Elastomer Processing

M. A. Fancy, Reethamma Joseph and Siby Varghese

Abstract Generally elastomer processing involves two major steps. First one is the designing of a mixing formulation for a specific end-use and the second one is the production process by which rubber compound is transformed into final product. When designing a mixing formulation the compounder must take account not only of those vulcanisate properties essential to satisfy service requirements but also cost of the raw materials and the production process. There should always be a compromise between cost of production and quality of the product. This chapter is an attempt to deal with different processing techniques normally used in the rubber industry.

1 Introduction

The processing of a rubber formulation is a very important aspect of rubber compounding [1]. The raw polymer can be softened either by mechanical work termed mastication or by chemicals known as peptisers. Under processing conditions various rubber chemicals, fillers and other additives can be added and mixed into the rubber to form an uncured rubber compound. These compounding ingredients are generally added to the rubber through one of the two basic type of mixers; two roll mill or internal mixers.

2 Two Roll Mill

The first use of the two roll mill was in the 1830s in USA. Hancock's Pickle was patented in 1837, although models had actually been in use from the early 1820s.

M. A. Fancy · R. Joseph · S. Varghese (✉)
Technical Consultancy Division, Rubber Research Institute of India,
Kottayam 686 009 Kerala, India
e-mail: sibyvarghese100@yahoo.com

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Fig. 1 Two-roll rubber mixing mill (Website for this image: http://gdrubbermachine.com)

The first machine that appears suitable for rubber was a twin rotor design patented by Paul Pfleiderer in 1878/1879 [2].

Two roll mill consists of two horizontal, parallel heavy metal rolls which can be jacketed with steam and water to control the temperature [1–17]. These rolls are connected to the motor through gears to adjust the speed. Rolls turn towards each other with a pre set adjustable gap or nip to allow the rubber to pass through to achieve high shear mixing (Fig. 1).

2.1 Friction Ratio

The speed of the two rolls is often different [41–46]. The back roll usually turns at a faster speed than the front roll, this difference increases the shear force. The difference in roll speeds is called friction ratio, which is dependent upon the mill's use. For natural rubber mixing a ratio of 1:1.25 for the front to back roll is common [3].

2.2 Cooling

Cooling is employed either through cored rolls or through peripherally drilled rolls. The principal one employs cored rolls i.e., water is sprayed onto the outside of an axially drilled central core.

2.3 Other Attachments

Mills are fitted with a metal tray under the rolls to collect droppings from the mill. Guides are plates which are fitted to the ends of the rolls to prevent the rubber from contamination with grease etc. Safety measures are also attached to the mill for protecting the operator as well as the mill.

2.4 Mixing Process

There are five stages in the mixing process [4, 5]. They are:

1. Banding the rubber on the first roll.
2. Viscosity reduction by mastication or peptisation [5].
3. Incorporation of ingredients.
4. Distribution.
5. Dispersion.

When a highly elastic rubber of high molecular weight is fed into the mixer, it must be converted to a state in which it will accept particulate additives. This stage is called viscosity reduction. It is achieved either by a physical mechanism called mastication or by chemical means called peptisation. Now the rubber is ready to flow around the additives, incorporating and enclosing them in a matrix of rubber. Incorporated additives are then available for distribution. For better incorporation and distribution, with the help of a cutting knife give suitable cuts from either sides of the front roll.

During distributive mixing the rubber flows around the filler particle agglomerates and penetrate the interstices between particles in the agglomerate and the rubber mix becomes less compressible and its density increases [19, 20, 23]. The rubber which has penetrated the interstices becomes immobilised and is no longer available for flow. This immobilisation reduces the effective rubber content of the mixture. The incompressibility of the mixture allows high forces to be applied to the particle agglomerates, causing them to fracture. This action is called dispersive mixing, which serves the purpose of separating the fragments of agglomerates once they have been fractured. The addition of plasticizers facilitates easy incorporation of the fillers. Curatives are added at the end of the mixing cycle. After thorough incorporation of all the ingredients the mix is homogenised and the batch is then sheeted out. For best mixing procedure the temperature is kept at 75–80 °C by careful adjustment of flow of cooling water through the rolls. The sequence of mill mixing is as follows [4]:

1. Band the rubber
2. Mastication/peptisation
3. Addition of cure activators
4. Half of the filler and oil
5. Rest of the fillers
6. Curatives
7. Homogenisation
8. Sheeting out the compound.

It is better to keep the rubber compound at ambient temperature for one day, for better consistency in properties.

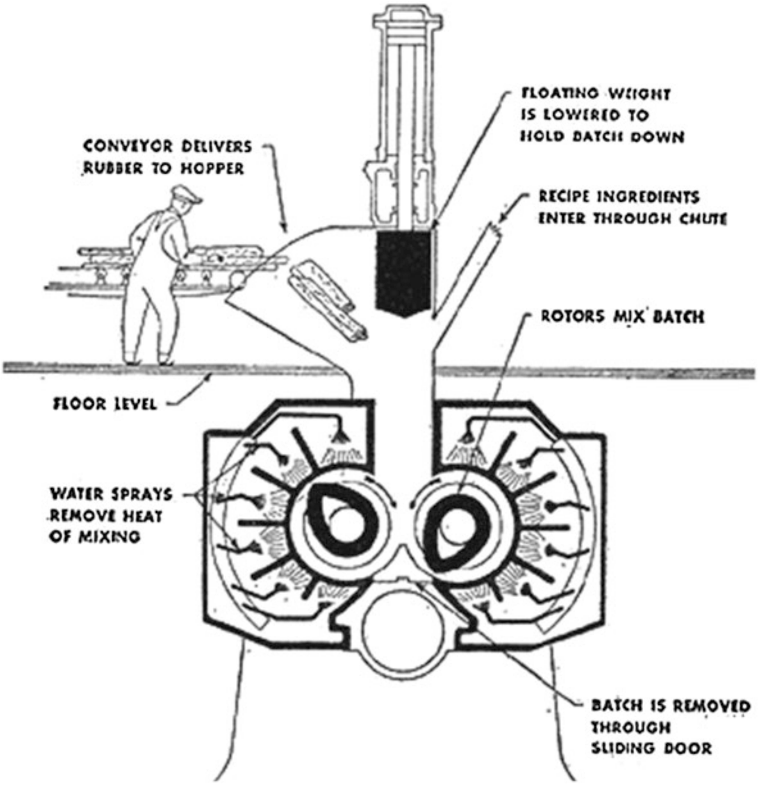

Fig. 2 Diagrammatic section of Banbury mixer (Website: http://bouncing-balls.com)

3 Internal Mixers

The internal mixers were initially developed by Fernley H [1, 2, 29, 30] Banbury from 1916 onwards. Both two roll mills and internal mixers are batch mixers, mill mixing is relatively a slow process, and the batch size is limited. Internal mixers overcome these problems by ensuring rapid mixing and large output [6, 18, 21–23]. An internal mixer consists of two horizontal rotors with wings or protrusions, encased by a jacket (Fig. 2).

