EGE UNIVERSITY GRADUATE SCHOOL

OF APPLIED AND NATURAL SCIENCES

(MASTER OF SCIENCE THESIS)

REDUCTION OF FRICTIONAL COEFFICIENT BETWEEN POLYCARBONATE AND METAL SURFACE

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Chemical Engineering

January, 2006

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II

Sayın **Ural Hüseyin AKSOY** tarafından **YÜKSEK LİSANS TEZİ** olarak sunulan "**Reduction of Frictional Coefficient Between Polycarbonate and Metal Surface**" başlıklı bu çalışma E.Ü. Lisansüstü Eğitim ve Öğretim Yönetmeliği ile E.Ü. Fen Bilimleri Enstitüsü Eğitim ve Öğretim Yönergesi'nin ilgili hükümleri uyarınca tarafımızdan değerlendirilerek savunmaya değer bulunmuş ve 18 Ocak 2006 tarihinde yapılan tez savunma sınavında aday oybirliği/oyçokluğu ile başarılı bulunmuştur.
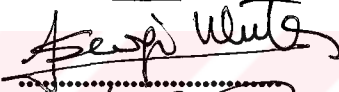
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ÖZET

POLİKARBONAT VE METAL YÜZEY ARASINDAKİ SÜRTÜNME KATSAYISININ DÜŞÜRÜLMESİ

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Ocak, 2006, 52 sayfa

Plastik malzemelerin sürtünme davranışları, kimyasal bağlar, moleküller arası bağ kuvvetleri ve sertlik gibi faktörlerden etkilenirler. Polikarbonat ile metal yüzey arasındaki sürtünme katsayısı iki değişik yöntem kullanılarak düşürülmeye çalışılmıştır.

1) Pentaeritritol stearat ve montanat esterleri gibi kaydırıcılar katılarak,
2) Malzeme farklı sürelerle, camsı geçiş sıcaklığı (T_g) altında tavlanarak.

Tüm deneyler sabit sıcaklık, basınç ve nem koşullarında yapılmıştır. Sürtünme katsayısı hareketli tabaka üzerinde iğne (pin on plate) yöntemiyle, 80 mm/s hız ve 50 N sabit yükte dinamik sürtünme olarak ölçülmüştür.

Bu çalışmada, Polikarbonat ve çelik yüzey arasındaki sürtünme katsayısı 0.50 − 0.55 aralığından, değişik kaydırıcılar katılarak % 40 oranında bir azalma ile 0.35 değerine düşürülmüştür.

Anahtar kelimeler: Sürtünme katsayısı, polikarbonat, kaydırıcı madde, tavlama

VI

ABSTRACT

REDUCTION OF FRICTIONAL COEFFICIENT BETWEEN POLYCARBONATE AND METAL SURFACE

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January, 2006, 52 pages

Friction behaviors of plastic materials are affected by factors such as chemical bonds, intermolecular bond forces and hardness. Coefficient of friction between Polycarbonate and metal surface is studied to be reduced by using two different methods.

1) By adding slip agents such as pentaerytritol tetrastearate, montanate ester.
2) By annealing at the temperatures close to glass transition temperature, T_g, of the material for different time intervals.

All the tests have been performed at constant temperature, pressure and humidity conditions. The dynamic friction by using "pin on plate" method has been measured at a velocity of the plate 80mm/s and 50 N constant load.

The coefficient of friction between Polycarbonate and steel surface which is in the range of 0.50-0.55 has been reduced by 40 % to a value of 0.35 by adding different slip agents.

Keywords: Coefficient of friction, polycarbonate, slip agent, annealing

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1. INTRODUCTION

The friction in between Polycarbonate and metal surfaces is a big problem for the manufacturers in some industrial applications. Textile tubes (bobbins) which spun with fibers have been placed on an automatic machine in textile industry.

These tubes are made of several plastics such as ABS, polycarbonate, polybuthylene terephthalate; polypropylene should be put on to the spindle easily. Therefore, low frictional coefficient between the polymer and metal surface is important. Bobbins material, made of Polycarbonate is preferred because of its superior mechanical and electrical properties. However, this material suffers from its high coefficient of friction. High coefficient of friction may cause various difficulties. The technicians and engineers have been working for many years to reduce the friction by applying different methods. In this project, addition of slip agents into the polymer and annealing techniques were tried to reduce coefficient of friction between polycarbonate and metal surfaces.

