only by the elastomer usage alone. All of the materials in rubber compound have to be environmental safe. This means meeting the current demands arising from the current chemical effect knowledge. Compound should also meet the occupational health and

safety requirements, not to mention the processability in the manufacturing facilities and cost effectiveness. (Nokia tekninen kumi N.D. 51; Johnson 2001, 9; Mark & Others 2005, 325, 401; Brown 2006, 65, 72, 76, 82–83, 104–105; Hahtola 2006, 25; Vuori 2006, 6, 13, 17; Kothandaraman 2008, 13, 140; Lipasti 2008, 18, 20; Murtoniemi 2010, 8–10; Laurila 2011, 39–44.)

In mastication natural rubber which has very long molecule chains, is compounded alone. This way the longest chains are cut to shorter ones. Mastication helps the following modification because the rubber gets softer. It requires the presence of oxygen because oxygen binds the new created reactive chain ends and prevents them to rejoining to each other again. Mastication helps to reduce the molecule weight of natural rubber but it is not needed for synthetic rubbers. Their molecule weight is adjusted already in the polymerization phase. (Nokia tekninen kumi N.D. 51; Johnson 2001, 9; Mark & Others 2005, 325, 401; Brown 2006, 65, 72, 76, 82–83, 104–105; Hahtola 2006, 25; Vuori 2006, 6, 13, 17; Kothandaraman 2008, 13, 140; Lipasti 2008, 18, 20; Murtoniemi 2010, 8–10; Laurila 2011, 39–44.)

Rubber compound is blend of different substances. It can be divided into elastomers, filler systems, stabilizer systems, vulcanization system components and special materials. There are also several other different classifications for the rubber compound substances, depending from the point of view. Every substance added to the compound, will have some effect to the processability no matter what is the real purpose of the substance in question. Table 2 is presenting few interesting compound substances and their features.

TABLE 2. Rubber Compound Components (Nokia tekninen kumi. N.D. 20; Gent 2001, 25, 28–29; Johnson 2001, 61–62, 64, 83; Mark & Others 2005, 368–369; Kothandaraman 2008, 111, 118–119, 141–143; Lipasti 2008, 18–19)

Component	Examples of substances	Effect to the compound
Fillers	Carbon blacks, clays, silicas, silicates, calcium carbonate ($CaCO_3$), magnesium carbonate ($MgCO_3$), talc	Small particle size and good dispersion with the compound reduce resilience, improve tensile strength Lowers prize Carbon black add of 30 % can increase the tensile strength 1000 %
Plasticizers	Oils (aromatic oils, naphthenic oils, paraffinic and chlorinated paraffinic oils) Mineral oils (cheapest ones), liquid polymers (the most expensive ones), fatty acids, pine tar, rosin, esters, factice	Content generally around 25 % When content arises plasticizers are called extenders Gives toughness, lowers prize, improves resilience and resistance to low temperatures Reduces heat build-up during mixing Gives better flame-retardation with halogenated plasticizers
Other additives	Fibers, cross-linking agents, pigments, oils, resins, perfumes, metal oxides	For adjusting toughness and compound drying For better smell and appearance Can be a tackifying addition
Additives		
Accelerators	Sulfur	Cross-linking and chain length adjusting
Activators	Metal oxides (like ZnO), fat acids (stearic acid)	To activate vulcanization systems accelerators
Retarders	Magnesium oxide (MgO) for halobutylrubber compounds	Delays the initiation of vulcanization, reducing the possibility of premature vulcanization or scorch
Protective agents	Antioxidants, antiozonants, protection waxes (aromatic amines, phenolics, phosposites)	Thermal and UV resistance, antioxidants, antiozonants (like PVC into NBR) These agents move to the surface of product which can lead to dyeing
Mixing agents	Soap-like agents, chemical peptizers (sulfonic acids and pentachlorothiophenol)	Processing aids that lowers viscosity
Coupling agents	For silica filler	Links between fillers and elastomers, without decrease of resilience Reinforcement, improves strength
Blowing agents	Gas releasers and solvents	Creates puffiness and cells inside the matrix

Compound recipe is created in phr (per hundred rubber) units where every component are counted in relation to hundred elastomer units. For example, recipe can start from NR 90 phr and EPDM 10 phr with addition of carbon black 30 phr. This is why recipes are always more than hundred units. In good quality compound the elastomer content is around 50 – 60 % but more often in reality it is 35 – 40 % depending from the rubber application and machining method. High elastomer content in compound is expensive although the other substances are not either free of charge. Oil loads into the compound reduce viscosity and mechanical properties. Extrudability is improved with reinforcing fillers but heat generation is also increased during mixing. This may cause over mixing and reduce mechanical features. Processability can be improved by adding liquid rubbers in unsaturated rubbers, for example, liquid NR into NR compounds when it becomes part of the cross-link net. This way mechanical properties are not reduced. (Nokia tekninen kumi N.D. 51; Johnson 2001, 9; Mark & Others 2005, 325, 401; Brown 2006, 65, 72, 76, 82–83, 104–105; Hahtola 2006, 25; Vuori 2006, 6, 13, 17; Kothandaraman 2008, 13, 140; Lipasti 2008, 18, 20; Murtoniemi 2010, 8–10; Laurila 2011, 39–44.)

Large scale compounding is done in mixing chambers where horizontally installed rotors rotate to opposite directions. These chambers are huge three-store high automatically controlled mixing units. Before these chambers, mixing was done with mill rolls. Small volumes can still be mixed with these. Some smaller manufacturers can still use mill rolls but it is more common for them to buy the compounding from a bigger rubber company. (Nokia tekninen kumi N.D. 51; Johnson 2001, 9; Mark & Others 2005, 325, 401; Brown 2006, 65, 72, 76, 82–83, 104–105; Hahtola 2006, 25; Vuori 2006, 6, 13, 17; Kothandaraman 2008, 13, 140; Lipasti 2008, 18, 20; Murtoniemi 2010, 8–10; Laurila 2011, 39–44.)

Mixing the compound needs tack and adhesion to the mill roll or chamber. These features can be increased by tackifying resins add. When fillers are added in high loads there can be drying of the stock, this is why fillers should be added considerable. Steric acid and waxes can fight against compound drying likewise prevent it to get stuck on to the processing equipment. One of the most important phenomenons to avoid during all the way mixing and machining is heat build-up. It can lead to thermal degradation, unwanted vulcanization or even fire. The most critical point in rubber processing is mixing which leads to problems later on if distributive or dispersive mixing is

incomplete. (Nokia tekninen kumi N.D. 51; Johnson 2001, 9; Mark & Others 2005, 325, 401; Brown 2006, 65, 72, 76, 82–83, 104–105; Hahtola 2006, 25; Vuori 2006, 6, 13, 17; Kothandaraman 2008, 13, 140; Lipasti 2008, 18, 20; Murtoniemi 2010, 8–10; Laurila 2011, 39–44.)

Compound mixing process starts from feeding elastomer and other substances into a mixer, in correct quantities, at right time and in specific order and in right temperatures. The mixer is unloaded after actual mixing and this is followed by shaping and cooling down the compound before the final step which is packing. Compounded rubber has few unique features which are anomalous from other materials: high elasticity, abrasion resistance and dampening properties. Compound storage before it has been machined has effects to the compound. Viscosity increases during the storing until it reaches its steady state. With natural rubber this is studied to take longer (600 hours) than with synthetic rubbers (300 hours). Storing effects depends on the compound consistency, for example, the viscosity change will be greater with high filler loads. (Nokia tekninen kumi N.D. 51; Johnson 2001, 9; Mark & Others 2005, 325, 401; Brown 2006, 65, 72, 76, 82–83, 104–105; Hahtola 2006, 25; Vuori 2006, 6, 13, 17; Kothandaraman 2008, 13, 140; Lipasti 2008, 18, 20; Murtoniemi 2010, 8–10; Laurila 2011, 39–44.)

Basic commercial elastomers are available in thousands of different product names. Choosing the right one is easy if there is computer database from the different elastomer products and compound recipe features. When profile of the needed features is entered into the database, it will provide the most suitable components and elastomers to the user. This way the work is faster and more reliable, than choosing the best from experience based knowledge or memory. (Nokia tekninen kumi N.D. 51; Johnson 2001, 9; Mark & Others 2005, 325, 401; Brown 2006, 65, 72, 76, 82–83, 104–105; Hahtola 2006, 25; Vuori 2006, 6, 13, 17; Kothandaraman 2008, 13, 140; Lipasti 2008, 18, 20; Murtoniemi 2010, 8–10; Laurila 2011, 39–44.)

3.3   Machining methods

Rubber products can be machined several different ways. One of these methods, extrusion, is treated more profound in chapter 4. Other machining methods are calendaring, different mold techniques, coating and dipping.

Calendaring

With calendaring the product shape produced is rubber sheet. In calendaring machine there are usually three to six cylinders and the product manufactured with it can be sheet, film or reinforced sandwich structure, like conveyor belt. (Nokia tekninen kumi. N.D. 41; Lipasti 2008, 22; Murtoniemi 2010, 15.)

Molding

Compression molded rubber products are the most common ones and this method is also the most versatile processing method, it combines shaping and vulcanization together. Transfer molding is a bit more advanced method compared to compression molding. In this method compound is transferred from chamber threw channels to the molds. Injection molding is the most advanced method compared to the other molding methods. It combines extrusion screw-like part which warms-up and transfers the rubber compound into a hot closed mold. This machining method suits the best for the large quantity series. (Nokia tekninen kumi N.D. 41; Lipasti 2008, 22; Murtoniemi 2010, 15.)

Brushing / coating

In this method rubber paste is brushed onto fabric, after this solvent is evaporated and rubber coated fabric can be vulcanized. One of the oldest products made with this method are rain clothes likewise inflatable rubber boats are made this way. (Väliaho 1998b, 27.)

Dipping

A wide range of medical rubber products are manufactured by dipping, like gloves, catheters and condoms. In this technique a product-specific tool is dipped first into coagulation liquid and after that into latex liquid. After wanted layer is achieved, by dipping the tool several times into the latex liquid, it is put into a heat oven where drying and vulcanization happens. (Väliaho 1998b, 26.)

3.4 Vulcanization

Un-vulcanized rubber has the same features as chewing gum: it is sticky and do not maintain its shape after a large deformation. Vulcanization is a vital process step in rubber product manufacturing and will cause profound changes at the molecular level. Vulcanization system consists of vulcanizate, accelerators, the activators for accelerators and possible retarder. During the vulcanization elastomer chains are cross-linked together resulting into molecular sized network (figure 5, adapted from Mark & Others 2005, 322, modified). Cross-linking will happen in carbon double bond (C=C) or in the pendant group of the elastomer.
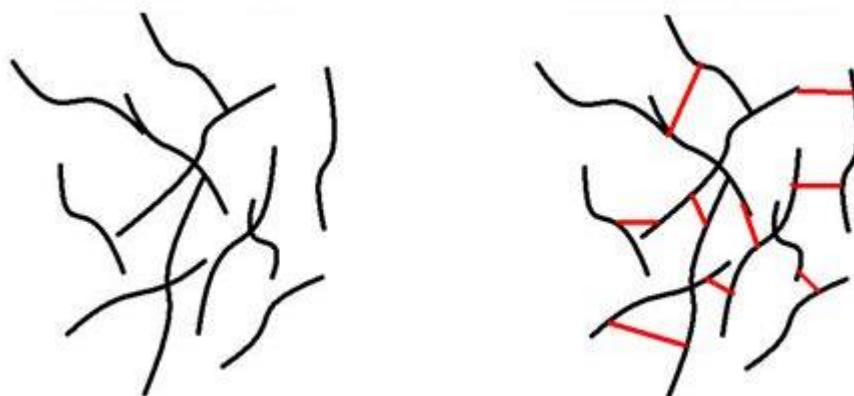
FIGURE 5. Unculcanized Elastomer Chains and Vulcanized Network (adapted from Mark & Others 2005, 322, modified)

Crosslink can be a single sulfur atom between the elastomer molecular chains (–R–S–R–), an ionic cluster, a group of sulfur atoms in a short chain (–R–S_x–R–), a carbon to carbon bond (–R–C–C–R– / –R–C=C–R–), a polyvalent organic radical or polyvalent metal ion. Sulfur cure is the most common one used and it reacts with the unsatisfied bonds in molecule chains. Sulfur curatives are the cheapest ones and give also the best mechanical properties. Polysulfide cross links may also improve fatigue life. When sulfur cure is used, if the sulfur content of partially soluble in rubber is more than 0.5 % it reduces tack in built up. This high sulfur content causes also blooming on to the final products surface spoiling the appearance. The usage of insoluble sulfur helps and it does not reduce the scorch safety in compound storing. The risk of premature vulcanization increases while compound is been stored. Blooming can be avoided by covering some of the sulfur with sulfur donor substances. Another common cure is peroxide cure. It

gives good heat and set resistance. (Nokia tekninen kumi N.D. 42; Gent 2001, 23; Mark & Others 2005, 321–324; Hahtola 2006, 25; Vuori 2006, 33; Kothandaraman 2008, 8, 94, 141–144; Murtoniemi 2010, 8–9; Laurila 2011, 32–33, 84–98.)

After the vulcanization rubber is relevantly insoluble into any solvent and cannot be processed in any way which requires it to flow. Controllable vulcanization process is vital in rubber product manufacturing if vulcanization starts too early the final form of rubber article cannot be achieved. There is also the possibility of reversion if compound is over-cured. This means crosslink loss due to the non-oxidative thermal aging. Most severe reversions happen when temperature is above 155 °C and with the compounds which contains many polysulfic crosslink. This leads to the usage of vulcanization delay aids and scorch preventions. Still the wanted cross-linking should happen fast when needed to and to be ended precisely at the right stage. Rubbers do not conduct well thermally, which means the vulcanization time increases hand-in-hand when the product size is getting larger. The vulcanization method, time and temperature should be carefully chosen depending on the rubber product in question, to avoid the surface to be over-cured and the inside to be uncured. (Nokia tekninen kumi N.D. 42; Gent 2001, 23; Mark & Others 2005, 321–324; Hahtola 2006, 25; Vuori 2006, 33; Kothandaraman 2008, 8, 94, 141–144; Murtoniemi 2010, 8–9; Laurila 2011, 32–33, 84–98.)