3.1 The Intermix [6]

The concept of Intermix was developed in the UK during the early 1930s by an unknown engineer of the ITS Rubber Company. Construction and detailed design

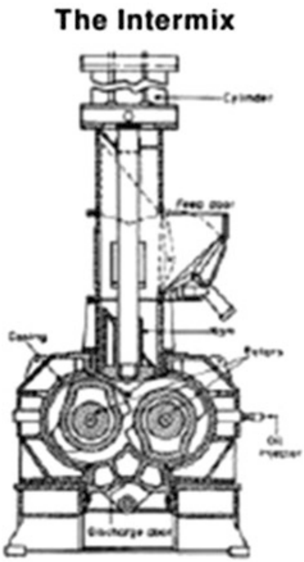

Fig. 3 Diagrammatic section of Shaw Intermix (Courtesy Francis Shaw & Co, Ltd)

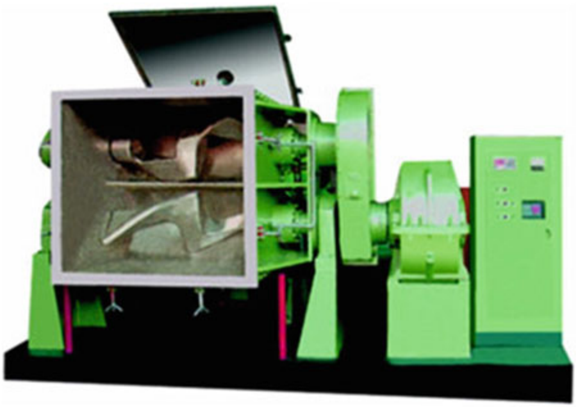

Fig. 4 Rubber kneader (www.rubber-machinary.in)

of the Intermix was contracted to Francis Shaw a company of Manchester, who eventually acquired and patented the design (Fig. 3).

3.2 Rubber Kneaders [7]

There are two different types of internal mixers used in the industry at large. The first type is more commonly known as a "Banbury®" type intensive mixer and the second type is known as a “Kneader” [7]. The primary difference between the two types of mixers is rotor, throat, chamber and floating weight design. The former also discharges the batch through a bottom door where as the kneader tilts to discharge the batch (Fig. 4).

Conventional Kneaders have two tangential non-intermeshing rotors as well as pneumatic operated floating weights. With the conventional kneader design the temperature in a batch can not be sufficiently controlled to achieve 1 pass mixing. With conventional kneaders the batch temperature after the primary kneading stage is high because of poor temperature transfer from the mixing contact surfaces to the batch. Therefore, the batch has to be either cooled down or transferred to another kneader for the final kneading stage. This additional step is cost prohibitive as well as time consuming.

The MXI-Intermeshing Kneader imparts superior dispersion by reducing filler particle size during the kneading process. The reduction of particle size is achieved by the intermeshing rotor design.

Traditional kneaders have two counter rotating rotors with each mixing rotor having two wings affixed on it. The two wing rotors typically rotate at two different speeds through connecting gears. The wings move material from one portion of the chamber to the other while also providing material movement along the rotor axis. These kneader do not have intermeshing rotors and therefore can have differential rotor speeds.

Conventional Kneaders have a one piece rotor design which includes a rotor shaft with two wings welded on the shaft. Water cooling is provided through a passage in the rotor shaft and small jackets in each wing. This cooling method is not sufficient for single pass mixing. The MXI-Kneader consists of a two piece rotor design. An over-sized rotor shaft and a cast blade shell portion. The cast blade shell is provided with a spiral water passage which is close to the material contact surface. The assembled rotor has a much larger outside diameter than conventional kneaders. This allows for more cooling surface as well as larger mixing surfaces.

Conventional kneader rotors have a shaft and two wings one wing is typically shorter than the other, to have adequate material movement inside the mixing chamber. The MXI-Kneader has a rotor shaft with one long wing (blade) and two nogs (small blades) for mixing. The conventional kneader’s blades are typically long high and narrow. The new MXI-Kneader has much wider land width and stubby in shape. The much wider rotor tip (land width) greatly enhances the dispersion effect. The materials are subjected to a larger smearing action of the batch against the rotor tip to chamber wall as well as the rotor tip to rotor shaft. In the non-intermeshing type kneader no mixing occurs between the rotor tip and rotor shaft due to the non intermeshing design.

Conventional kneaders use pneumatic pressure to push the batch down into the rotors and mixing chamber with a floating weight (ram). This pneumatic system is unreliable and inconsistent. The pneumatic ram moves completely uncontrolled and the ram position is controlled by the rotor dragging force as well as the size of rubber pieces it is trying to force into the rotors. The hydraulic ram exerts positive pressure on the batch and can be accurately controlled in the desirable position which leads to better batch to batch consistency.

3.3 Intermix and Banbury

In Tire factories and large rubber factories the internal mixers has practically replaced the two roll mill for the preparation of compounds. Both these machines are used in rubber industry [1]. Compared to tangential system in Banbury the Intermeshing system in Intermix have more effective temperature control, drive power is around 10–20 % higher. But optimum fill level is 5 % lower because of the narrow intermeshing zone.

The basic difference between the two machines lies in the rotor design. The intermix is an example for the interlocking type rotors and the Banbury is of non-interlocking type. In both cases the rotors run at even speed and the nogs or wings are designed to produce a friction ratio between the rotors. In the Banbury, the mixing process is carried out between the rotors and the jacket. In the Intermix the work is done between the rotors. Both the machines are fitted with a ram to ensure that the rubbers and powders are in contact [8, 24, 34, 35].

3.3.1 Machine Sizes

A range of sizes of machines are available. The most popular size of machine is one with a batch load of about 200 kg of compound.

3.3.2 Rotor Speeds [3]

Internal mixers of 200 kg size can be obtained with rotor speeds in the range of about 20–66 rev/min. To carry out a mixing, certain number of rotor revolutions are needed, then the mixing time is directly proportional to the rotor speed.

3.3.3 Ram Thrust and Fill Factor

The thrust applied to the ram affects the output of the internal mixer. Increase in the ram thrust reduces the voids in the machine [3, 32]. For efficient mixing the fill factor is also important.

For a given rotor speed and ram pressure, there is a correct volume of the compound to give efficient mixing. If this is divided by the volume of the chamber the fill factor is obtained. For rubber compounds normally it will be 70–80 %. The remaining corresponds to the voids in the mixture. If the fill factor is accurate, large output of better quality will result. Increase in the ram thrust increases the rate of increase of temperature, and reduces the mixing cycle, and gives more rapid ingredient absorption, and gives greater reproducibility in mixing.

3.3.4 Cooling Arrangement

Drilled sides are now common for cooling arrangements. The drilled sides comprise cooling passages drilled under the surface of the body. If cooling is higher, slippage can occur between the rubber and the rotors. As this gives inefficient mixing, warm water is circulated through the machine. The temperature of the water can be regulated by cooling water when heat is being generated and by electrical heaters when the machine is too cold.