1.1. Frictional Coefficient and Polymer Friction

The frictional behaviour of polymers is of importance in many applications involving abrasion, wear, and scratching of polymers .It is desirable to have high friction of a tire against a road surface or a shoe sole against many surfaces, including plastic floor tile. Low friction is wanted in plastic bearings or for plastic coated skis against snow (Nielsen and Landel, 1994).

Surface analysis is an important component in tribology since interfacial forces and material properties are determined by the composition of the interface (Ferrante, 1989).

The field of lubrication, friction and wear is known as tribology. It is generally accepted that the applied force, **F**, is a linear function of applied load, **W**, shown by **Equation 1.1** (Progelhof and Throne, 1993).

$$F = \mu\, W \qquad\qquad \textbf{Equation 1.1}$$

μ is the coefficient of friction and F is the tangential force required to produce motion at the interface between two surfaces when they are pressed together by a normal load. In **Figure 1.1**, the representative figures for frictional force are shown.
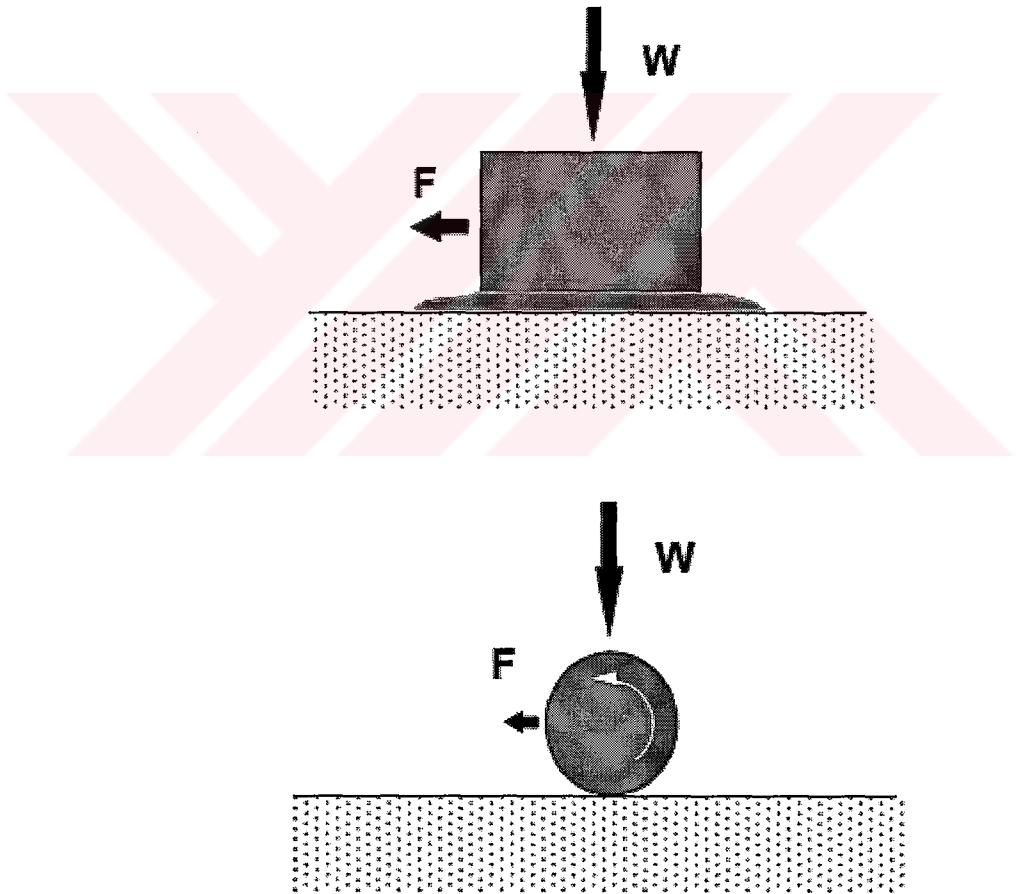
Fig 1.1. Representative figure for frictional force, [1]

The materials involved in tribology span the entire range: metals, ceramics, polymers and all combinations of these are in contact with one another (Ferrante, 1989).

Friction can be divided into three classes: static, dynamic and rolling. The static or starting coefficient of friction (μ_s) is related to the force measured to begin movement of the surfaces relative to each other. The kinetic (dynamic) or sliding coefficient of friction (μ_k) is related to the force measured in sustaining this movement (ASTM D 1894). These different classes of friction have different values. For flat surfaces touching each other static and dynamic friction forces are involved while spherical surfaces having tangential touch lead to rolling type frictional forces.