Rubber is a viscoelastic liquid, no matter is it vulcanized or not. Solid rubber product manufacturing necessitates elastomer chains to be linked chemically together by curing agents. This leads to volume changes during the curing process because van der Waal traction forces between elastomer molecule chains are replaced with shorter covalent bonds. This phenomenon is demonstrated in figure 6 (adapted from Mark & Others 2005, 323, modified) where on the left side is seen un-vulcanized and on the right side vulcanized rubber compound.
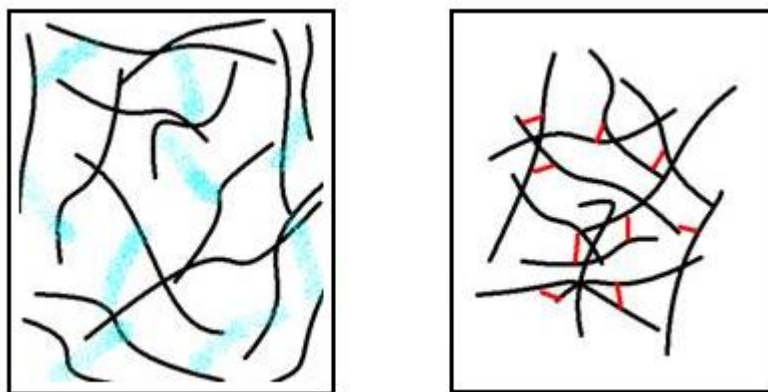
FIGURE 6. The Volume Change of Elastomer (adapted from Mark & Others 2005, 323, modified)

3.4.1 Vulcanization methods

There are different methods to vulcanize rubber compound. The method may include, for example, dry hot air, direct or indirect steam, microwaves, radiation or salt bath. Vulcanization process can be continuous or batch working. In continuous method the vulcanization happens straight after the machining. For example, after extrusion the profile can go on conveyor belt through a vulcanization tunnel. Continuous vulcanization demands special features from the compound like non-volatile and moist-free additives. Batch working method means that machining and vulcanizations are done in different stages. First the product is machined and stored up for a short period of time when it has to wait access to a batch working vulcanization oven. Dimensional stability is reached by connecting the elastomers, and other components of the compound, together with the help of heat and chemicals. Simplest way to achieve this is with the mold compression where during the machining the temperature of 150 – 200 °C will vulcanize the rubber compound. With calendar sheet products it is possible to vulcanizate the sheet when it goes over a big hot cylinder after the machining. (Nokia tekninen kumi N.D. 42; Gent 2001, 23; Mark & Others 2005, 321–324; Hahtola 2006, 25; Vuori 2006, 33; Kothandaraman 2008, 8, 94, 141–144; Murtoniemi 2010, 8–9; Laurila 2011, 32–33, 84–98.)

One of the most common vulcanization methods for rubbers is steam vulcanization which is done in autoclave. Autoclaves are also used in other places, like hospitals and laboratories where they are used for sterilizing equipment. In autoclave hot high

pressured steam is surrounding the rubber products. Direct steam vulcanization leaves the profile surface scaled that are called water prints. Generally used pressure varies from 9 to 15 bars, while the temperature range is 180 – 200 °C. With extrusion it is most common to have continuous vulcanization line which can be a hot air tunnel or salt bath. Hot air vulcanization is recommended to extrudates with mass under 0.5 kg / m. Salt bath contains generally 53 % potassium nitrate (KNO_3), 40 % natrium nitrate ($NaNO_3$) and 7 % natrium nitrite ($NaNO_2$). It suits for EPDM profiles which are peroxide vulcanizates. After bath profile is washed and cooled down. (Nokia tekninen kumi N.D. 42; Gent 2001, 23; Mark & Others 2005, 321–324; Hahtola 2006, 25; Vuori 2006, 33; Kothandaraman 2008, 8, 94, 141–144; Murtoniemi 2010, 8–9; Laurila 2011, 32–33, 84–98.)

With polar elastomers like NBR it is also possible to have microwave tunnel where friction heats up the extrudate around 200 °C. Microwave tunnel is more economical when the profile sizes are bigger. There are also available several other vulcanization methods like infrared, fluidized method and radiation based. Fluidized method includes small glass balls (diameter of 0.1 mm) in hot air temperature of 200 °C. Shock vulcanization method with temperature of 600 °C is suitable for cellular rubber products. (Nokia tekninen kumi N.D. 42; Gent 2001, 23; Mark & Others 2005, 321–324; Hahtola 2006, 25; Vuori 2006, 33; Kothandaraman 2008, 8, 94, 141–144; Murtoniemi 2010, 8–9; Laurila 2011, 32–33, 84–98.)

Vulcanization method and precise parameters are determined and based on the specific compound features, only this way manufacturing is successful. Incompatible compound cannot be cured successfully with any vulcanization. Compound, machining method and vulcanization method are depended on each other. No features or deviations in compound can be corrected in machining or vulcanization. (Nokia tekninen kumi N.D. 42; Gent 2001, 23; Mark & Others 2005, 321–324; Hahtola 2006, 25; Vuori 2006, 33; Kothandaraman 2008, 8, 94, 141–144; Murtoniemi 2010, 8–9; Laurila 2011, 32–33, 84–98.)

3.5 Finishing

Finishing can increase the manufacturing costs if complex finishing methods are needed. After cooling down the vulcanized products they are checked if the surface quality and dimensions are still according to the requirements. Finishing may include one or more work steps like blast finishing when the rubber products are small-sized, tearing, cutting with the large-sized products, grinding or punching. Cutting can be done with water jet cutting or with laser which is quite expensive, though. (Väliaho 1998a, 50–51.)

3.6 Recycling

Rubber recycling is very complicated because vulcanization is irreversible process. There are no good enough commercial method to recycle it. This is why the first approach to recycling is minimizing the left-over volumes. The better are the production planning, machining methods and process performance the less are the left-over volumes. Vulcanized rubber is infusible thermoset material but un-vulcanized rubber can be re-used quite easily even though it is processed. Reclaimed rubber means depolymerisated vulcanized rubber where molecule chains are cut to smaller ones. More profound method is devulcanization where the cross-link structure of rubber is destroyed. This lateral method is more energy consuming and expensive. (Mark & Others 2005, 663–665; Kothandaraman 2008, 123–125; Lipasti 2008, introduction, 13–16.)

Reclaimed rubber is said to be a good improver for compound extrusion properties. It gives better shape retention to the extrudate and also reduces die swell and shrinkage. Un-vulcanized rubber can be mixed (only in small quantities) back into the virgin rubber compound and then it can be processed again. Of course, the additives and compound formula will restrict this. Some carefulness has to take while mixing because rubber is unique material with its memory. Once processed rubber has some minimalistic differences compared to the unprocessed rubber depending from the current situation, compound and machining method. Extra compound rubber left over from processing cannot be stored for a long time because compound will age quickly to

un-usable state. (Mark & Others 2005, 663–665; Kothandaraman 2008, 123–125; Lipasti 2008, introduction, 13–16.)

Used old rubber products or new disqualified vulcanized articles are much harder to recycle. Every different recycle method starts usually from the step where the rubber waste is grinded. This grinded rubber can be used as cheapening additive up to 10 % in new products but its usage is more and more restricted. Nowadays, rubber products have got tight quality requirements and more demanding technical applications where reclaimed rubber might have some negative effect. Grind can be used to non-critical applications of rubber. It can also be used in landfill or in asphalt and cement modifying but nowadays these too, are more restricted. One way to re-use tires is burning them into energy but because of the risk of air pollution this is also currently more limited. (Mark & Others 2005, 663–665; Kothandaraman 2008, 123–125; Lipasti 2008, introduction, 13–16.)

Recycling methods can include retreating, reclaiming, pulverization, microwave and ultrasonic processes, chemical treatment, pyrolysis or incineration. Microwave method can be used when rubber has polar links, like sulfur. It is very energy-intensive. This is due to the fact that rubber-waste is made into devulcanized rubber with breaking the molecular level network formed in vulcanization. Although, after this rubber can be added to a virgin rubber without any loss in mechanical properties. Ultrasonic method only depolymerizes the rubber waste which means the rubbers re-usage properties are poorer. Cost level between virgin raw-material and regenerate is more or less the same. This means that manufacturers do not have any strong need for recycling as long as virgin raw-material is cheaper and easier to use than the regenerate. Rubbers unique material features leads to the situation where the creation of processed left-over rubber or even just left-over compound is better to avoid in first place than recycle afterwards. Tire industry has multiple rubber-waste volumes compared to other industries using rubber. This is the reason why tire industry will presumably show the way and lead other rubber industry branches to the possible new solutions in rubber recycling. (Mark & Others 2005, 663–665; Kothandaraman 2008, 123–125; Lipasti 2008, introduction, 13–16.)

4 EXTRUSION

In this chapter extrusion is examined more detailed, unlike the other machining methods. This chapter is concentrating into a cold-feed extruder with one screw and one die. Studied linear packing of hatch cover is extrusion product, manufactured with cold-feed extruder with one screw and one die.

In the late 19th century Paul Troester and his business partners introduced the first screw extruders to the rubber industry. Extruder is over one hundred year old technical invention. First ones were cold-feed extruders that mean that rubber compound is in room-temperature and extruder has to heat-up the compound itself. Later on, hot-feed extruders were taken into usage. Hot-feed extruders had integrated heating units for the compound. Nowadays, there are several differently structured extruders available, with one or more screws, for example. Besides screw structured, there are also obtainable ram extruders. Most commonly used ones are one die extruders although there are available extruders with more dies. (Mark & Others 2005, 289; Lipasti 2008, 21; Laurila 2011, 139–159.)

Extrusion technique is used mainly in hose and profile product manufacturing. There are few prerequisites in extrusion like the correct compound behavior in die, which includes dimension stability after the pressure and shape effect given by the die has ended. Likewise rubber compound flow under steady pressure has to be achieved. In figure 7 is shown the basic layout of the extruder type which is under study in this final thesis. (Mark & Others 2005, 289; Lipasti 2008, 21; Laurila 2011, 139–159.)
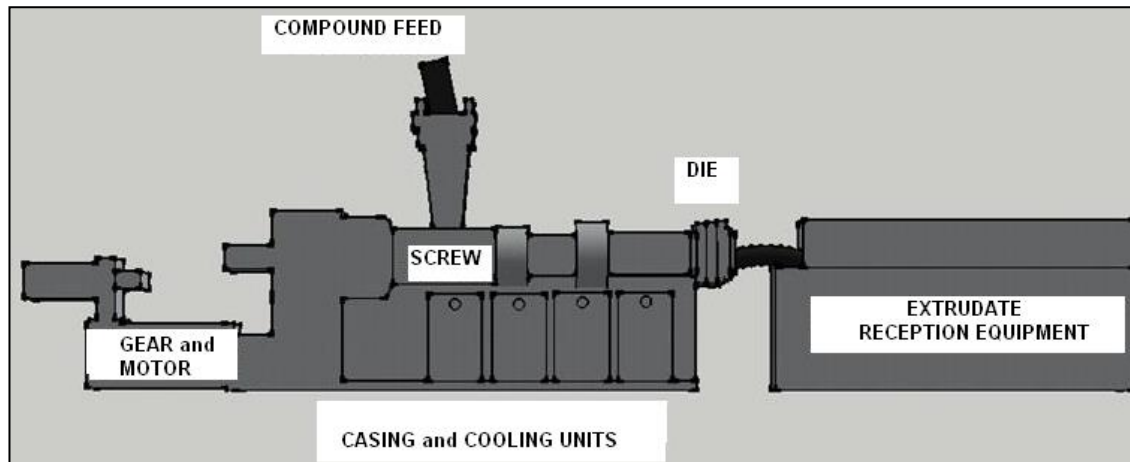
FIGURE 7. Extruder Layout (figure: Pauliina Peltola 2012)

4.1 Extrusion theory

In this chapter are only dealt with the basics of extrusion theory. Extrusion principle is simple but in practice extrusion is actually quite complicated and sensitive process. Main parameters in extrusion are temperatures, head compound pressure and screw speed. The dimensions of extrudate are measurable and the line speed of its reception equipment is adjustable. They can also be considered as an extrusion parameters. Screw speed is kept as a sensitive extrusion parameter, although it is compound related. Compound pressure is not adjustable during extrusion same way as screw speed because it depends from the viscosity of compound. Different extrusion parameters have different time responses when they are changed during the extrusion and these are depending on the parameter. For example, altering temperatures will effect slowly because of the materials heat capacity, while altering the screw speed the effects are immediate.