When a mix has been completed in the internal mixer, cool it as quickly as possible. The batch of compound is either dropped into an extruder, or to a two roll mill. The compound is then treated with anti-tack prior to cooling and storing. Various degrees of automation are possible for these systems.

3.3.5 Mixing Procedure

The following facts should be noted for better mixing:

1. Generally the efficiency of mixing depends on the sequence of material input to the mixer. The steps for ingredient addition should be minimum. For each addition the ram should be raised, with the ram up, there is no pressure on the mix, which leads to little effective mixing.
2. Particulate fillers should be added at the earliest stage of mixing. This helps to achieve good dispersion as a result of the high viscosity at the initial low temperature. A higher viscosity will lead to an increased shear stress at a given rotor speed. For the same reason plasticizers should be added at the later stage. Oils may coat the rotors and chamber wall and cause slippage and reduce mixing efficiency. They are therefore added together with fillers to reduce this action.
3. The curative package should not be added at he elevated temperature stage. Batches are usually dumped from an internal mixer on to a mill where they may be further worked while being cooled. Curatives are added at this point.

3.3.6 Upside Down Mixing

This method involves adding all the dry ingredients other than the elastomer to the mixer first, then all the liquids, and finally the elastomer [9].

3.3.7 Advantages

1. It is faster and simplest.
2. It is employed when the polymer content is less than 25 %, and also for polymer having poor self-adhesion.
3. It is effective for compound having large volume of liquid plasticisers and large particle size fillers.

3.3.8 Disadvantages

1. Small particle size carbon blacks cannot be effectively mixed by this technique, as it does not provide a high level of dispersion.
2. If the polymer is of high viscosity upside down mixing will result in the development of temperature and lead to poor dispersion.
3. Clays which are difficult to wet due to low surface energy do not incorporate well in this method.

3.3.9 Take-Off Systems

After the mixing the batch has to be cooled and converted into strips or sheets suitable for feeding to the next process. This is done by dumping the batch through the drop door at the bottom of the mixer on to a cool mill capable of handling the entire batch. A three or four roll calender is used when uncured rubber is applied to a textile fabric or steel cord as a coating. Extruders are used when the uncured stock is to be shaped into a tyre tread, a belt cover, or hose tube for example. Extruders with lower screw length to screw diameter (L/D) ratios are considered hot feed extruders while one with high ratio are called cold feed extruders.

4 Continuous Mixers

The continuous mixing of rubber compounds is very much in its infancy. The earliest machines used for continuous processing of true curable materials were the Extruding, Venting and Kneading (EVK) machine made by Wernar and Pfliederer and Mixing, Venting, Extruding (MVX) machine made by Farrell Bridge. EVK primarily used in EPDM extrusion compound area using powdered polymer, MVX for cable compounding and in the production of tire compounds using granulated Polymer [2, 10]. Recent work on continuous mixing of rubbers has centred on modified twin screw compounders that have been used for some considerable number of years for in the plastic compounding industry. Because of the numerous compounding ingredients used in the tire industry in their varying physical form, an economic and sufficiently accurate proportioning of the compounds in a continuous mixer is barely possible. Now-a-days continuous mixers are used in rubber compounding only for partial operations such as making batches either consisting of elastomer and filler or another one containing chemicals.

Both mills and internal mixers are batch mixers. In order to replace the batch mixing process, attempts were made since world war II to develop a continuous mixing technique. Examples are Double R mixers from Francis Shaw in the late 1940s, the continuous mixer from Farrel's Corporation in the 1960s, and the Transfer mix from U.S Rubber Company in the late 1960s. Continuous mixing normally demands that solids are fed in a particulate form [11]. In order to convert rubber bales into pellets; disintegrators are needed. All continuous mixing operations face the problem of how to weigh continuously the multiplicity of very variable weights of rubbers and their compounding ingredients with the accuracy required. Disintegrating rubber will consume power and powdered rubbers cost more than baled rubber.

5 Trouble Shooting the Mixing Process [9]

Problems in the mixing process are usually due to inadequate dispersion, contamination, poor processability on the dump mill, scorchy compound and batch to batch variation. Once the problem has been identified, corrective action is often simple. The list below suggests possible causes of such problems.

1. Inadequate dispersion or distribution
   - Insufficient work input, mixing time
   - Order of ingredient addition not proper
   - Batch size too large or too small
   - Insufficient ram pressure, wrong rotor speed, wear of rotors and chamber wall
   - Cold polymer (this applies especially to natural rubber, EPDM and butyl)
   - Excessive moisture in fillers
   - Oils added at temperature below pour point.
2. Scorchy compound [33]
   - Too high a heat history after addition of curatives
   - Accelerator added too soon
   - Inadequate distribution of curatives
   - Too high a rotor speed
   - Materials added at too high a temperature
   - Inadequate cooling of compound after take-off.
3. Contamination
   - Physical contamination of one or more ingredients
   - Insufficient clean-out between batches of different base polymers

- Oil-seal leak.

4. Poor handling on dump mill

- Incorrect roll temperatures, speed and friction ratio
- Too high a loading of clay fillers, viscous plasticizer
- Poor distribution or dispersion
- Scorchy compound
- Compound left on mill too long.

5. Batch to batch variation

- Variation in initial loading temperatures, ram pressure, cooling water flow, or temperature
- Variation in compounding ingredients
- Variation in dump time, temperature, or energy input
- Variation in milling time or mill settings
- Variation in amount of cross-blending on mill.

6 Extrusion Process

6.1 Introduction

In rubber processing, extruder is mainly used for shaping the rubber compound into the desired profile before it is finally processed. There are two type of extruder—ram extruder and screw extruder. Ram extruder has high operating cost and lower output. Now, the screw extruder is used mainly for the production of tubing, channel, tire treads and for the insulation of the wire and cables (Fig. 5) [16].