The coefficient of friction depends on many factors. External factors include those such as temperature, velocity of sliding, and load. Local factors at the contact include nature of the surfaces (smooth rough), contact area of the surfaces, presence or absence of lubricants, and type of measuring apparatus (Nielsen and Landel, 1994).

It appears that the dynamic friction is independent of the sliding velocity and the temperatures attained are not sufficient to soften the polymer thermally; continued sliding, however can modify the polymer surface and so affect the friction. For a given polymer, the values were influenced by adsorptions or desorptions from the polymer surface (Vaziri et al., 1987).

When polymers slide against metal counter faces, transfer films are formed. This is also the case when sliding occurs between a polymer and another polymer (Bahadur, 1999). The friction between polymers can be attributed to the two main mechanisms: deformation and adhesion. The deformation mechanism involves complete dissipation of energy in the contact area while the adhesion components is responsible for the friction of polymer and is a result of breaking weak bonding forces between polymer chains in the bulk of the material (Lancaster, 1990; Tewari et al., 1989; from Mimaroglu and Unal, 2003).

1.2. Types of Friction

It is common practice to consider the frictional force to be a sum of two effects, the adhesion force and the drag or deformation force. Polymeric responses to frictional loading can be categorized as given in the following section (Progelhof and Throne, 1993).

Virgin friction: The surface energy of the load is very high and no interfacial deformed layer exists. The primary mode of frictional resistance is adhesion bonding between the two surfaces. The coefficient of friction is very high.

Clean friction: The coefficient of friction is high and depends on the oxide layers on metal surfaces. There are no interfacial layers.

Transitional boundary friction: A very thin layer of deformed polymer forms a tertiary or interfacial layer between the bulk of the polymer and the metal load. Adhesion bonding forces decrease and deformational forces increase with time. The frictional coefficient can decrease with time as the interfacial layer builds.

Pure boundary friction: The interfacial layer thickness is stable with time. As a result, the frictional coefficient is now a function of the physical nature and mechanical properties of the metal, polymer and interfacial material, as well as the experimental conditions, including pressure, sliding velocity, temperature, polymer surface roughness, metal surface roughness and so on.

Transitional hydrodynamic friction: The interfacial boundary layer provides substantial lubrication to the sliding surface. This material can be adducting of the polymer, an externally supplied lubricant, or even the polymer itself. In certain instances, lubricants are deliberately added to the polymer for friction-and-wear control. Under pressure and/or frictional heat, these lubricants diffuse or "bloom" to the primary polymer surface. In some cases, frictional heating can be intense enough to locally melt the polymer, thus providing the hydrodynamic layer.

Pure hydrodynamic friction: the interfacial layer is a true lubricant. The sliding performance here can be modelled with traditional lubrication theory, where the shear viscosity of the lubricant is a major property. Static and dynamic coefficients of friction of different polymers are given in **Table 1.1**.

Table 1.1, Static and Dynamic Coefficient of Friction of Some Polymers (Progelhof and Throne, 1993)

Polymer	Steel on polymer		Polymer on polymer	
	μ_s	μ_k	μ_s	μ_k
PTFE	-	0.05	0.04	0.04
LDPE	0.27	0.26	0.33	0.33
HDPE	0.18	0.12	0.12	0.11
POM	0.14	0.13	-	-
PVDF	0.33	0.25	-	-
PC	0.60	0.53	-	-
PET	0.29	0.28	0.27	0.20
PA 66	0.37	0.34	0.42	0.35
PVC	0.45	0.40	0.50	0.40
PVDC	0.68	0.45	0.90	0.52

Transfer of polymer is important during sliding contacts involving some polymers. For the amorphous polymers, polystyrene and poly(metylmethacrylate), and for the semicrystalline polymer, polypropylene, there was no transfer at room temperature but transfer occur at higher temperatures up to 150°C (Vaziri *et al.,* 1987) since as the temperature increases, the polymer comes closer to rubbery phase.