Flow in extruder is combination of transverse flow, drag flow, pressure flow and leakage flow. In order to compound transfer inside the extruder friction between compound and casing have to be greater, than friction between compound and screw. This is why screw temperature is held higher than casing temperature. The better the adhesion with rubber, the better the grip to barrel and the output will be greater. Between cold metal and rubber there is no adhesion but as the temperature arises about 50 – 70 °C adhesion will appear. Above that temperature range grip again fades out because rubber becomes softer. This is why feed zone is kept in that temperature range

mentioned, screw even higher and barrel cold. Figure 8 is showing a schematic diagram of an extruder flow channel (adapted from Johnson 2001, 96). (Johnson 2001, 96–98, 106; Hahtola 2006, 40, 43–45; Laurila 2011, 145.)
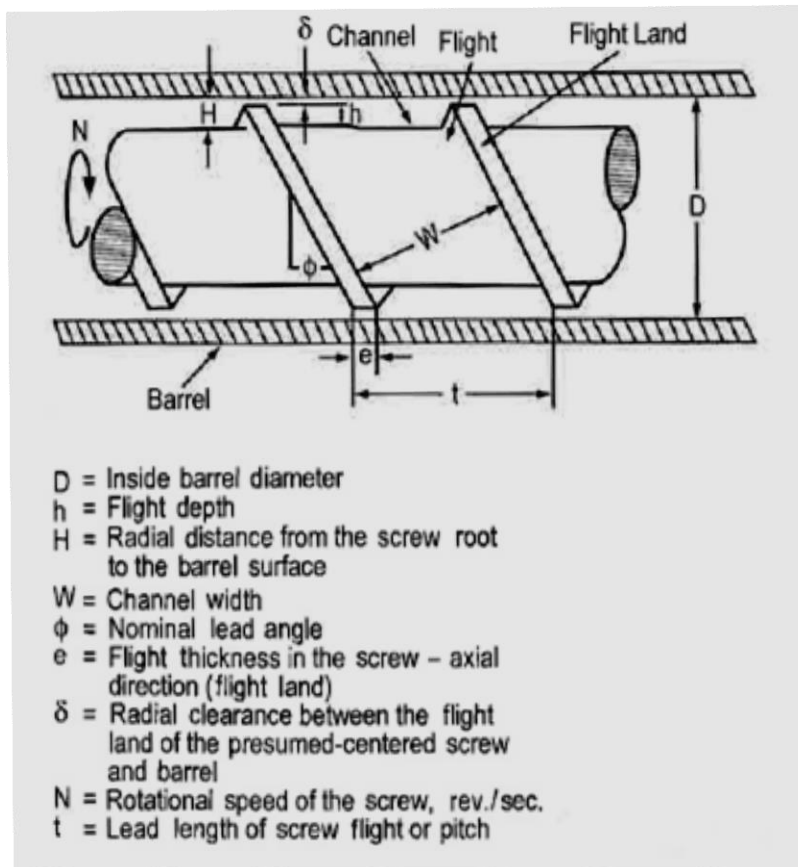
FIGURE 8. Extruder Flow Channel (adapted from Johnson 2001, 96)

Rubber behaves like a viscous fluid all the way in screw channel and transverse circulating flow happens in all cross-sections of the screw channel. The level of circulations is studied depend upon back pressure. (Johnson 2001, 96–98, 106; Hahtola 2006, 40, 43–45; Laurila 2011, 145.)

4.2 Extrusion set-up

Feed

One important issue which affects to the result of the extrusion quality is feed and the steadiness of feed (Väliaho 2012). First step in extrusion set-up is the rubber compound feed which can be done by hand or by machinery. In the feed of extruders there is cylinder which rotates to the opposite direction than the screw and this way transfers the

compound to the screw. The diameter size of feed cylinder is 1 – 2 times bigger than the feed screw diameter. Fixed ratio roll drive cannot take variations of feed strip size. For high precise extruding the feed strip has to be consistent width and thickness. Constant rate of the feed is also vital, which means there should not be no flooding or starving in feed hole. One interesting set-up in this step is the possibility of gear pump usage. These pumps are more used in plastic extrusion but there are good results from applying them into rubber extrusion. Rubber industry has been avoiding gear pumps because of their sensitivity although they provide pressure and constant output of the melt. This helps extruder to process more material when it is not used for pressure build-up anymore. When gear pump is integrated into extruder it increases considerable the productivity regardless of viscosity. (Aho 2008, abstract, 33–34.)

Screw

Gear and motor reduces the power to the screw which transfers the rubber compound forward to the extrusion head. Extrusion screw geometry is complicated and it could be said to be its own science. One basic feature of the screw is L / D relation which means the screw length and diameter relation to each other. Commonly the L / D relation is from 16 / D to 18 / D. These are longer screws for heating up the compound and the relation means, for example, when the diameter of screw is 200 mm the length is 16 times bigger than the diameter, 3200 mm. Compound heating happens due to its friction between the cylinder walls and screw. Screw mixes the rubber compound and it has different zones in it: feed zone, compression and transfer zone, homogenous zone. Another key figure in extruder is compression relation which means the volume change of screw channels during the screw range. How much it gets smaller when moving towards the extrusion head. Common compression relation is from 1: 1 to 1: 1.4 meaning the feed zone volume is 1.4 times larger than homogenous zone. Without steady pressure behind the extrusion die the out-coming profile will not achieve the right dimensions and shape. (Johnson 2001, 93–94, 106; Hahtola 2006, 22, 43; Vuori 2006, 25, 27; Laurila 2011, 139–144, 158.)

Casing

The casing of extruder is divided into different longitudinal areas which have their own, separately adjustable water-circulation that is generally used to cooling down the compound heated by friction. There should be enough output in water-circulation pumps to be able to produce efficient thermal exchange. Compound temperature differs

from these casing areas because of rubbers poor thermal conductivity. Only small surface area of the compound is in contact with the casing and they have only short contact time due to the high-speed processing. Under lower processing speeds these cooling areas have effect to the compound but when compound is pushed through the extruder in high-speed there is no time to heat transfer to happen in real-time. When compound temperature is higher, the mass expands and molecules are more separate from each other which lead into easier slip of the molecules. When this optimum temperature stage is been passed by, for example, with too high-speed extrusion, rubber will finally be scorched. This means clusters of vulcanized rubber inside the profile and / or on the surface of it. In figure 9 (adapted from Laurila 2011, 158, modified) is shown different aspects which are related to extrusion. These are not just the extruder machine related matters. (Johnson 2001, 93–94, 106; Hahtola 2006, 22, 43; Vuori 2006, 25, 27; Laurila 2011, 139–144, 158.)
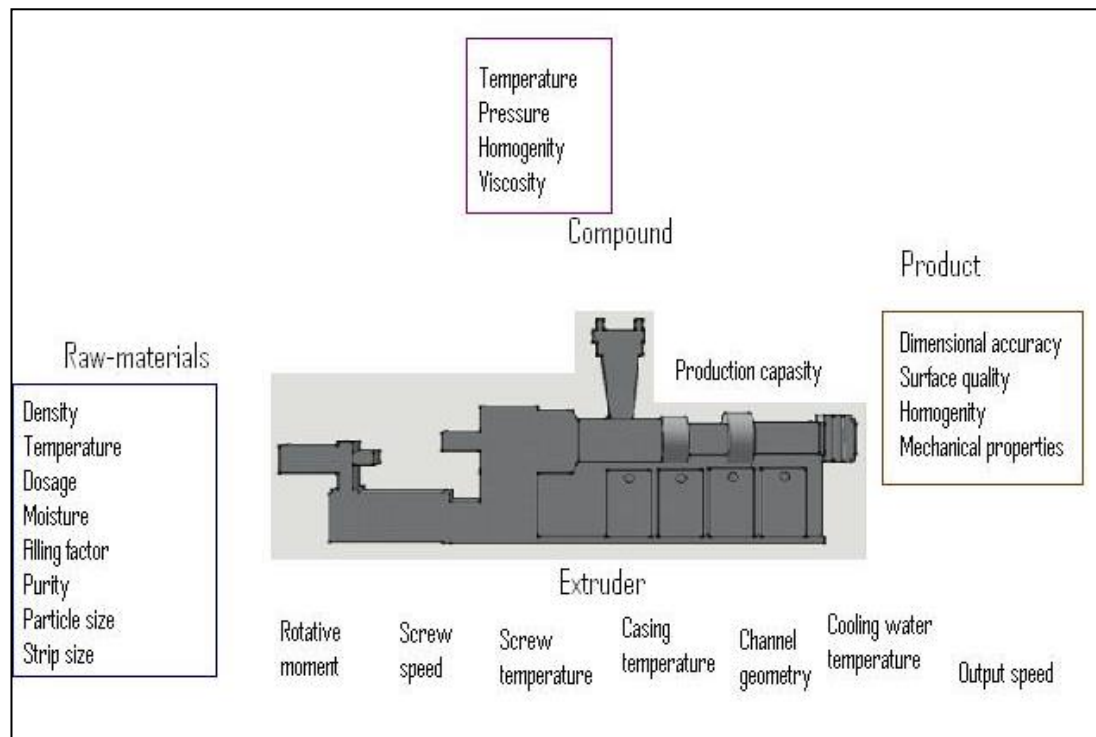

FIGURE 9. The Aspects Related to Extrusion (adapted from Laurila 2011, 158, modified)

4.3   Extrusion head

Extrusion head consist of screen, breaker plate and die, plus their holder cone in which they are located. The functions of extrusion head is balancing the pressure across the profile, guide rubber to the die and hold other items like sensors. In figure 10 is shown demonstration of extrusion head, starting from left: screen, breaker plate, cone and die.
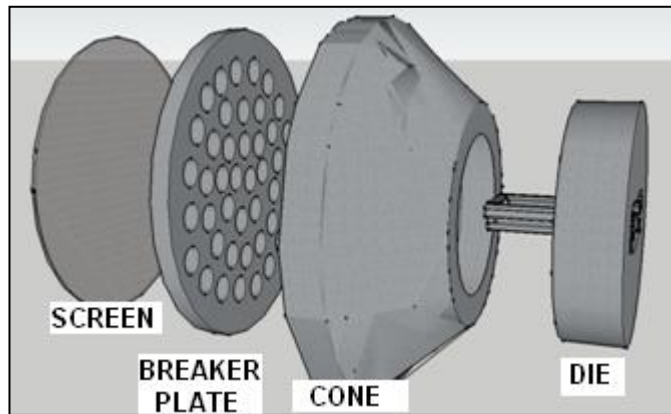
FIGURE 10. Extrusion Head Layout (figure: Pauliina Peltola 2013)

Inside the extrusion head compound has enough space to be used as container where constant and steady flow is possible to the die, even though feed experiences some changes. Volumetric flow does not change while it passes through the head but the change in cross-sectional area leads to an increase of linear velocity as the rubber undergoes elongational flow or stretching. This is why extrusion head should be long enough to eliminate any pulsating flow. Pulsating flow can be formed because of non-uniformity in compound viscosity level and homogeneity. Screen (see picture 1) collects the clumps and wastes, although compound must be free of any clumps and waste. If any they will quickly obstruct the screen and it has to be cleaned or replaced interrupting the machining. Breaker plate (see picture 2) stops the compounds rotation movement and works as a background plate for the screen. (Johnson 2001, 98, 108–109; Hahtola 2006, 35, 41, 83; Vuori 2006, 29.)
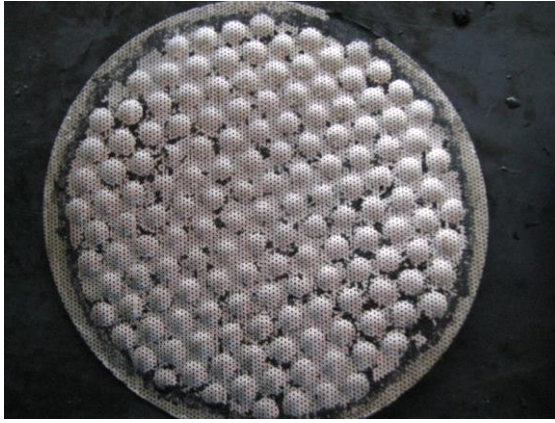
PICTURE 1. Screen (picture: Pauliina Peltola 2012)

PICTURE 2. Breaker Plate (picture: Pauliina Peltola 2012)

With different hole sized breaker plates the resistance and friction based heat can be affected. The smallest resistance is gained when large holed breaker plate is used together with large profile sized die and no screen is used (see figure 11 right side). Understandably, when a small hole sized breaker plate with fine screen and small sized profile die is used the resistance is larger (see figure 11 left side).
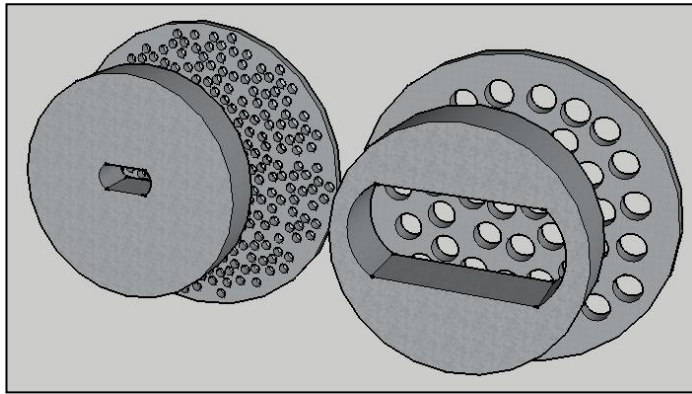
FIGURE 11. Small Hole Size Die and Breaker Plate Compared with a Big Hole Size Die and Breaker Plate (figure: Pauliina Peltola 2013)

The head pressure and the length of the fully filled screw zone are depending on the die resistance and operating parameters. When screw becomes fully filled with rubber the extruder is no longer a feed controlled. On the contrary, it operates in a metering mode. Deviations in extrusion head pressure will cause poor homogeneity. One important feature of the extrusion head its technical smartness related to the practical work while processing. For example, automatic screen-changing devices and two hinge-mounted heads or front head sections will ease the operating. These two lateral options give the possibility of continuous extrusion while another one is used and the other one is under normal extrusion maintenance. (Johnson 2001, 98, 108–109; Hahtola 2006, 35, 41, 83; Vuori 2006, 29.)