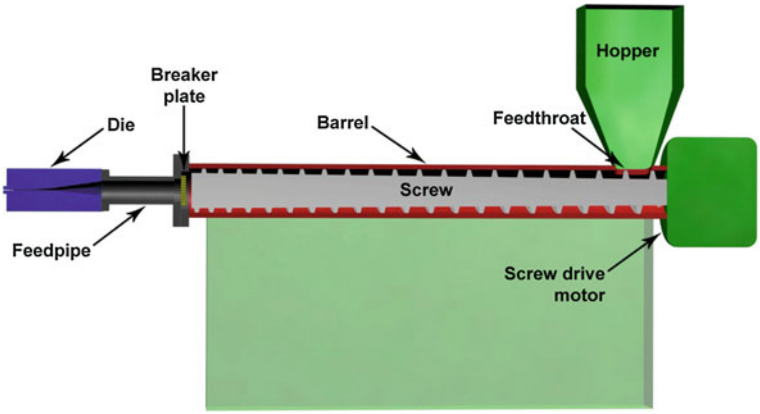

Fig. 5 Schematic representation of a rubber extruder (www.http.wikipedia.org/wiki/Extrusion)

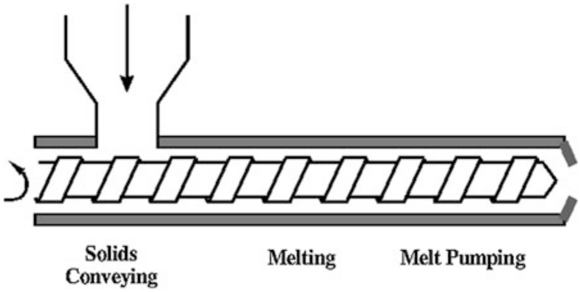

Fig. 6 Screw extruder (http.www.polymerprocessing.com/operations/screw/big.html)

6.2 Screw Extruder

The extruder consists of a feed hopper, cylindrical barrel, rotating screw, head attachment and a die [3, 14]. The screw is driven by the an eletric motor through appropriate reduction gear system. The compound to be shaped is fed into the machine through the feed hopper. The width of the compound strip fed is slightly less than the width of the feed hopper and the thickness of the strip should be slightly less than or equal to the depth of the flight of the screw. The barrel is usually made of hardened steel and is jacketed for the circulation of steam or cold water. Heating of the barrel is necessary in the early stages, when it is started temperature is developed inside in this stage, steam supply is cut off and cold water is circulated to maintain the temperature (Fig. 6).

The head attachment of the extruder varies in shape according to the purpose for which it is used [25, 27, 29]. The design of the head is very important to get free movement of the compound at equal pressures and speeds from all side of the head into the die. Any point within the head where the compound doesn't move is known as dead spot. Provision for heating and cooling should be provided at the head attachment for better control of temperature.

The die of the extruder shape the compound into the desired profile. For better shape and finish of the extrudate, the design of the dies is very important. The die is the hottest part of the extruder and is usually heated initially by a gas flame. The cross sectional area of the die should never be lower than 5 % less or greater than 30 % more of the cross sectional area of the extruder.

The extrudate coming out from the die is usually carried to the next stage of processing, through conveyor system. Cooling of the extrudate is done by immersion in water or by a spray of cold water. Talc is applied to the extrudate.

6.2.1 Parameters Affecting the Processing [3]

1. The screw should have a lower volume in the flights at the out going than at the in going end. It is most important that an extruder screw is full at the discharge end, otherwise dimensional changes in the extrudate may occur.

2. The design of the head is very important, the head equalizes the pressure from the screw and barrel and the compound moves smoothly to the die at equal pressure and speed.
3. The last stage is die, which forms the compound into the desired shape. Die should be designed to operate under conditions of minimum stress and at pre determined running speed and temperature. The extrudate should be produced under these conditions. The lower the viscosity of the compound, the greater is the through put to be expected in unit time. Dimensional variations is at minimum when the compound has the minimum entrapped stress.

6.2.2 Hot Feed, Cold Feed and Vacuum Extruder

Depending on the design of the screw and barrel, extrudate can be three types namely, hot feed, cold feed and vacuum extruders. The screw of the vacuum zone there is provision at the barrel for connecting it to a vacuum device. In the vacuum zones, the screw is either deeper or more widely cut or the cylinder in that zone is slightly bigger than in the other zones. Vacuum extruder helps to remove any traces of moisture or entrapped air from the compound. Hence it is used in shaping articles for open steam cure, hot air cure, molten salt cure and fluidized bed cure. Since moisture and air trapped in the compound is removed during vacuum extrusion, the product will be free from porosity.

Depending on the design of the screw, the extruder may be used for hot or cold feeding of the compound. The hot feed extruder has got a short barrel, the length to diameter ratio of the screw is low, in the range of 5:1 and the compression ratio is nearly equal to unity. In the case of cold feed extruder the length to diameter ratio of the screw is high, in the range of 20:1 and the compression ratio is greater than unity [28].

In hot feed extruders, pre-milled rubber is fed into the extruder, output will be uniform and the production equilibrium can be attained within a short time. As its name refers cold rubber compound can be fed into cold rubber feed extruders. Out put depends on the nature of the compound and it takes longer time to attain production equilibrium. Hot feed extruder has high operating cost and higher output than cold feed extruder. Product of consistent quality can be obtained only if the compound fed into the machine is uniform viscosity, temperature and volume. Maintain the temperature of the barrel, screw, head and die constant.

6.2.3 Defects in Extrusion

1. Die swell

As the compound comes out from the die, it shrinks along its length resulting in slight increase in overall dimension of the extrudate. Nature of the compound, uniformity of the speed stock and speed of the screw and take off conveyer systems can affect die swell.

2. Rough surface

Poor finish of the extrudate may be due to poor dispersion of the compounding ingredients, very high money viscosity of the polymer, very low temperature and pressure of extrusion. By proper adjustment of this good finish of the product can be obtained.

3. Porosity

This is due to the presence of excess moisture in the compounding ingredients, use of high volatile compounding ingredients and presence of entrapped air. Proper drying of fillers before using, addition of material like calcium oxide in the compound and use of vacuum extruder can reduce porosity in the extrudate.

4. Collapse of the material

Collapse of the extrudate occurs when the quality of the polymer used is poor, viscosity of the compound is very low and when the processed material is recycled several times.

6.2.4 Troubleshooting the Extrusion Process [9]

Despite the many feedback microprocessor control system available on the market, it is still often the skill, experience, and understanding of the extruder operator that determines the success or failure of an extrusion operation. Success or failure has to be measured in economic terms, that is the hourly production rate of the process. This depends on minimizing scrap and downtime both in start-up.

7 calendering

7.1 Introduction

Calenders are used in the rubber industry primarily to produce rubber compounds and sheets of various thicknesses, coating textiles or other supporting materials with this rubber sheet or frictioning fabrics with rubber compound.

7.2 Machinery

A variety of products like sheeting for lining, hospital bed sheets, films, frictioning of tire fabrics for Bicycle/motor cycle/Auto tires, hoses beltings, profiling, cushion gum, single coating, laminating doubling etc. Special Calenders for profiles and Inner liner can be done. The Rubber Calender Machines are made in a wide range of sizes, from small laboratory unit up to the largest production calender machines (Fig. 7).