1.3 The Structure and Properties of Polycarbonate

A polycarbonate plastic, characterized by the -OCOO- heterochain unit, can be made either from phosgene and bisphenol A or by ester exchange between bisphenol A and diphenyl carbonate (Billmeyer, 1970). The structure of Polycarbonate is shown in **Fig 1.2.**
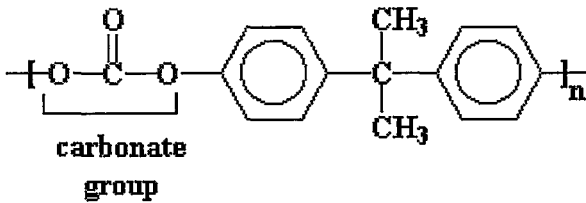
Figure 1.2. Structure of polycarbonate, [2]

Reactions of forming of Polycarbonate are given in **Figure 1.3.**

Polycarbonate is classified as amorphous engineering thermoplastic because of its excellent balance of toughness, clarity, and high-heat deflection temperature. Dimensional stability, excellent electrical properties, and inherent ignition-resistant characteristics are other outstanding properties.
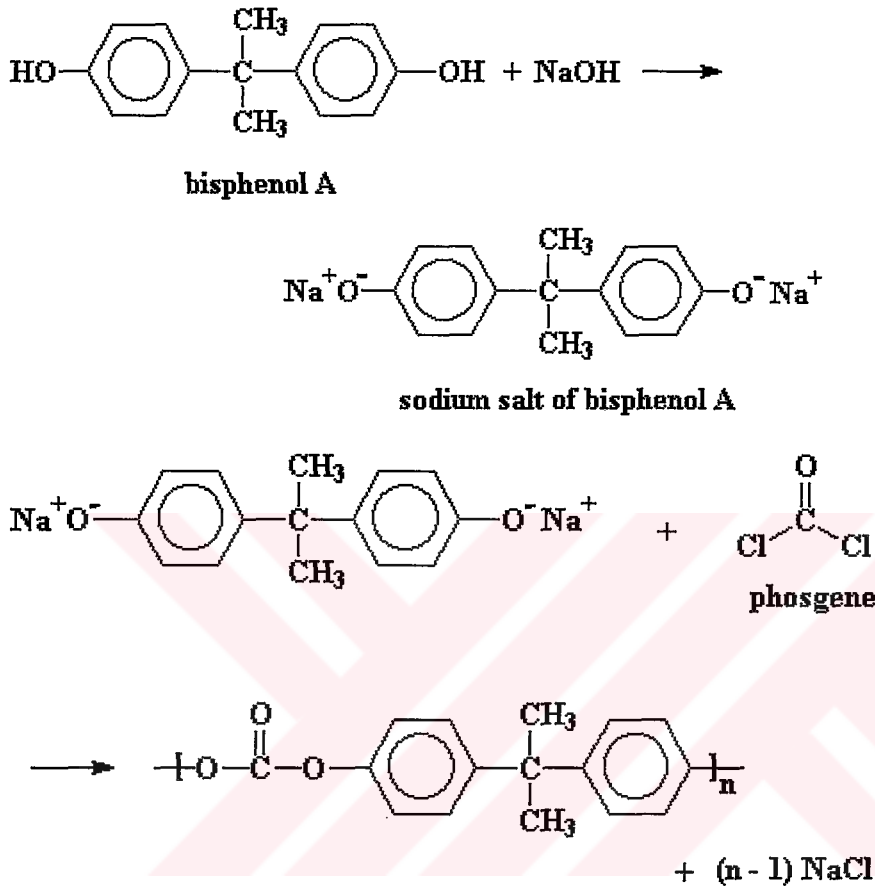
Figure 1.3. Formation reactions of polycarbonate, [2]

Molecular weights for typical commercial polycarbonate vary from 22,000 to 35,000. Standard commercial grades are available in melt flow ranges from 4 to 23. Additives, coating, or co extrusion technology can minimize concerns about weathering, chemical resistance and scratch resistance (Modern Plastics, 1976).

1.4 Methods for reduction of coefficient of friction of polymers

Friction is a natural resistance to sliding motion between two surfaces. It is quantitatively described by dynamic and static coefficients. These provide an estimate of energy requirements for moving part. The lower the coefficient of friction, the easier the two surfaces slide over each other.

Friction is relatively easy to measure but no simple model predicts or calculates friction coefficients for a given pair of materials. Frictional values, for example, may rise during an initial break-in period, and then gradually drop to a steady state. The first period corresponds to the static friction while the steady state gives the dynamic friction.