The geometry of extrusion head channels effects to the rubbers swelling and shrinking. The longer and wider the channels are, the more relaxed the rubber is. Extrusion head cone should have optimized shape what comes to the rubber flow. If different sized profiles are extruded there should also be available few add-one cones that can be used to adjust the inside size of the cone. If the profile size is small compared to the inside volume of extrusion head rubber compound dwell time will be long and it will lead to different quality problems. Extrusion head should be as simple as possible to the rubber flow, meaning there should not be any corners or loose spaces where compound can be swirling around. Figure 12 is showing there are shown different inside volume sized cones and rubber compound flows in them. As the figure 12 demonstrates the best solution is the cone first from the right where the inside volume of cone is the smallest. This leads to the situation where compound is most easily flowing through it to the die and forward. (Johnson 2001, 98, 108–109; Hahtola 2006, 35, 41, 83; Vuori 2006, 29.)
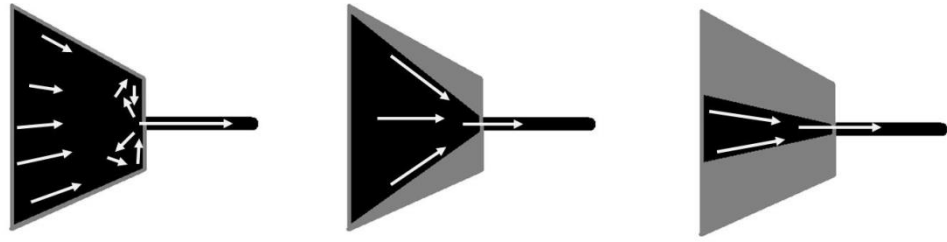
FIGURE 12. Compound Flow in Extrusion Head (figure: Pauliina Peltola 2012)

4.4 Extrusion dies

Simplified die is the rubber profiles negative. This is not the whole truth because with die shaping one has to take under consideration several different phenomenon, like the die swelling. Extrusion die is the most demanding and complex part of the extrusion process and success requires a lot of special professional experience from the workers and die-makers. Rubber material has unique characteristic due to its viscoelastic nature and special ingredients likewise their combination of effects in the compound. In equation 1 (adapted from Johnson 2001, 98) is presented the volumetric output through the die that equals the quantity conveyed by screw, minus the backflow down the screw and the leakage flow. (Johnson 2001, 107–108, 111–112.)

$$Q = Q_{drag} - Q_{pressure} - Q_{leakage} \tag{1}$$

Leakage flow is a result of the wearing of screw ridges and casing. The situation in wearing should be kept under observation of operators. Transverse flow is vital in heat transfer and distributive mixing. It also gives better physical and thermal homogeneity of compound when it reaches the die. When compound viscosity is decreased it will reduce the extrusion output because pressure flow and leakage flow are increased. On the other hand, increase in viscosity will reduce the compound homogeneity because leakage flow is decreased and this leads to poorer miscibility. (Johnson 2001, 107–108, 111–112.)

The operating conditions of extruder depend from the screw and die features. If these are put to a graph of volumetric output and head pressure the operating point of this specific screw and die combinations can be found from the intersection of the curves. In

figure 13 is presented a simplified extruder operation diagram of four different screw and die combinations (adapted from Johnson 2001, 107).
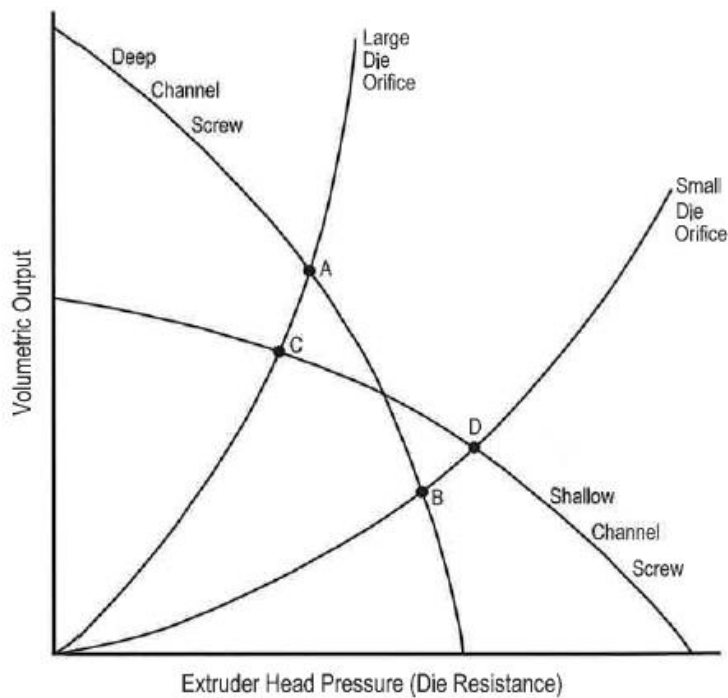
FIGURE 13. Extruder Operation Diagram (adapted from Johnson 2001, 107)

In figure 13 is seen that back pressure has more effect on deeper channel screw than shallow one. High back pressure also creates greater back flow with deeper channel screw and small die than with the large die resulting into a better output with the lateral one. This situation described in figure 13 is up-to-date only as long as screen pack is clean. (Johnson 2001, 107–108, 111–112.)

When a simple pipe shape is extruded, the die output Q depends only from pressure and viscosity while the fixed terms of die dimensions stays the same. In equation 2 is presented die flow Q and how it depends from die length L, pressure P, viscosity η and the radius R of die openings (adapted from Laurila 2011, 148).

$$Q = \frac{\pi R^4 P}{8 \eta L} \tag{2}$$

Die shape is unique for that one specific extruder and most often, for that one elastomer compound recipe. Extrusion process, including extrusion parameters and die shape,

should be so robust that no small variations in compound should have effect on it. When the same extrusion product is done from two totally different compound recipes the difference in their coefficient of thermal expansion leads to a different shrinking magnitude and to the need of different die shaping. The coefficient of thermal expansion for rubber varies from $50 - 200 \cdot 10^{-6}$/ K. By using a cold die the smallest delicate profile geometry is deformed because the rubber gets stuck into the cold die and do not flow smoothly through it. (Johnson 2001, 107–108, 111–112; Metalliteollisuuden Keskusliitto, MET 2001, 156; Mark & Others 2005, 291; Hahtola 2006, 21, 36; Kothandaraman 2008, 14; Laurila 2011, 148–150.)

Die swelling happens when residual stresses accumulated by elastomer in extrusion are released. Die swelling will increase when molecular weight and viscosity are decreased. Die swelling is also greater if extrusion temperature is low. Swelling can be reduced by reducing the elastic compression. Die L / D relation also helps prevent the die swelling when the delay time inside the die channel is longer and the stresses have enough time to release inside the die. Another way to reduce swelling is slower screw speed but this means also degradation in processing capacity. By ensuring streamline flow, eliminating dead spots and minimizing pressure drop the die swell will be more controllable. (Johnson 2001, 107–108, 111–112; Metalliteollisuuden Keskusliitto, MET 2001, 156; Mark & Others 2005, 291; Hahtola 2006, 21, 36; Kothandaraman 2008, 14; Laurila 2011, 148–150.)

Thermal homogeneity of the compound entering the die becomes more important as the profile shape gets more complicated. Die swell cannot be eliminated but it has to be as controlled as possible. If swelling is not evenly distributed in profile the reason is uneven shear rates in the cutoff walls of die. In corners the shear rate is smaller than in the middle of the cutoff wall. This leads into greater rate of recovery in the middle of the cutoff wall than on the edges. In profile this is seen as a bulge. (Johnson 2001, 107–108, 111–112; Metalliteollisuuden Keskusliitto, MET 2001, 156; Mark & Others 2005, 291; Hahtola 2006, 21, 36; Kothandaraman 2008, 14; Laurila 2011, 148–150.)

Pressure drop is the other important phenomenon besides die swell with the extrusion dies. Sudden intake from taper to die can cause extrudate distortion when output rate is low. Distortion can be also result of velocity differences across the profile at the die exit. Die designing aims to avoid high pressure drop and too high temperature rise.

Pressure inside the rubber just before entering the die has to be demolished completely in that passage through die and out. Pressure drop consists of entrance losses, die losses and exit losses. Entrance loss is greater than exit loss and it is depending on extensional flow. Pressure loss in the die is only dependent of die length. Internal and external lubricant addition can ease the pressure drop phenomenon. Incompatible material, like oil in NR, creates wall slippage which leads to a greater entrance pressure drop. Compatible material, like fatty acid derivates, reduces entrance pressure losses. (Johnson 2001, 107–108, 111–112; Metalliteollisuuden Keskusliitto, MET 2001, 156; Mark & Others 2005, 291; Hahtola 2006, 21, 36; Kothandaraman 2008, 14; Laurila 2011, 148–150.)

4.4.1   Die shaping

The design of die depends on the wanted profile and specific compound used. Often die shaping evolves into handicraft process where experimental extrusion is done with the prototype die shape. After a vulcanized profile has been examined the needed corrections are done with detail shaping of the die. Shear rates and local temperatures have to be taken account, for example, around extrusion head is cooling-water circulation but the die made from metal is warming up and has not got any cooling possibilities. The hole-maker pins are located inside the hot compound and can develop problems when the viscosity of compound and screw speed is high. In figure 14 are demonstrated some optimum shapes of die. The left side of figure 14 is showing this demo-die from the compound entering direction, notice the thickness of die. The right side of figure 14 is showing the same die from the compound exiting direction and the demo-profile extruded with it, notice the relation between the hole and whole die. This demo-die has breaker surface plate marked with red and chamfers marked with green.
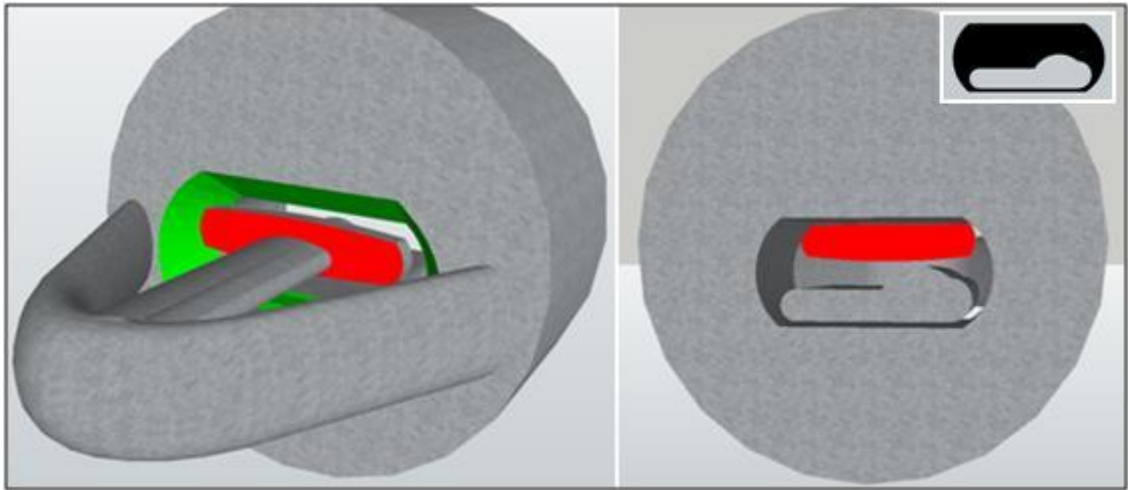
FIGURE 14. Optimum Die Shaping (figure: Pauliina Peltola 2013)

The figure 15 is presenting the details of this same optimum die: the red breaker surface plate and the green chamfers. Breaker surface plate prevents the powerful free-flow of compound into the open-space part of this particular profile. Without this breaker surface plate compound is flowing through from this open-space more easily than through the smaller space under the hole-maker pin that gives the thin wall shape to the bottom of the profile. This way out-coming profile will be twisted downwards because more rubber mass is flowing through the upper part of the die. Green chamfers guides the compound smoothly into the long die where it has enough time to organize its molecule chains to be more longitudinal orientated.

FIGURE 15. Optimum Die Shaping Details (figure: Pauliina Peltola 2013)

In figure 16 is demonstrated unsuccessful die shaping when the wanted profile is the same as in figures 14 & 15. The left side of figure 16 is showing thin die from

compound flow direction. Its relation between the hole size of die and the diameter of die is large. This relation is leading to poorer compound flow. Compound flow is been stopped to the large wall area that keeps the rubber swirling around in the same place. The 'handle' where the hole-maker pin is attached is much closer to the surface of t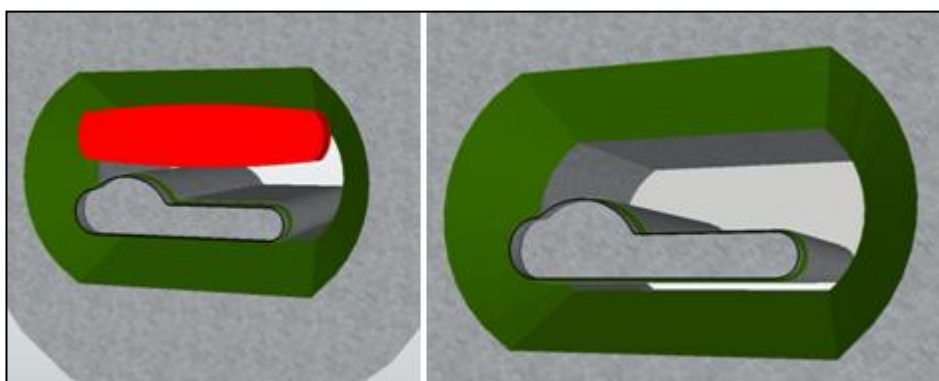he die than in the optimum die presented in figure 14. This makes the change from round flow into a profile shaped flow too sudden. The right side of figure 16 is showing details of this poorly shaped die without breaker plate surface or chamfers.
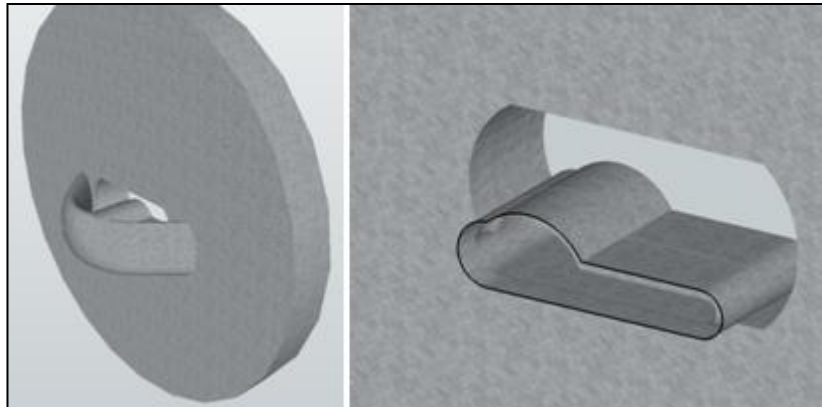
FIGURE 16. Unsuccessful Die Shaping (figure: Pauliina Peltola 2013)

4.5   Challenges in extrusion

The biggest challenge in extrusion is the extrusion itself which means the delicate nature of this process where everything affects everything. Although there are several mathematic equations included into extrusion, a lot more than presented in this chapter 4, the extrusion is most of all dependent from the users' skills and intuition. Best results are often found with gut feeling.