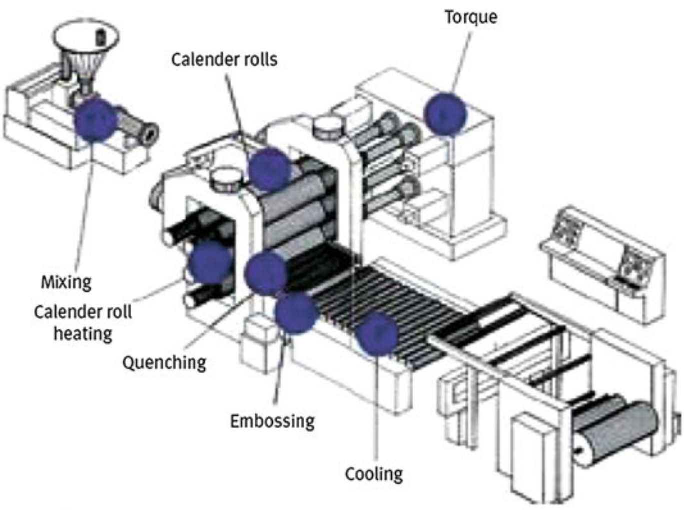

Fig. 7 Calendering unit (www.http:/wikipedia.org/wiki/calendering)

7.3 Calendering Unit

Rubber calenders are differentiated by the number of rolls, their arrangements, and their size (diameter and width). They can have two, three, or four rolls in a variety of configuration. For the production of tire stock, belting, and sheeting the 3 roll vertical calender with 24″ diameter, 68″ width rolls, and four-roll Z and L calenders with 28 × 78″ rolls are standard. Four-roll calenders are used for applying compound to both sides of tire cord fabrics in one operation.

7.3.1 Types [11]

There are three main types of calender—the I type, L type and Z type (Fig. 8).

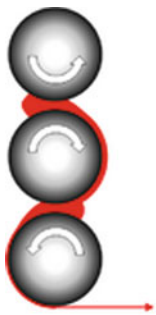

Fig. 8 Roller setup in a typical 'I' type calender (www.appropedia.org/polymer-calendering)

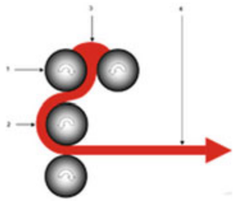

Fig. 9 Roller setup in a typical inverted 'L' type calender (www.appropedia.org/polymer-calendering)

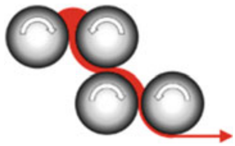

Fig. 10 Roller setup in a typical 'Z' type calender (www.appropedia.org/polymer-calendering)

The "I" type, as seen in Fig. 1, was for many years the standard calender used. It can also be built with one more roller in the stack [8, 12]. This design was not ideal though because at each nip there is an outward force that pushes the rollers away from the nip (Fig. 9).

The L type is the same as seen in Fig. 2 but mirrored vertically. Both these setups have become popular and because some rollers are at 90° to others their roll separating forces have less effect on subsequent rollers. L type calenders are often used for processing rigid vinyls and inverted L type calenders are normally used for flexible vinyls (Fig. 10).

The z type calender places each pair of rollers at right angles to the next pair in the chain. This means that the roll separating forces that are on each roller individually will not effect any other rollers. Another feature of the Z type calender is that they lose less heat in the sheet because as can be seen in Fig. 10 the sheet travels only a quarter of the roller circumference to get between rollers. In most other types this is about half the circumference of the roller.

7.3.2 Feeding [9]

To ensure steady operations of the calender, and to control shrinkage, the compound has to be preheated to around 93 °C, and thoroughly fluxed and plasticized before being fed to the calender.

Calenders use rolls with axial drilling about 50 mm under the surface, through which water at a pre-set temperature is continuously circulated. The rolls with the axial hole through the centre are known as cored rolls and the latter are periphery drilled rolls. Periphery drilled rolls without controlled—temperature water going through them are unsatisfactory in operation, since hot and cold water used alternately increase and decrease the roll temperature too rapidly. Periphery drilled rolls are normally heated and cooled at a speed of 1 °C/min i.e., it give much better control.

7.3.3 Sheeting [25]

This process is carried out on a three—roll calender with thickness control by a feed back system from the product. The rolls are crowned to compensate for deflection under load, and so to maintain a constant roll gap across the width of the sheet.

7.3.4 Frictioning [25, 26]

This is impregnating a textile or metallic fabric between two rolls running at different speeds so that the rubber compound is forced into the interstices of the substrate.

7.3.5 Spreading [3]

The main working part of a typical spreading machine as shown in (Fig. 11).

A roll of dried or pre-treated fabric is fitted on to location A and the leader cloth is fed through the rest of the machine until finally taken up on roller J. from A, the cloth passes over a spreader bar B to ensure that all creases are removed from the fabric and to keep it under the correct lateral tension. The smooth tensioned fabric is then fed over the bearer roller C and under the doctor blade D, which is pre-set to give the correct build-up of dough on the fabric surface. The angle between the blade and the fabric and the distance between them control the coat thickness and the degree of 'strike through' (degree of penetration) of the dough. The greater the angle at which the blade meets the moving fabric, the greater the degree of penetration.

The fabric then enters the steam chest area, where the solvent is driven off and removed by means of the extraction unit F; the speed of travel of the fabric is dependent on the rate of solvent removal. On emerging from the end of the steam

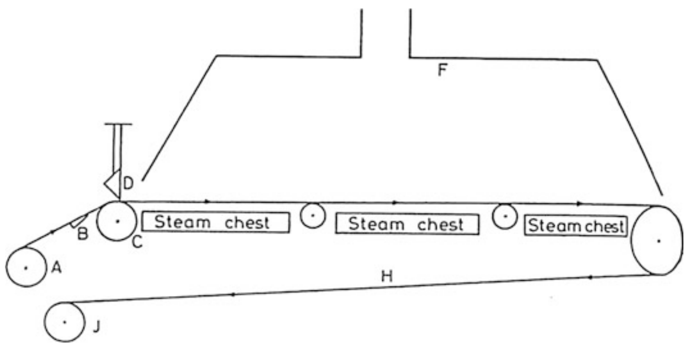

Fig. 11 Diagrammatic sketch of spreading machine. Courtesy ICI dyestuffs division

chest, spread fabric requires cooling before it is rolled up on roller J. This is achieved by means of the festooning device, placed at H, which may consist of a single or several rollers; if the dough is of a sticky nature, it may also necessary to use a liner cloth or dust the surface with talc to prevent blocking together of the rubber-fabric laminate during storage.

Once a machine has been set up to run, it is necessary to carry out the spreading of the first few yards at the low speed to check the coating thickness against specification, either by means of a vernier gauge or electronically. Normal running speed of the order of 10 m/min.

7.3.6 Skim Coating or Topping by Means of the Calendering

The operation of applying a substantial thickness of rubber to fabric on a calender is termed skim coating or topping. In this method, compound is fed around a calender roll from a calender nip, and the sheeted compound is applied to the fabric at a second nip. The rubber sheeting must be travelling at the same speed as the fabric at the point where it is laid on to the fabric; however, sheeting can be produced from roll which run at the same speed or with a friction ratio in the nip (Fig. 12).

7.3.7 Temperature Effects

The temperature of the fluid melt has been found to be highest at the rollers. This happens for two reasons:

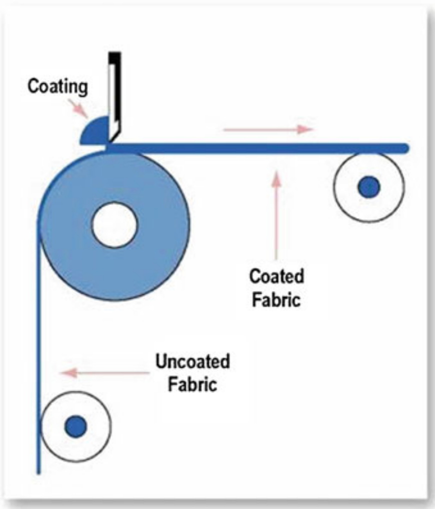

Fig. 12 Topping by means of a calender (www.appropedia.org/polymer-calendering)

1. The shear is highest at the sides in laminar flow and therefore friction and heat is also highest there.
2. The heat is added to the system through the rollers, and the fluid doesn't conduct it very well.

The effects of this tend to grow in magnitude with more and more viscus the fluid is. If one were to raise the rolling temperature there would be changes in the above fluid mechanics. It would decrease the viscosity; consequently decreasing the power input, pressure and roll separating forces in the fluid. It would also lower the chances of a fracture in the fluid and make the surface finish better, but this all comes at the price and increases the chances of thermal degradation.

7.3.8 Velocity Effects on Final Product

The calender is able to produce the polymer sheeting at a fast rate. It can produce sheeting at a rate between 0.1 and 2.0 m s^{-1}. By increasing the speed the heat has even less time to spread throughout the fluid from the rollers causing an even greater temperature variation. It also causes an increase in shear forces in the fluid at the rollers, which increases the chances of surface defects like fractures. The speed clearly needs to be chosen very carefully in order to produce a quality product.

7.3.9 Roll Bending

In calendering the rollers are under great pressures, which can reach up to 41 MPa in the final nip. The pressures are highest in the middle of the width of the roller and due to this the rollers get deflected. This deflection causes the sheet being made to be thicker in its center than it is at its sides. There are three methods that have been developed to compensate for this bending:

1. Roll crowning
2. Roll bending
3. Roll crossing.

Roll crowning uses a roller that has a bigger diameter in its center to compensate for the deflection of the roller. Roll bending involves applying moments to both ends of the rollers to counteract the forces in the melt on the roller. With roll crossing the rollers are put at a slight angle to each other and because of this the force of the rollers on the melt is higher in the middle where the rollers are on top of each other more, and less force is applied on the edges where the rollers are not directly over top of each other.

7.3.10 Roll Cambering

The calender rolls are usually cambered and are not parallel to compensate for variation in thickness across the sheet. This is an ideal solution for a calender which produces one gauge of sheet from one compound. Calenders can be re-cambered in a few hours to accommodate a permanent compound change or to take up the wear of the roll; if more than one compound is processed then some other device for resetting the crown will be needed.

7.3.11 Calendering Technology

Rubber compound behave as viscous non-Newtonian liquids. If a uniform gauge of sheeting is to be produced, then the viscosity of the compound must be constant.

In order to achieve uniform viscosity, the temperature of both the compound and the calender must be controlled, as the viscosity of rubber compound is affected very considerably by temperature (Fig. 13).

When an unsupported sheet is taken from a calender nip, it shrinks along its length and increases in the thickness and the width. This results in rubber sheets having a crown, i.e., they are thicker in the centre than at the edges.

7.3.12 Unsupported Sheeting

Two-, three-, or four—roll calenders are used for the production of sheeting containing no textile fabric reinforcement.

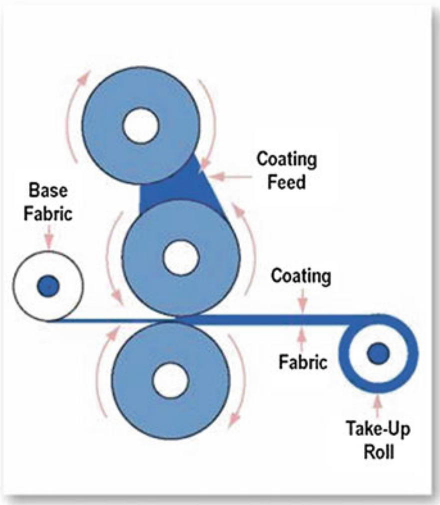

Fig. 13 Rubber–fabric coating by calendering (www.appropedia.org/polymer-calendering)

For precision gauge control, a sheet is produced in a first nip, and this is then fed round a roll to a second nip. The second nip gives either less blistering or a thicker sheet for the same amount of blistering. The quality of sheeting is more dependent upon the quality of feed than on any factor other than the temperature of the calender rolls. Occasionally, three nips are used for calendering, i.e., a four-roll.

7.3.13 Application of Rubber from Solvent Dispersion or Dough

When it is necessary to apply a coating of rubber to a fabric which is too delicate for the calendering process, or when the compound is not suitable, the technique of spreading is used. This process consists of the application of the compound dispersed in solvent at high concentration in the form of dough, as it is termed. A stationary blade (commonly called a doctor) regulates the thickness applied to the fabric as it is passed underneath the blade. The fabric then drawn over a heated chest where the solvent is evaporated and usually recovered for re-use by adsorption on an active carbon.

7.3.14 Troubleshooting Problems in Calendering [9]

1. Scorch
   - Poor temperature control
   - Running speed too fast, leading to excessive shear heating
   - Stock warmed upon mill too long.
2. Blistering
   - Roll temperature too high
   - Feed bank too large, resulting in entrapped air
   - Sheet thickness too high.
3. Rough or Holed sheet
   - Inadequate stock warm-up
   - Amount of material in bank too small, or too large, to form rolling bank
   - Varying stock temperature.
4. Tack
   - Temperature of rolls too high
   - Incorrect stock feed temperature.
5. Bloom
   - Low solubility of some ingredients in formulation.

8 Continuous Vulcanization System [9, 31]

As a rubber compound containing a curative system is held at the curing temperature the production of cross-links causes it to change from a viscoelastic fluid to an elastic solid. As it leaves the die the compound is still a fluid, and as the stresses built up in the passage through the head and the die relax, the dimension of the profile, originally those of the die, change.

8.1 Pressurized Steam Systems

These are commonly used for products having a core or other reinforcement and profile that are easy to seal, such as wire, cable, and hose. The time required for heat to penetrate to the centre of the cross-section depends on the diameter. The weight of rubber per unit length is proportional to the square of the diameter.

8.2 Hot Air Curing Systems

These consists, basically, of an insulated tunnel, a metal mesh conveyor to support and move the profile through, and a counter current of air, heated to up to 300 °C. Heat transfer is poor (coefficient 70 $kJ/m^2/h/°C$) and so lines of 100 ft are required to complete the curing process. With compounds (e.g., EPDM), which are not readily susceptible to oxidation ultrahigh temperature, shorter ovens can be used.