Feed starvation

Feed starvation reduces the distributive mixing action of the extruder and reduces viscous heat generation. Starvation of the extruder can be avoided with assuring better feed, increasing the size of the feed-strip or adding an undercut near the feed throat. More certain way is to add more power to the feed system. The joints of feed strips should also be under observation meaning too long joints will have effect to the steadiness of feed. (Johnson 2001, 94–96, 98–99, 106, 113; Hahtola 2006, 86; Kothandaraman 2008, 14; Laurila 2011, 143, 152, 156.)

Limiting factors

When power is available quality and temperature are limiting factors in cold-feed extrusion. If neither of these two is not in their limit extruder is not working optimum. Practically the maximum permissible temperature is the main limitation in extrusion. Most of the energy goes to the cooling of the process. This is due to the fact that only way to get heat out of the compound inside extruder is direct contact with the cooled surface. This is why complicated compound flow patterns are vital in cold-feed extrusion success. These flow patterns keep the surface contact continuously fresh by offering new rubber surface to the casing and screw surfaces. This leads into more efficient and faster heat exchange. Pressure development is lower when the screw is cooled and this leads also to lower pumping volumes. Due to this, compound has longer residence time in extruder with distributive mixing. This is resulting into a better thermal consistency of the compound and it is important aid for extrudate dimension control. (Johnson 2001, 94–96, 98–99, 106, 113; Hahtola 2006, 86; Kothandaraman 2008, 14; Laurila 2011, 143, 152, 156.)

Moisture and volatile components

Moisture and volatile components in rubber compounds will produce porousness which is prevented with vacuum extruder. It creates vacuum into the cylinder and the light components are sucked out before homogenous zone. Vacuum extruder consists of in a way two extruders, cold-feed and hot-feed, located one behind the other. Vacuum prevents porosity but the extrusion output is lower and temperature higher when it is used. (Johnson 2001, 94–96, 98–99, 106, 113; Hahtola 2006, 86; Kothandaraman 2008, 14; Laurila 2011, 143, 152, 156.)

Scorch

Compound rotating together with the screw can lead into partially vulcanization of the compound and worse profile surface quality. It can be prevented by placing pins to the cylinder towards the screw. Pins will slow down the circular movement in compound created by the screw. Pins will also create laminar swirls. The wearing of screw ridges and casing will eventually increase the delay-time and leakage-flow as presented in chapter 4.4. (Johnson 2001, 94–96, 98–99, 106, 113; Hahtola 2006, 86; Kothandaraman 2008, 14; Laurila 2011, 143, 152, 156.)

Melt fracture and shark skin

Typical challenges in extrusion are melt fracture and shark skin on the surface of extrudate. Melt fracture is due to the helical distortion and elastic turbulence. Shark skin means transverse ridges on the surface and they are caused by tearing of the melt. Shark skin happens on higher extrusion outputs. When viscosity increases and the molecular weight are broader these two problems will be solved. (Johnson 2001, 94–96, 98–99, 106, 113; Hahtola 2006, 86; Kothandaraman 2008, 14; Laurila 2011, 143, 152, 156.)

Cold flow

Cold flow means that extrudate will collapse from its own weight and it has also poor green strength. This is due to gravity and the fluidic nature of extrudate before it is cured. Problem will be solved with increase of molecular weight in order to get some entanglements. Also branching of the main chain will solve the problem when more cross-links are created. One way to maintain a better shape of the profile after it exits the die is the usage of shear head. Shear head heats up the die and the extrudate into its new shape by pre-vulcanization. After all, excessive process optimizing can weaken the end-products features or affect in a negative way into the profitability of compound manufacturing. (Johnson 2001, 94–96, 98–99, 106, 113; Hahtola 2006, 86; Kothandaraman 2008, 14; Laurila 2011, 143, 152, 156.)

5   RUBBER TESTING

Rubber testing is a wide area and it is dealt in this chapter only on general level, concentrating to those features and tests methods which are used in hatch cover seal production of this certain packing product. Rubber testing can be divided into two areas; before and after the vulcanization. There are several different features that can be tested: mass, density, dimensions, short term stress / strain properties, dynamic stress and strain properties, tack, creep, relaxation, set (permanent deformation), friction, wear, fatigue, electrical tests, thermal properties, effect of temperature, environmental resistance, permeability, adhesion, corrosion, staining. Only few of these are used with each rubber product. Depending on what kind of rubber application it is and what are the most important features of it that are affecting on its quality as a product. (Brown 2006 index, 31.)

What comes to rubber testing the same scientific general considerations will be present as with any other material testing. To get reliable results the test equipment has to be right, calibrated and in good condition. The used test methods have to be standardized and the person conducting tests have to be professional. Test conditions likewise the history of test piece has to be taken into account. The person making decisions based on the test results has to understand deeply enough what has been tested and why likewise how to use the results in statistic analyzing. With rubber testing there are international standards to follow. Standards can also be national or company leveled. The International Standardization Organization is widely known across the world. Their standards are named ISO. (Brown 2006 index, 31.)

5.1   Testing before vulcanization

Testing before vulcanization means that the interest is the rubber compound before it becomes a product. These tests are done to find out what the processability of rubber compound is like. What is done in compounding or what kind of raw materials are used in it cannot be corrected in anyway afterwards with rubber machinery. Routine tests of the rubber compound will save costs because any deviation in quality can be detected before proceeding into machinery. Tests will also tell if there are any other features that

could be corrected before proceeding or which will cause difficulties compared to the normal machinery of rubber. One important feature is dispersion quality which tells how well has the compound mixing been done. Are the added substances particles in big agglomerates or evenly distributed across the board with the elastomer. Dispersion quality effects to the final products surface roughness.

5.1.1   Rheology

Rheology investigates the viscoelastic flow behavior such as stiffness and fluidity. When rubber is highly plastic it deforms or flows easily. Plasticity is the inverse of viscosity. With unfilled rubbers viscosity depends from molecule weight average, chain flexibility and long chain branching. Viscosity tells how much energy is needed to process the rubber compound. There are different test equipment to measure the viscoelasticy of rubber. Extrusion rheometers simulate in micro scale the real extrusion process: rubber mass is pressed through a small hole. Although, there are extrusion rheometers, none of those are as popular as Mooney shearing disk viscometer is. With this viscometer, the right vulcanization process phases and scorch resistance can be studied to each rubber compound batch. (Mark & Others 2005, 325; Brown 2006, 65, 72, 76, 82–83, 104–105; Kothandaraman 2008, 13, 140; Laurila 2011, 187–188.)

Mooney is a rotation viscometer where viscosity is continuously measured: rotor turns at a constant rate inside a closed cavity containing the test piece so that a shearing actions takes place between the flat surfaces of the rotor and the walls of the chamber. The torque required to the rotation is measured as a function of time and the test piece consist of two rubber discs (d = 50 mm and thickness 6 mm). Results are in Mooney units where 8.3 ± 0.02 Nm =100 Mooney units. Viscometer is standardized in ISO 289-1. Standard for uncompounded rubbers is ISO 1795 and for compounded rubbers ISO 2393. (Mark & Others 2005, 325; Brown 2006, 65, 72, 76, 82–83, 104–105; Kothandaraman 2008, 13, 140; Laurila 2011, 187–188.)

Mooney is also convenient to finding out the scorch and cure rate. It is often hard to separate these three different features plasticity, scorch and cure rate. This means that with Mooney it is possible to find out all of these three at the same time. Cure rate means the time and temperature what is needed to vulcanize the rubber. It also tells the

start time of cure. This is very important information to be used in the rubber machinery, in which ways it is possible to process the rubber compound to avoid the scorch. One can also be investigating the best cure way of some rubber compound. In this kind of study different times and temperatures are tested together with the vulcanized compound features after some specific cure parameter. (Mark & Others 2005, 325; Brown 2006, 65, 72, 76, 82–83, 104–105; Kothandaraman 2008, 13, 140; Laurila 2011, 187–188.)

Desirable Mooney depends from the applications. When compound is high loaded with fillers low raw material viscosity close to 30 Mooney units is wanted. For economical compounds where the oil loading is high, high Mooney close to 100 is wanted. High viscosity can be achieved with temporary cross links in branched grades, like in liquid SBR. These cross links break during mixing providing easy mixing with high viscosity. Raw adhesion is also one of the measured features of un-vulcanized rubber and it is the ability of the un-vulcanized rubber to get stuck to itself. (Mark & Others 2005, 325; Brown 2006, 65, 72, 76, 82–83, 104–105; Kothandaraman 2008, 13, 140; Laurila 2011, 187–188.)

5.2   Testing after the vulcanization

For most tests there are standard methods available that usually requires the test piece to be rested one day after vulcanization, and to be tested at 23 °C with the air humidity of 70 %. There are also many tests for features to be checked without any standard, like surface appearance and its roughness.

One important issue and special feature of rubber to consider and measure is dimensional stability. This means in extruding the die swelling after the extruding when the rubber is relaxing. Dimensions can also be changed when there is some liquid, like solvents or oils, absorbed into rubber, this leads also to swelling. Another feature that has effect to the rubber product is thermal dimensional change. (Brown 2006, 104, 173, 259, 342–343; Kothandaraman 2008, 144; Murtoniemi 2010, 48; Laurila 2011, 189–198.)

Elasticity can be measured, if needed, by dropping a metal object on to the rubber sheet or with pendulum test machine. In standard ISO R 1767 can be found specific instructions for this. There are also different electrical tests that can be done with the rubber products: resistance, resistivity, surface charge, electrical strength, tracking resistance, power factor and permittivity. None of these are done in the hatch cover seal testing because there is not any electricity involving in their usage. Electrical tests are more important in other rubber applications like in automotive industry. Electrical properties depends on not just the elastomers features but from the different features of the fillers which compound is consisting of. (Brown 2006, 104, 173, 259, 342–343; Kothandaraman 2008, 144; Murtoniemi 2010, 48; Laurila 2011, 189–198.)

Radiation effects are necessary to find out if the rubber application is used in a nuclear power plant, or some other places where some kind of like radiation is present. Sometimes it is also important to find out features concerning biological attack. These are more likely to be microbiological but also some animals like rats or insects could be destroying the rubber products. Then solutions to protect the rubber are vital to find. (Brown 2006, 104, 173, 259, 342–343; Kothandaraman 2008, 144; Murtoniemi 2010, 48; Laurila 2011, 189–198.)

Short term stress / strain properties are studied in tension, compression and shear tests. Most common and important of these is the compression test, what comes to the hatch cover seals. Short term dynamic stress and strain properties: dynamic testing means that the test piece is under some kind of cycles of movement or forces for a certain time. This could be, for example, an abrasion test in test bench with 2000 cycles, divided into 8 hour periods per day. Different dynamic testing can be united with specific temperature. (Brown 2006, 104, 173, 259, 342–343; Kothandaraman 2008, 144; Murtoniemi 2010, 48; Laurila 2011, 189–198.)

5.2.1 Hardness

One important and commonly tested feature is the hardness of rubber. Difference between hardness and modulus is that hardness is modulus at very low strain, while modulus tests are done at higher strains (100 – 300 %). Hardness and modulus can be altering separately from each other although increase of cross link density will improve

them both. Hardness cannot be the only criteria what is been measured because it can be easily increased with cheap fillers, while the rest of the properties are dramatically reduced. Hardness is measured with a durometer on the Shore –scale in the hatch cover seal testing. Shore A –scale is for the soft rubbers, Shore D for more harder rubbers and ShOO for sponge and cell rubbers. On Shore A –scale the rubber with 20 ShA is very soft and rubber with 80 ShA is hard as a rock. Durometer is spring based meter but there is available different equipment for conducting other methods like dead load test method. One of them is the International Rubber Hardness Degress (IRHD) method that is described in ISO 48 standard. (Brown 2006, 110, 118, 127, 133–134, 149–150, 159, 161; Kothandaraman 2008, 141; Murtoniemi 2010, 44; Laurila 2011, 189–191.)

5.2.2   Tensile stress

Tensile stress strain testing is very important to those rubber products that are used in tensile positions or have tensile movement during their usage. Hatch cover seals are avoiding tensile stress in macro scale because their function as a product is based on compression. Still there are internal tensile stresses present in the microstructure of the seal (see chapter 5.2.10). In tensile test stress is aimed to the rubber test piece and the elongation correlation to the stress is examined. This is very common and widely used test and there are available standards, for example ISO 37, defining the test equipment, test pieces and the details of this test method. (Brown 2006, 110, 118, 127, 133–134, 149–150, 159, 161; Kothandaraman 2008, 141; Murtoniemi 2010, 47.)