8.3 Microwave System

Microwave system provide quick and uniform heating throughout the profile, which is especially useful for thick profiles, profiles of varying thickness, and for sponge. The compound has to be microwave receptive (i.e., polar), which most polymer are not. However, many carbon black are, and if necessary, it is also possible to add other chemicals specifically to increase microwave receptiveness. Usually, a short microwave section is used immediately after the die to boost the extrudate temperature to curing temperature, followed by a hot air tunnel to maintain temperature until the profile is cured. There is much less heat loss with a microwave system than with the system described previously because the heat is generated in the rubber itself. This high energy-efficiency makes the use of electricity, a more expensive source, economically feasible.

9 Moulding [3]

Moulding is the operation of shaping and vulcanising the plastic rubber compound by means of heat and pressure in a mould of appropriate form. There are three general moulding techniques:

1. Compression
2. Transfer
3. Injection moulding.

9.1 Compression Moulding [9]

In compression moulding a pre-weighed, pre-formed piece is placed in the mould. The mould is closed, with the sample under pressure as it vulcanises. For the satisfactory large scale production of components, it is necessary to use carefully designed and well constructed steel moulds, suitable hardened and finished depending upon the surface quality required for the product. Cavity pressure is maintained by slightly overfilling the mould and holding it closed in a hydraulic press. Heat is provided by electricity, hot fluid or steam.

Compression moulding is the oldest and most universally used technique and for many products the cheapest process because of its suitability for short runs and because of the low mould cost. The press used for conventional compressional moulding has two or more platens, which are heated either electrically or by saturated steam under pressure. The platens are brought together by pressure applied hydraulically to give a loading from 75 to 150 kgf/cm^2 of projected mould cavity area (Fig. 14).

9.2 Advantages [4]

1. Moulds have low investments cost.
2. Due to the simplicity in the mould design, it is suitable for curing thick rubber articles. Hence large rubber articles (tyres, belts etc.,) and small articles (gaskets, washers etc.,) maybe cured by this process.

9.3 Transfer Moulding

Transfer moulding involves the transfer of a rubber compound from a heated reservoir or transfer pot, through a narrow gate called sprue or runner into the closed cavity of a mould by a piston where the compound is cured at pre-determined temperature and pressure (Fig. 15).

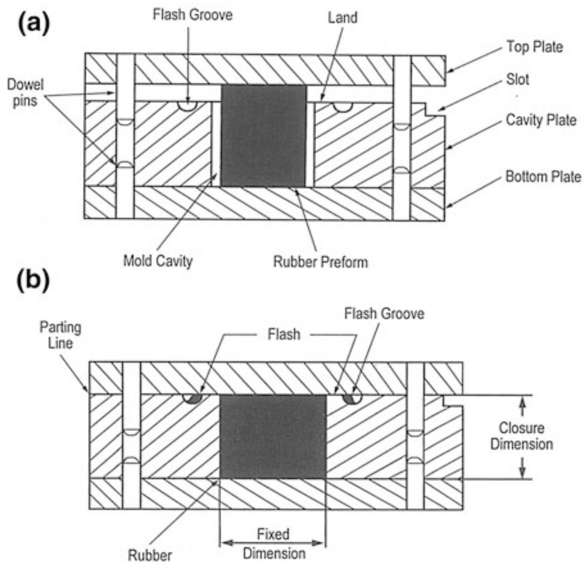

Fig. 14 Compression mould containing a rubber prefoam. **a** Before closing and **b** after closing (Courtesey of J.Sommer and Rubber Division ACS)

Transfer mould consists of three parts. The upper part called piston, the lower part the mould itself. Both upper and lower parts are attached to hydraulic press. The centre part which contains the cylinder, the injection nozzle is removable. Though the moulds are more expensive, this process permits better heat transfer. Important points to be remembered during transfer moulding.

1. Clearance between the transfer pot and plunger (piston) should be optimised [4].
2. The plunger should not tilt in the pot.
3. The plunger face area should be larger than the projected cavity area.
4. Compound should be optimised to reduce the vulcanised scrap in the mould cavity and the sprue.
5. Changes in pressure should be monitored by pressure transducers, since pressure variations during the transfer process can open the mould cavity to flash.

9.4 Advantages

1. As the mould is closed before the rubber charge is forced into it, closer dimensional control is achievable.
2. In the transfer process fresh rubber surfaces are produced. This allows the development of a strong rubber to metal bonding with any insert in the mould.

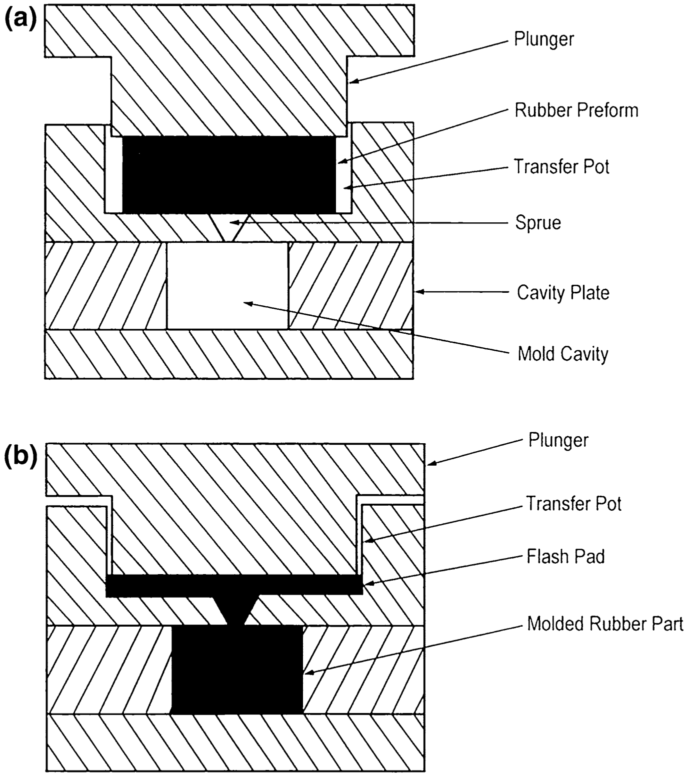

Fig. 15 Transfer mould showing. **a** preform transfer pot before closing **b** after closing (Courtesey of J.Sommer and Rbber Division ACS)

3. Production cost is lower due to shorter cure times as a result of heating the rubber due to flow through sprue, runner and gate and shorter downtime between runs as only one charge blank is necessary even if a multi-cavity mould is used.