5.2.3   Compression

Compression is tested with the final product and in the specific compression environment of the rubber application. Compression stress / strain features are the most important features, what comes to the hatch cover seals. Compression of hatch cover packing is measured from the final product test piece the length of 200 mm in the profile holder which is imitating a rubber channel (see figure 17). This set-up is the same as it is when the packing is finally installed into the hatch cover. The test piece is compressed evenly at specific speed two times to get a compression curve which tells to a practiced eye how the sealing is working in a real situation. In compression test the

compression force is coming from above and one also has to take under consideration the force-free areas on the both ends of the test piece, as demonstrated in figure 18. When the packing is installed into the rubber channel of hatch cover it does not have such force-free areas.
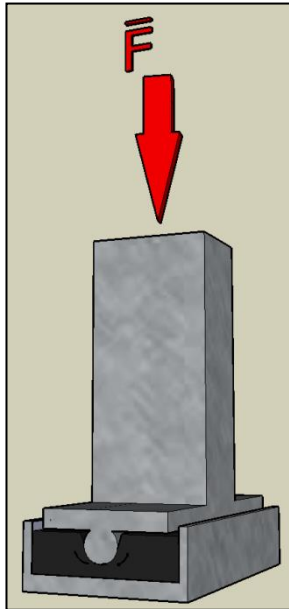
FIGURE 17. Compression Test (figure: Pauliina Peltola 2013)
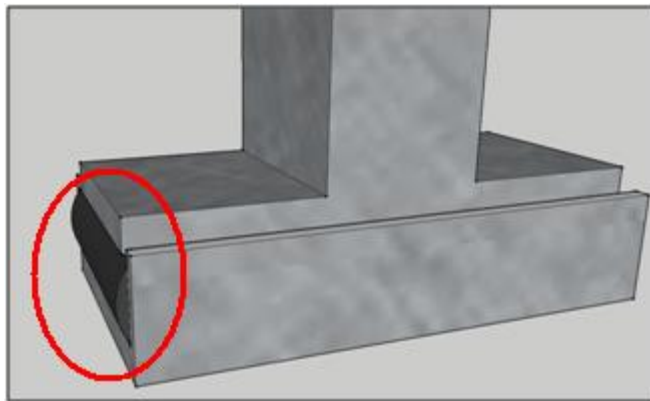
FIGURE 18. Force-free Area in Compression Test (figure: Pauliina Peltola 2013)

Hatch cover seal compression is measured force (*N*) as a function of compression (*mm*) from a test piece the length of 200 mm but the standard compression curves for each seal product is presented in *kN / m*. Results are in units *N / mm* and they are converted as follows. Test piece compression forces are multiplied with 5 to get the needed force

for 1 m length of the same rubber profile to have the same compression amount. In equation 3 is demonstrated this conversion with one example (200 N / mm = 1 kN / m).

$$\frac{\frac{(200\ N \cdot 5)}{m}}{2\ mm} = \frac{\frac{1000\ N}{m}}{2mm} = \frac{1kN/m}{2\ mm} \tag{3}$$

5.2.4 Tear

Tear is also essential feature to find out from rubber products. What comes to the hatch cover seals, the tear test tells how the rubber is able to withstand the hard conditions of cargo ship. More specific, how it withstands the loading actions, when there could be some hits and abrasion from the loading equipment accidentally getting contact with the hatch cover seal. Tear is roughly depiction as a nature of rubber or ability to resist the flaw spreading, meaning how the rubber resists the continuous of the tear. Depending on the application and the location of the tear, small tear is not necessarily harmful but if it spreads to a bigger one the product is not working properly anymore. There are a few different ways to conduct the tear test. One way is to make trouser test piece and pull the other leg to another direction and the other to other direction. In standard ISO 34 this tear testing method is defined more precisely. (Brown 2006, 110, 118, 127, 133–134, 149–150, 159, 161; Kothandaraman 2008, 141; Murtoniemi 2010, 47.)

5.2.5 Creep, relaxation and set

Creep, relaxation and set are based on result of an applied stress or strain together with time. In creep test the rubber test piece is under a constant force and its deformation during this time is recorded. Set test investigates how the rubber test piece can recover when it is released from the stress or strain. There are physical and chemical reasons that influent on these three phenomena. The first is due to the viscoelasticity of rubbers and the second arose from the rubbers ageing. (Metalliteollisuuden Keskusliitto, MET 2001, 144; Brown 2006, 201–202, 204, 211, 213.)

The relaxation and set are more essential test features, than creep, what comes to the hatch cover seals. Relaxation under compression is very unwanted feature with seals if

the relaxation is big enough the seal is not working anymore. Relaxation tolerances are dependent of the seal product end-use environment and requirements. Hatch cover seals are medium-sized rubber products to be used in very rough conditions and they are weathertight. Weathertight hatch cover keeps the hold dry when 1 m water statue, called wave load, is placed on top of the hatch cover. Weathertightness means that no water can enter into cargo hold through the packing arrangement while watertightness means that no water can enter or exit the hold through the packing arrangement (Taylor 2001, 41).

Set test can be carried out in tension or in compression, depending of the rubber product final usage. Set in compression is very important feature to be examined with the hatch cover seal products. Although the mass of the hatch cover is adjusted to be on the bearing pads and not on the seal, the seal also has a quite rough compression force over it. And addition to this, there is the forces due to the swell of the sea. If the maintenance of a vessel is not up to date, the seal has to carry more weight as it should. Hatch cover seals spend the most of their life being compressed and only a while without the compression during the loadings and un-loadings. Compression set test tells the force limit which the seal can recover from and in what point, it cannot recover anymore from the compression.

Usually compression set with rubbers is not noteworthy inside the temperature range from 0 °C to 80 °C. Set test is commonly done as follows; rubber piece is compressed in the room temperature and then moved into the testing temperature for 24 hours. After that the compression is moved and test piece can rest 30 minutes before measuring if there is any set. More information about this method can be found in standard ISO 815. (Metalliteollisuuden Keskusliitto, MET 2001, 144; Brown 2006, 201–202, 204, 211, 213.)

5.2.6 Friction and wear

There are three types of wearing phenomena: grinding wear abrasion, sticking wear adhesion and degrading wear due to the oxidation, heat and chemical wear. Friction is part of the abrasion phenomenon of rubber products. Abrasive wearing is the result of two phenomena: oxidative decay due to the heat formation from friction and mechano-

chemical breakdown started by shear-induced fracture of chemical bonds. (Metalliteollisuuden Keskusliitto, MET 2001, 140; Mark & Others 2005, 492; Brown 2006, 219, 227.)

Hatch cover seals are compressed against to a steel surface of the coaming or against to a compression bar made of steel. Seals have to be very tenacious to be able to resist the rough conditions of the end-use environment. The wear of packing is measured in a test bench (see figure 19) and it can be lubricated with seawater or some covering on the top of the seal to ease the friction force to be smaller. With hatch cover seals, the seal with covering is more difficult application than with some other more gently used seal products, like the car window seals manufactured by automotive industry. Hatch cover seals undergo such rough movements that the covering is easily worn out.
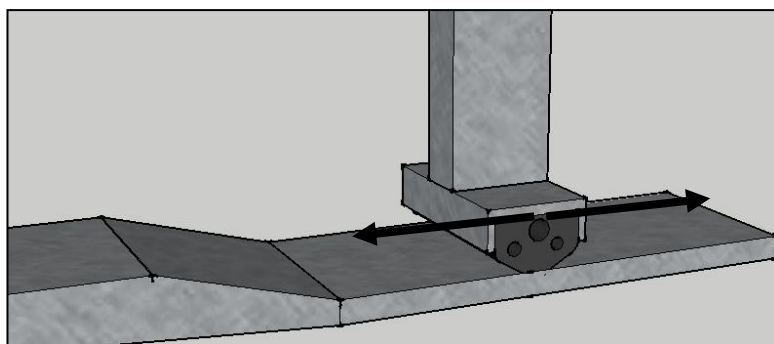

FIGURE 19. Sliding Test with Sliding Type of Hatch Cover Packing (figure: Pauliina Peltola 2012)

5.2.7   Fatigue

With fatigue is meant all those deformations which are due to the long term dynamic tests. When rubber is under continuing dynamic movement of some kind there will be in some point, effects to its hardness and mechanical properties. This fatigue can be due to a thermal breakdown, ozone or oxidation attacks, not forgetting the rubber physically been torn out. For example, with a seal product fatigue test can be one, where seal is compressed and released continuously over and over again. After some specific period the test is stopped and the seal is overall examined, to find out is there any fatigue happened. There are several different ways to conduct these fatigue tests depending on the rubber product. In some case it can be necessary to find out how the presence of mineral oil, for example, will affect to a long term static compression test. Overall,

fatigue test can be the ones which imitate the end-use environment. (Metalliteollisuuden Keskusliitto, MET 2001, 146; Brown, 2006, 245.)

5.2.8   Effect of temperature

Effect of temperature is very important area with the hatch cover packing because they have to withstand variable weather conditions, depending on where the vessel is sailing. Most extreme weathers can be -40 °C, or even -50 °C, when the vessel is an arctic research vessel to be used near the naval areas. There are special hatch cover seals for this purpose, although the normal cargo vessels also need quite good temperature resistant packing especially if they sail on some colder passages.

Temperature effect test include both high and low temperatures. Low temperature effects can be measured with the rate of recovery, change in stiffness and brittleness point measurement. One of the recovery tests is temperature-retraction test (TR test) which is standardized with ISO 2921. In TR test a rubber test specimen is in strained position of 50 % in holder which is put into -70 °C where it is kept for 10 minutes. After this, it is released from the holder and warmed-up 1 °C / minute. This way, the temperature where 10 % of the strain is recovered is the TR_{10} and so on. Brittleness point is the temperature where the rubber becomes a fragile and glassy. (Mark & Others 2005, 190; Brown 2006, 287, 291; Kothandaraman 2008, 3, 5, 144; Laurila 2011, 194.)

The glass temperature T_g presents cooling rate function at the pressure where it is determined. T_g depends from chain stiffness, interchain attractions, molecular symmetry, copolymerization and its types. Also presence of solvents or plasticizers, branching and cross-linking have got influence to T_g. Above this temperature rubber is soft and flexible and under it rubber is hard and brittle. Plasticizers and solvents will go between elastomer chains and this will cause decease of the T_g. In figure 20 is presented T_g and damping features of natural rubber (adapted from Laurila 2011, 28, modified). In glass transition region the internal damping of natural rubber is at its maximum. Best choice to lower operating temperatures is the rubbers with the lowest T_g. In table 3 is shown T_g values for few elastomers. (Mark & Others 2005, 190; Brown 2006, 287, 291; Kothandaraman 2008, 3, 5, 144; Laurila 2011, 194.)
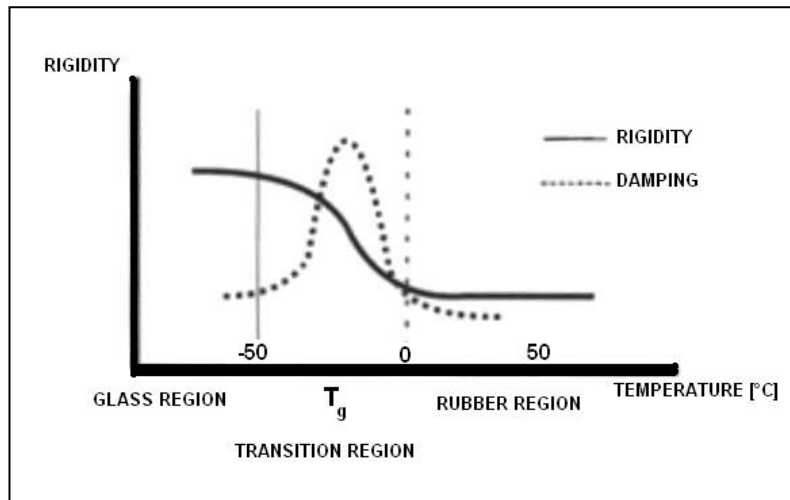
FIGURE 20. Natural Rubber T_g (adapted from Laurila 2011, 28, modified)

TABLE 3. T_g Values for Few Elastomers (Gent, 2001, 13–17)

Elastomer	T_g
SBR	-55 °C
NR	-70 °C
BR	-100 °C
CR	-50 °C
IIR	-70 °C
EPDM	-60 °C
Q	-127 °C

The elasticity of elastomers is depending on temperature. Elastomers have very long non-symmetric molecule chains which can rotate freely. When polymer is crystallized its molecule chains are packed together symmetrically but elastomer chains are left non-symmetric. Un-vulcanized rubber can crystallize even in + 10 °C but this is reversible phenomenon. (Mark & Others 2005, 190; Brown 2006, 287, 291; Kothandaraman 2008, 3, 5, 144; Laurila 2011, 194.)

5.2.9   Fire-resistance

The fire-resistance of rubbers has not been under general concern as much as plastics. Most rubbers burn and burning features can be divided into different aspects like ease of ignition, rate of burning and smoke production, to mention a few. Synthetic rubbers are mostly oil-based products and when the rubber burns it is like solid oil is burning. There are not any ISO standards for the fire test of solid rubbers. (Brown 2006, 343–344.)

Generally the ignition of rubbers is more difficult than with other materials in the burning environment where rubbers are commonly the ones to start burning last. That does not mean they are fire safe, it is the opposite, when rubbers burn they are hard to extinguish and most of them will produce a lot of harmful or even toxic smoke during their burning. There are fire-resistant rubber compounds that can be used in hatch cover seals. More often customer wants non-fire-resistant rubber compounds which are more inexpensive ones. When the other marine seal products are used in a vessel where there are passengers or roll-on-roll-off cargo it is more important to have also the seals fire-resistant. This is because the seals are located inside the vessel in the compartment doors and ramps. (Brown 2006, 343–344.)

5.2.10   Ozone

Ozone (O_3) is more aggressive natural form of oxygen gas (O_2) in the nature and it is mostly present in the higher atmosphere. Ozone level varies around the world. It is more usual to conduct only ozone test that measures the ozone resistance between different rubber compounds than test the rubber in end-use environment ozone levels. Rubbers are very delicate to ozone and even 1 part per hundred million (pphm) can cause cracking in rubbers if they are in strained situation. Cracks will happen always perpendicularly against the strain direction when ozone cuts the double bonds (C=C) of the rubber. When rubbers are used in applications where there are tensile strains focused on it, the ozone resistance is very important to cover. Hatch cover seals are in compression but there are still tensile strains present in the microstructure of seals (see figure 21). Because of this, it is also very important to measure ozone resistance, due to the absorption and diffusion of the rubber material. Usually the ozone levels in the tests are in the range from 25 pphm to 200 pphm, 50 ± 5 pphm being the general standard

level. (Metalliteollisuuden Keskusliitto, MET 2001, 150; Brown 2006, 327–329, 331, 333.)
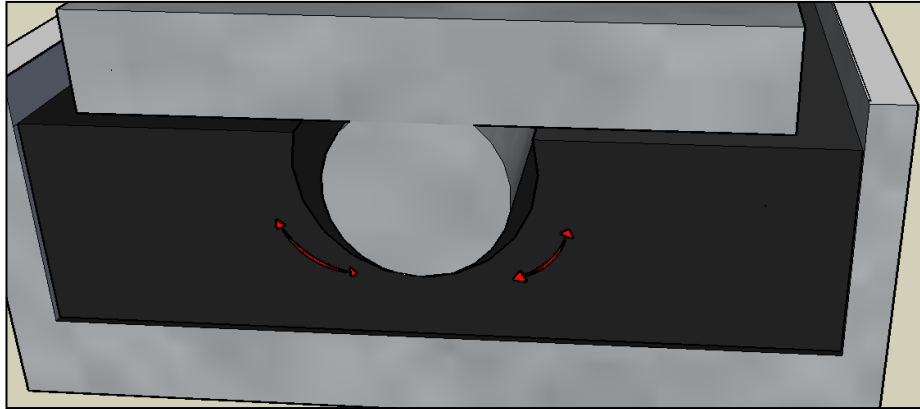

FIGURE 21. Local Tensile Stress in Microstructure of a Hatch Cover Seal (figure: Pauliina Peltola 2013)

Ozone testing is quite complicated because there are also two other factors present: time and the amount of strain, besides of the ozone concentration. These three together will make different variable situations and the ozone cracking factor is quite hard to define. Even if the rubber compound has very good resistance to ozone its threshold level in the strained position can be very low. Normally the ozone tests are accelerated tests and done in special ozone cabinets where the material of cabinet is chosen to be undecayed one to ozone. One important thing to consider in closed ozone cabinet is that the rubber test piece itself can give off gases which can have effect to the results. If test piece has some minimalistic flaws or patterns they will act as stress raisers and encourages the cracking during the test. In standard ISO 1431 the test method is described in more details. (Metalliteollisuuden Keskusliitto, MET 2001, 150; Brown 2006, 327–329, 331, 333.)

5.2.11 Environmental resistance

Rubber products are often exposed to a combination of different chemical and physical features at the same time. This is why it is more practical to conduct test which will simulate the working conditions of the rubber than just test the rubber separately with these different features.

Moist heat testing will tell more efficiently the features of rubber product in real end-use environment than dry heat testing. This kind of product which needs moist heat testing can be a steam hose or some other rubber product which is in contact with steam. The effect of different liquids also is very important thing to test. Liquid effect is commonly tested with the volume change of the rubber when it is in contact with liquids. There can be different liquids in contact with the rubber product even though not directly supposed to. Regarding hatch cover seals, the most contact it has is with the sea water which has the salt content of 3.0 – 3.8 % NaCl. The seal will be in contact with other liquids too, although it would be a bulk vessel, carrying dry cargo. For example, there is always sulfur present in the coal bulk and when it comes in contact with sea or rain water, sulfur acid is formed (see chapter 6.3). (Brown 2006, 317, 319, 326, 339–341, 349–350.)

There are also other gases besides ozone which are sometimes needed to test with the rubber products. Hatch cover seals are usually only tested for the ozone resistant but there are some seal applications where other gases are present. It is necessary to find out the permeation of the different gases threw the rubber with those applications. In this kind of situation seal can be working properly stopping the liquid but not the vapor. Difficulties will arise, when it is necessary to find out permeation in very high pressures. The test conditions and equipment have to be very safe. Most likely the equipment has to be made uniquely for only testing this certain application. (Brown 2006, 317, 319, 326, 339–341, 349–350.)

Depending of the vapor or gas and the rubber compound, it could be said that every rubber is permeable in some scale. Whether this is a problem or not is a consequence of the applications where the rubber product is used. When rubber is used in some water vapor barrier or in some gas sealant system it is obvious that no permeability is aloud. Even mechanically flawless rubber product will let threw some gases or vapors threw the absorption and diffusion. (Brown 2006, 317, 319, 326, 339–341, 349–350.)

Weathering means combination of several different factors at the same time in contact with the rubber product. It is very different to test ozone resistance and temperature features separately than at the same time. Testing them separately could give too optimistic test results leading than when the testing is weathering type. These tests

could be divided into real outdoor tests and into the artificial ones that are simulation tests in laboratories. Weathering could be roughly said as a test where ozone, oxygen, temperature, moisture and sunlight are affecting the rubber. These are the natural factors in outdoors but in some cases it would be more truthful to test the rubber product in the conditions it will be used. For example, if there are any other factors included, like crude oil or solvents. These kind of special factors in the rubber products end-use environment could turn the normal weathering test results to its opposite. (Brown 2006, 317, 319, 326, 339–341, 349–350.)

When the temperature is normal oxygen will effect very slowly to the rubbers. Sunlight has not been as concerning issue with the rubber, than with the plastic products. Rubber is most likely to be affected from sunlight only by its surface, although, the exception are non-black rubbers. All hatch cover seals are black and their permanent position is quite effectively hidden from sunlight inside the hatch cover steel construction. The same thing, as with the ozone, is seen with direct UV-light. When the rubber is stressed or has some flaw the cracking is more likely to happen. Even if the ozone level is low UV-light will cause cracking. It has been studied and confirmed that the effect of UV-light can be quite large although rubber compound includes carbon black. In same study ozone effects were demonstrated to be also significant. Ozone resistant should be first considered before conducting any thermal ageing tests, when one is trying to find out the expectable service life. New hatch cover packing products are always tested in the final stage on-board at least a year and the results are carefully studied before releasing the new product into the markets. There is ISO standard available for exposure to a maritime environment but it is only for plastics. (Brown, Butler & Hawley 2001b, 12; Brown 2006, 317, 319, 326, 339–341, 349–350.)

6   CARGOSHIPS AND HATCH COVER PACKING

There are several cargo ship type classes and these classes are divided further into sub-categories based on size or cargo type, for example. There are also available different types of hatch cover depending on the specific technical application needed for the vessel. This chapter is accentuating only into bulk carriers and one type of hatch cover because this final thesis is studying the extrusion of packing product used only in side-rolling hatch covers.

6.1   Cargo ship types

All cargo ships can be roughly divided into bulk carriers, container vessels, general cargo ships, roll-on-roll-off (Ro-Ro) vessels and tankers. Bulk carriers are clarified better in the chapter 6.1.1. Picture 3 (adapted from Cargotec 2013) is showing different types of vessels, starting from left, container vessel, general vessel and Ro-Ro vessel.

PICTURE 3. Container, General and Ro-Ro Vessel (adapted from Cargotec 2013)

Container vessels are specialized to transferring containers and there is no other cargo besides of them. General cargo ships are more flexible with their cargo possibilities than other vessel types. They can take on-board containers, bulk cargo and different kind of general cargo, for example, machines or paper baggy reels. General cargo vessels can also have their own cranes on-board. Ro-Ro vessels are carrying cargo which is on-wheels, like trucks and cars. Tankers are bulk carriers but they are separated into their own class because the cargo is in unpacked liquid form and in bulk carriers the cargo is in unpacked solid form.

6.1.1 Bulk carriers

Bulk carriers are cargo vessels that carry solid unpacked cargo. In picture 4 (adapted from Cargotec, 2013) is seen a bulk vessel. Bulk carriers can have, for example, grain, ores, coal, minerals or products of chemical industry (like fertilizer) in their holds. In new building the planned general cargo manifest sets demands for the vessel structure. Main thing to consider is the movement of bulk cargo in the holds, the slipperiness of bulk and rolling tendency which sets demands to the stability of vessel. Moving bulk cargo in the holds makes dynamic moments which try to careen the vessel. Bulk carrier sizes are classified often by the sea-lanes they are taking or ports they are visiting, some examples are shown in table 4.

PICTURE 4. Bulk Carrier (adapted from Cargotec, 2013)

TABLE 4. Bulk Carrier Types (Räisänen 1997, 24-1–24-16; Bimco 2011)

Bulk carrier	Explanation	Weight in dead weight tons (means everything on board and the vessel itself)
Small	Specific vessels, build for some special purpose (most of these are general cargo ships)	-25,000
Handy-sized (usually with 5 cargo holds)	Convenient bulk vessels, because they can access to almost every bulk harbor with the 11 m draught	25,000 – 45,000
Panamax-sized (usually with 7 cargo holds)	Max. width 32.20 m (because of the narrowness of Panama canal)	60,000 – 99,000
Cape-sized (usually with 9 or more cargo holds)	The biggest bulk carriers, which are determined to take the routes from the South when moving past Africa or South-America, due their size, no canal is big enough	100,000 – 199,000
Very large ore carriers, VLOC (usually with 7 cargo holds)	Gigantic vessels for iron ore, build to reduce the cost per tonne mile of cargo	+200,000

Most important specification to the bulk carrier is the stowing factor of bulk cargo. The specific gravity of iron ore is very high. This is why the hold departments are small and extra strong build in ore carrier. Another specific feature with bulk carriers is dust which spreads onto the surroundings when the cargo is loaded into the vessel or unloaded from the vessel. Coal cargos also have different risks on the bulk carriers like the occurrence of methane, which can lead to explosions and the spontaneous combustion of the coal if the hold temperature rises too much. (Räisänen 1997, 24-1–24-16.)

Bulk cargo is quite vulnerable depending on which type of cargo is been carried. Un-packed cargo can have specific demands concerning the wetting tolerance, air saltiness defects, caking and swelling, freezing, ageing and many more. Bulk cargo handling will most probably be more restricted what comes to loading and un-loading, in future. Environmentally concerns will push the load-handling into closed structures which will lead into a cleaner way for the surroundings to load and un-load the holds. Closed load-handling structure is actually a better way for the vessels components also when the bulk is not spread all over them. (Räisänen 1997, 24-1–24-16.)

6.2   Hatch covers and hatch cover packing

The main task for hatch covers is to protect the cargo inside cargo holds and carry cargo, like containers or special cargo, on top of them. This may seem like a simple task but actually it is surprisingly complex one. Hatch covers which are shielding the cargo in the holds are weatherproof although container vessels can have exception into that. Different hatch cover types are available depending on their needed function and the vessel they are designed to. One demand for hatch covers can be the ability to get them out of the way, into a very tight package when the hold is operated. In this case the hatch cover type could be folding hatch cover.

Hatch cover usage regardless of vessel type should be reliable, easy and fast. These guarantee short port time and undamaged cargo. There are available different kinds of hatch cover types: folding, lift-away and side-rolling. First two are seen in picture 5 (adapted from Cargotec 2013, modified).

PICTURE 5. Folding and Lift-away Hatch Covers (adapted from Cargotec 2013, modified)

Hatch cover packing was made of sponge rubber for a long time until sponge rubber was harder and harder to get. To solve this unfilled demand extruded hatch cover seals were invented and step-by-step more profile designs were created hand-in-hand with the current need from the operating field.

The hatch cover seals provided by the company have got unique geometry and functionality likewise high quality reaps the benefit compared to the competitors. Competition on the global markets is very hard and brutal. Manufacturers will make

copies from the most famous packing products around the globe and sell them using the same brand name as a general standard or description of the seal type.

When the hatch cover with its packing and other components is installed into the vessel its weathertightness is tested. Most common one is the hose test which is proved by many classification societies to be accurate enough when it is done with the particular standard features. Hose test is generally done as follows; water with the pressure of 2 – 3 bar is sprayed with a hose inside diameter of 20 – 30 mm from a nozzle with diameter 12 mm from a distance range of 1 – 1.5 m moving along the seal joint 1 m with every 2 seconds. Another test for the weathertightness is ultrasonic test. In this test ultrasonic generator is placed inside the cargo hold. After closing the hatch cover professional operator can interpret the readings from several sensors that are placed all around the compression joints. (Taylor 2001, 43; 44.)

Hatch cover tightening arrangement need different kind of packing pieces, like basic linear rubber, flat corners, standing corners, 3-way corners and end pieces. What comes to the hatch cover corners they can also be something else than 90° corners. This leads also to vary magnitudes of angle in packing corners.

Hatch cover seals can be conventional or sliding ones. Conventional ones are inside the rubber channel and they are pressed against a compression bar which is mounted onto the coaming, see figure 22 right side. Sliding ones have bigger movements and they are pressed against coaming, see figure 22 left side. When sliding seal is used the friction between coaming and rubber should be appropriate size. Too large friction will wear off the packing surface too quickly. Although too small friction can reduce the seal feature. Wear abrasion test is very important for the hatch cover seal because it has to undergo rough forces and movements during the swell of the sea. Rubber is designed to stay inside the rubber channel, due to the tight fitting and glue is used to achieve weathertigthness. Usually hatch cover packing is changed after 5 to 10 years or when they have damaged someway because of some special event.
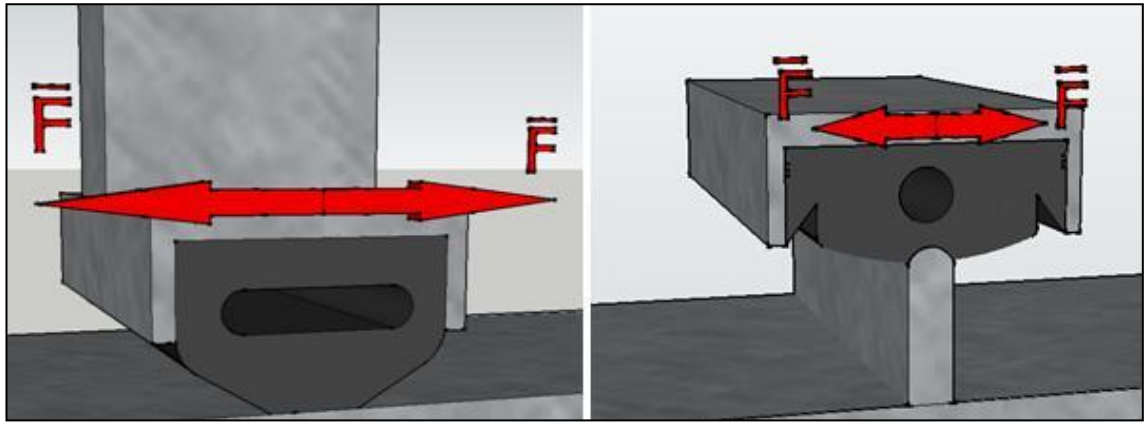
FIGURE 22. Sliding Seal Type and Conventional Seal Type Arrangements (figure: Pauliina Peltola 2012)

6.2.1 Side-rolling hatch covers and the new packing product

Side-rolling hatch covers are used in bulk carriers and they only have wave load but no payload on them. This hatch cover type is made with open steel structure. There are usually 4–8 pairs of panels, opening from the middle as seen in picture 6. Side-rolling hatch cover can also have only one panel which is opening onto the other side of the vessel (see picture 7).
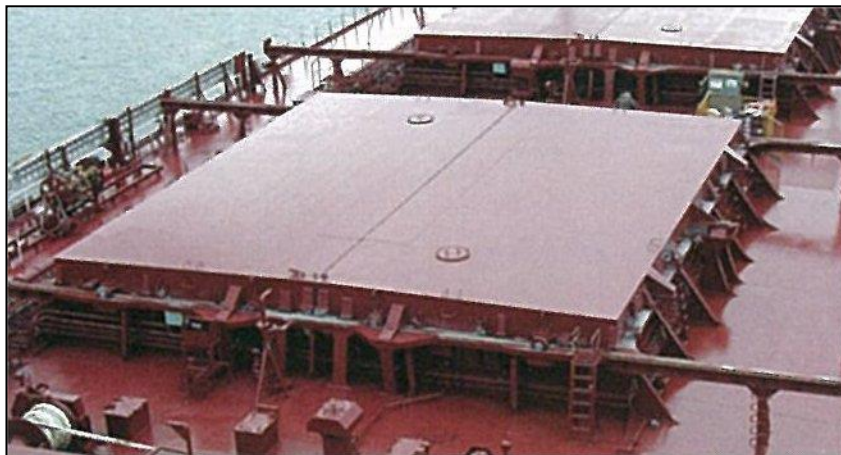
PICTURE 6. Side-rolling Hatch Cover with 2-Panels (adapted from SMBA 2010)

PICTURE 7. Side-Rolling Hatch Covers with 1-Panel (Macor Marine N.D.)