9.5 Injection Moulding [9, 13, 14]

Injection moulding is now a well established process in rubber industry. The operation of an injection moulding machine requires feeding, fluxing and injection of a measured volume of a compound, at a temperature close to the vulcanisation temperature into a closed and heated mould. The process also requires a curing period, demoulding and if necessary mould cleaning or metal insertion before the cycle starts again. For maximum efficiency almost all of the above operations should be automatic. The difference between transfer and injection process lies in

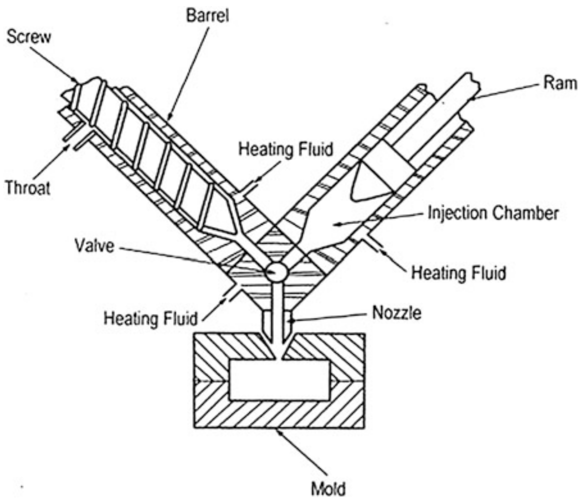

Fig. 16 Injection moulding machine with separate ram and screw (Courtsey o J. Sommer and rubber Division ACS0)

the degree of automation. In the injection moulding process there is always a reserve of material being heated and plasticized during the vulcanisation step.

The types of injection machines available depend on the method of heating and peptisation of the compounded rubber. The main types used are:

1. The ram type
2. The reciprocating screw type
3. Screw-ram type.

Among the three simple ram type machines cost less than screw machines [15]. The mix receives heat only by thermal conduction from the barrel, high injection temperature and thermal homogeneity are difficult to achieve and they are not widely used.

In the reciprocating screw type the screw acts both as an extruder and a ram. In this type of machine, the mix is heated and plasticised as it progresses along a retractable screw. When the necessary shot volume has accumulated in front of the screw. it is injected by forward ramming action of the screw. With this system more uniformly controlled feeding of the material can be achieved together with more rapid heating of the stalk, due to mechanical shearing, and a greater degree of thermal homogeneity. However, during the induction stage as the screw act as ram there is some leakage back past the flights of the screw and this limits the injection pressure. This type of machine is only possible for low shot volumes, or for very soft compounds.

The preferred basic design for the rubber injection moulding is the screw-ram type because they combine the advantages of both screw and ram type (Fig. 16). In the standard 'V' configuration the plasticated compound is fed through a check valve into an accumulation chamber. One disadvantage is that the first rubber fed through the check valve is the last one to be injected. This can lead to adhesion and build up of rubber on the face of injection piston, which can cure, break off and cause rejects and moulding problems. So modifications have developed to overcome this. In the first in-first out system the screw and ram though separate are inline. Initially the injection ram is in the forward position and the injection chamber is empty. As compound enters through the ram it is forced back by incoming material until a limit switch controlling short volume is activated. Injection then takes place through a special ball type torpedo which completes the plastication and thermal homogenisation. As the material does not reach the final injection temperature until it reaches the nozzle temperature earlier in the system can be relatively low (approximately 70 °C. Such inline systems have gained popularity in recent years.

Multi stage rotary press units can be fitted to many of the injection moulding system, thus enabling continuous moulding to take place. In this injection unit that feeds a number of moulds carried on a rotating carrousel. This system is economic and practical. Such machine may have automatic ejection of parts and runner system, cleaning and spraying of the moulds and automatic loading of metal inserts.

9.6 Compounds for Injection Moulding [9]

Compounds for injection moulding must have sufficient scorch safety to flow through the nozzle, runners and gates without scorching but still cures rapidly in the mould. For maximum productivity, the compound has to injected rapidly into the mould at near vulcanisation temperature. This area has to be optimised within which a particular material will flow well and cure effectively without the danger of scorching. The three major areas in which data on a compound are required are rheological behavior, rate of vulcanisation and heat flow into and through the compound.

9.7 Advantages [4]

1. A high output of production can be obtained.
2. Automation is the process can lead to cost saving and high quality.
3. Cure time may be reduced due to pre-heating of rubber.
4. Uniform curing of variable thickness component is possible.
5. Flash trimming is eliminated.
6. There is no bumping.
7. The finished products can be removed more rapidly.
8. Complete filling of mould cavity is ensured.
9. Feeding is much easier in the strip form and is more economical.

RIM involves the rapid mixing of two or more highly reactive low molecular weight compounds before the injection of the mixture in a closed mould. The reaction may be polymerisation or molecular network formation in a very short time, approximately 30 s The total cycle time is 1–2 min. RIM is important for urethene rubbers because the process is very energy efficient.

9.8 Trouble Shooting the Moulding Process [9]

9.8.1 Scorchiness of the Compound

Compounds must have sufficient processing safety to flow through the nozzle, runners and gates without scorching but still cure rapidly in the mould. For this the balance of viscoelastic and the curing characteristics of the compounds are extremely important. Most rubber compounds that will compression mould can be satisfactorily injection moulded, provided that they flow well enough and are not too scorch sensitive. For maximum productivity the compound has to be injected rapidly into the mould at near vulcanisation temperature.

9.8.2 Shrinkage

On cooling both the mould cavity and the moulded part contract usually by a differential amount because the metal and rubber have different coefficients of thermal contraction. Shrinkage is defined as the difference between the dimensions of the mould cavity and those of the moulded part, when both are measured at room temperature. The amount of shrinkage has to be allowed for in mould design. It will vary depending on the polymer, cure temperature, time and pressure.

9.8.3 Adhesion

Adhesion has two aspects, adhesion to the mould surface, which is not wanted, and adhesion to a metal insert in the part, which is wanted. Mould release agents are used to prevent the one, and adhesion promoters to ensure the other.

9.8.4 Backrinding [13]

This is the term applied to the torn look that occurs at the mould parting line of compression moulded parts and at the gates of transfer and injection moulds. It is caused by thermal expansion of the rubber after cross-linking, which can force the cross-linked rubber into the space at the parting line or gate, causing it to rupture. The best way to minimise this is to minimise the shot weight commensurate with filling the cavity. Increasing scorch time can also help because it ensures that the mould is filled before curing begins as the injection temperature can be raised.

9.8.5 Mould Fouling

The build-up of material in a mould especially in the corners is a major problem. The cause is usually deposition of chemicals and their subsequent oxidation or degradation. These agents may originate in the rubber, in fillers or from release agents. Thus, there are a wide variety of deposits whose severity varies from compound to compound and also depends on injection rate and mould temperature. Mould cleaning is often done by blasting with some abrasive particulate material such as glass beads, plastic or metal beads.

9.8.6 Orange Peeling

This is usually caused by the initial layer of rubber in contact with the heated mould surface having cross-linked before succeeding layers have filled the mould. Usually occurs in injection moulding and the remedy is to increase the scorch time of the compound.

9.8.7 Porosity

This is due to under cure and the presence of volatiles, especially moisture in the compound. Higher injection and mould temperature or longer mould closed time should resolve this.

9.8.8 Blisters

Air entrapped in the rubber compound is the usual cause. This can be eliminated by a higher back pressure, slower injection rate, or effective venting of the mould.

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