In figure 23 (adapted from Cargotec 2013, modified) is shown side-rolling hatch cover. In figure 24 is shown tightening arrangement of side-rolling hatch cover with 1-panel. These arrangements can evolve quite complex when steel structure of hatch cover consists of many different shapes that leads to complex 3-way seal joints.

FIGURE 23. Side-rolling Hatch Cover with 1-Panel (adapted 2013 from Cargotec. Side-rolling hatch cover drawings, modified)
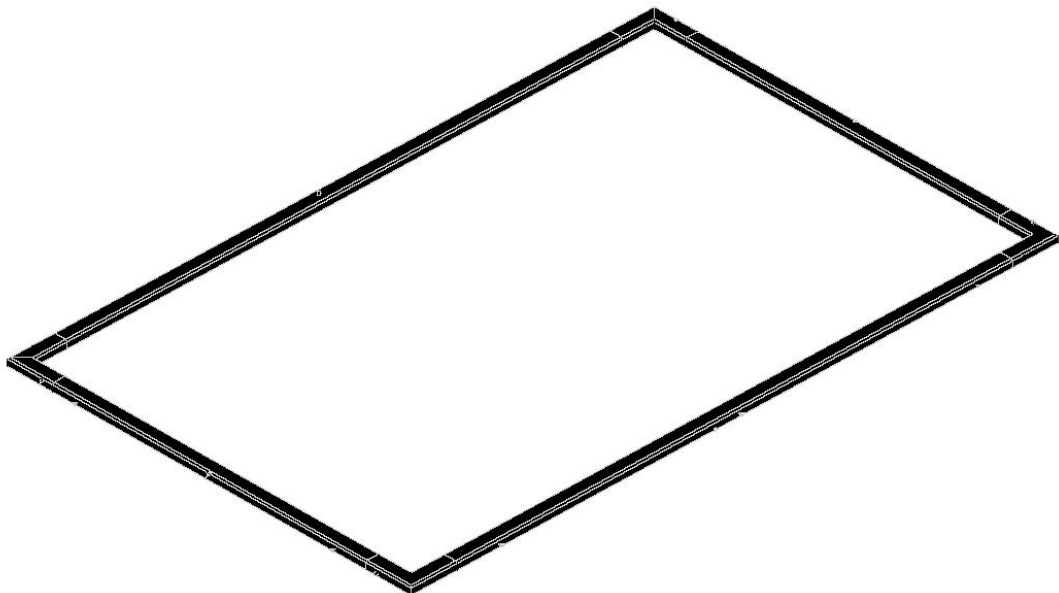

FIGURE 24. Tightening Arrangement of Side-rolling Hatch Cover with 1-Panel (adapted 2013 from Cargotec, modified)

Typical feature with openings of bulk carriers are their small size with relation to the cargo holds sizes. Bulk vessels have the biggest seal volumes compared to other vessel types. Into one bulk carrier is required few hundred meters of hatch cover seals. Commonly these hatch covers sizes are from 14 to 21 m. This leads to smaller movements of the opening during the swell of the sea. Bulk carriers are swimming deeper than the other vessel types. Hatch covers are calculated weatherproof with 1 m seawater on top of them. This means large weight on top of the hatch covers and large water pressure to the hatch cover seals. Packing arrangements can be solved with the conventional packing and compression bar (see figure 25) when the movements of openings and hatch covers are small.
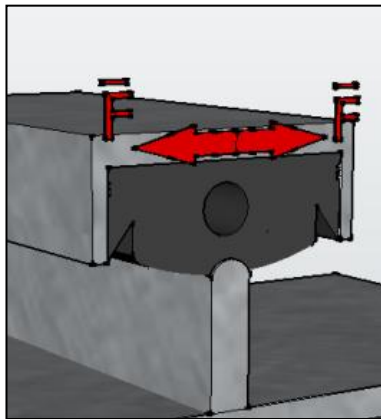

FIGURE 25. Conventional Seal Arrangement (figure: Pauliina Peltola 2012)

When a new product is coming to the markets it has to have a good reason for the customer to choose it. More often, the new product is better but also more expensive than the older version. This makes it a big step to take for the customer to change the reasoning to the new product version. The linear hatch cover packing product studied in this final thesis is seen in figure 26. It is easier to install into the rubber channel because it is lighter than its predecessor. Still this new version has the same compression capacity leading it to be a more sophisticated packing product.
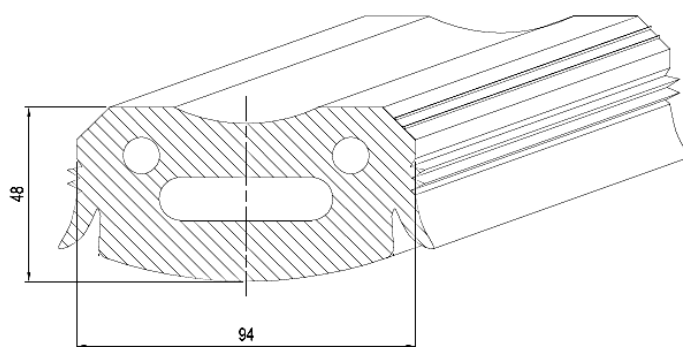
FIGURE 26. 3-holed Flexseal, Wingseal (adapted from Cargotec 2013, modified)

6.3 Operating conditions and demands for the hatch cover packing

The need of weathertight holds is the reason why seals are originally invented and used in hatch covers. Weathertightness is the first feature which is a basic demand for the hatch covers, including rubber application. This rubber application also has to be durable under rough conditions and have resistance to wide temperature range and possibly to wide chemical range. Operating temperature onboard can vary from - 40 °C to + 50 °C, although certain vessels are for specific sea-lanes and purposes, for example, arctic vessels are built for cold-conditions and the hatch cover packing is arctic quality.

Another easy thing to consider in the end-use environment is the salty seawater which does not cause as big problem to rubber as it does to the metal structures and components of a vessel. Steel components are rusting and it is very fast in sea-environment although the steel structures are treated with different protection layers. Cargo vessels are in a heavy usage and in a new vessel there soon will be scratches breaking the protection layer leading to rusting.

Ozone is present in everywhere on Earth and some special situation, like strong UV-radiation, can lead into increase of the temporary ozone levels. Another new aspect to consider in ozone testing of hatch cover seals is ballistic-water treatments with ozone. This causes high ozone levels to the air statue on the top of the ballistic-water surface and the hatch cover seal is exposed to this air statue.

Other chemical features could easily be left out from the wanted feature list of the hatch cover seal. These are the ones which unlike cargo or other features in vessel or at the

ports will cause. For example, coal cargo demands a lot from the materials in the hold. Coal contains sulfur compounds which in contact with water forms sulfuric acid (H_2SO_4). Another typical problem in the cargo holds is iron sulfate ($FeSO_4$) with its crystal waters. It frees very sour oxidative crystal liquid to the steel floor structure. If matters like these are taken under consideration when the new vessel is being under delivery or before the service has chosen the new spare seals to replace the old ones it will have positive effect to the service-life of packing. Most reclamation about hatch cover packing is due to some other factor than seal itself. Sometimes, if reclamation is done because the seals are decomposing in some way the reason could be harder to find out. In this situation the correct type of seal is manufactured and installed properly there still can be present some specific chemical feature onboard that is causing the problem. (Räisänen 1997, 24.1 – 24.16.)

In vessel during sea-voyage there are dynamic and static forces present (see figure 27) that are effecting to the tightening arrangement of hatch covers. Dynamic powers are due to the ship movements and static powers come from the normal usage of the seal which is under compression force. During the sea-voyage swell of the sea will cause multiple dynamic powers into the vessel and its components, like hatch covers. The hogging and sagging will twist the hold opening and packing along with it (see figure 28). (Räisänen 1997, 24.1 – 24.16.)
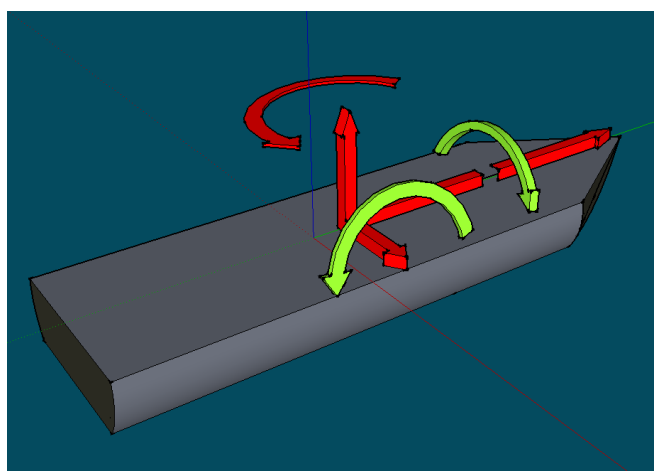

FIGURE 27. Ship Movements (adapted from Räisänen 1997, 24-1 – 24-16, modified)
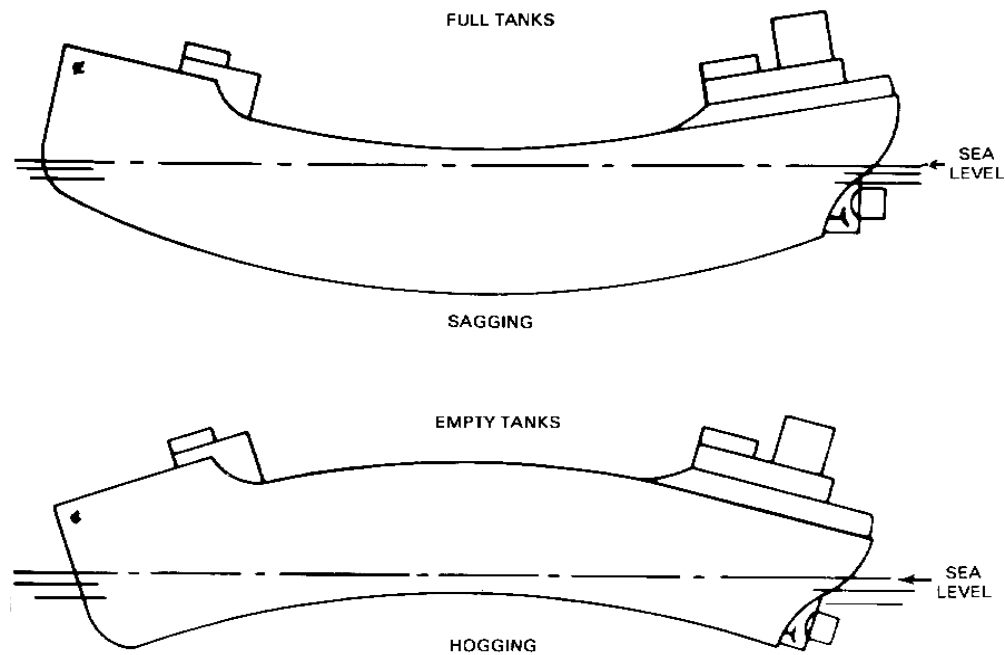
FIGURE 28. Hogging and Sagging (adapted from Global Security N.D.)

Hatch cover seal does not take the hatch cover weight on itself because the weight is guided on to the bearing pads. One hatch cover steel panel can have a weight of 30 tons and if it has 30 m of seal it leads to situation where 1 m seal portion has 1000 kg weight on it. Without bearing pads that are supporting the hatch cover weight, the hatch cover seal could not withstand the weight. It is also important that enough sealing force is available for the packing. This force is keeping the sealing surface of the rubber and the corresponding metal surface together. Sealing force is also needed for keeping the joint tight during the big side-way forces from waves focusing on to the side of the seal.

When the bulk carriers are loaded and unloaded there are always some dust and even bigger quantities of the cargo spreading on the top of vessel, including rubber seal. Seals are made into these rough conditions and the compression range covers the small objects between the seal and steel structures. In maintenance instructions there are advised one to clean the biggest dirt off from the sealant area before closing the hatch cover. In picture 8 is seen bulk cargo loading and demonstration of packing with some dirt particles on it. Even common sense should tell that seal would be working more properly without any objects from the bulk cargo attached to it.

PICTURE 8. Loading and Dirty Packing (adapted from de Souza 2009, modified)

6.3.1 The future of hatch cover packing

It is supposed that the demanding of rubber seals is decreasing because of the shipbuilding industry is slowing down. This derives from the global economic situation. Year 2014 is assumed to be better. (Nieminen 2012)

In container ships the coming trend is to build bigger vessels which freeboard height is increasing so much that they do not need weathertight hatch covers anymore and the rubber product volume is decreasing on the new-builds. In this vessel category high freeboard means that no wave is big enough to swept over the vessel and the speed of the vessel is decreased to 16 knots. Giant container vessels are not watertight from their holds and they have different kinds of labyrinth structure between the hatch covers to guide the rainwater into the ocean or pumps to get water away from the holds. (Nieminen 2012)

Shipbuilding industry and the markets around it are changing all the time. There can be totally different trends or better innovations coming around the corner that effect to the rubber packing products, also. (Nieminen 2012)

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ATTACHEMENTS

Attachement 1. Confidental