Frictional properties of thermoplastics differ from those of metals. Because thermoplastics have lower modulus (more flexibility) and are softer than metals, they do not follow the classic laws of friction as applied to metals. Unlike metals, thermoplastics usually have a static coefficient of friction (related to starting motion) that is less than the dynamic coefficient. This gives intermittent sliding motion when plastic moves against metal or another plastic. Adhesion of plastic to metal and deformation of the plastic surface characterize plastic-to-metal surface interaction. Such effects result in frictional forces those are proportional to speed rather than load [3].

In addition, the average friction coefficient is greatly affected by the drawing ratio and the sliding velocity and direction (Bekhet, 1999).

Lubrication additives used for the reduction of friction in polymer may be classified as:

1) Self-lubricating additives.

2) Lubricants (slip agents)

1.4.1. Self-Lubricating Additives:

Polytetrafluoroethylene (PTFE) gives the lowest coefficient of friction of any internal lubricant, forming a lubricious film on surface. (PTFE) modifies the mating surface after initial break-in period and improves wear rates in both similar and dissimilar polymer systems.

Perfluoropolyether (PFPE) is synthetic oil. It imparts good wear and low friction properties while maintaining a compound's physical properties. It also minimizes or eliminates "plate-out" associated with PTFE.

Silicone acts as a boundary lubricant because it migrates to the plastic's surface over time. As a partial alloying material with the base resin, some of it remains in the compound over its service lifetime. This continuous migration reduces start-up wear for low-pressure and high-speed applications.

Molybdenum disulfide (MoS_2) creates a harder and more wear-resistant surface in semi crystalline materials. It is ideal for applications against metals, as it fills the metal's microscopic pores and creates a smoother metal surface.

Graphite molecules slide easily over one another with little friction. This is especially true in aqueous environments thus making graphite one of the best lubricants for many underwater applications.

Aramid fiber commonly known as kewlar is softer and less abrasive than carbon or glass fiber. It decreases friction coefficient, increases wear resistance, and improves mechanical performance.

Carbon fiber improves mechanical and thermal performance of a compound. It may increase the coefficient of friction and can be aggressive to mating surfaces [3].

1.4.2 Lubricants (Slip Agents)

Lubricants are added to most polymers at levels to increase the overall rate of processing or to improve surface properties. A main function of lubricants is to prevent polymers that have tendency toward tackiness sticking on metallic parts of processing machinery; this is external lubrication. Another important function is to provide internal lubrication to the polymer under processing to improve the free flow of the melt bulk polymer by reducing friction between chain segments. These two combined functions give a better output from the processing equipment, and they also facilitate mould release (Stepek and Daoust, 1983).

Reduction of the adhesive force between polymer and solid surface has been described as a release effect. Lubricants can also act in another way by influencing the dynamic friction between the polymer melt and the wall of processing machine.

For certain applications, it is desirable for finished part surface to have good slip properties. Lubricating solids such as fluoropolymer powders or graphite are sometimes incorporated into materials for gearwheels, bearings etc. The fatty acid esters or hydrocarbon waxes commonly used as lubricants for the melt state are gradually exuded, if used in very high concentrations, thus yielding to permanent lubricating effects. Certain additives migrate so strongly to the surface, even during cooling, that a uniform invisibly thin coating is formed (Gachter and Müller, 1993).

The considerations for the selection of lubricants are as follows:

1. Metal soaps, mainly stearates, function as external lubricants, since they possess low affinity to all polymers.

2. Long-chain dialkyl fatty acids, alcohols, and amides act as internal lubricants for polar polymers such as PVC, polyamides, and so on, but have low affinity to non polar polymers such as polyolefin's.

3. Long-chain dialkyl esters have medium affinity to most polymers and can act both as external and internal lubricants for polymers; they are often used to obtain a balanced lubrication.

4. High molecular weight paraffin waxes function as external lubricants for polar polymers because of their low affinity to them, but they have a high affinity to polyolefin's and are used then as internal lubricants (Stepek and Daoust, 1983).

The preferred lubricants for engineering plastics are montanic acid derivatives. These provide good release and flow properties, have adequate compatibility and very high thermal stability. Their migration resistance is excellent but excessively low cloud points limit their use. Stearyl stearate can be used in reinforced polycarbonate. While pentaerythritol stearate is generally used in transparent polycarbonate, montanat esters with their more effective release action are preferred for the technically very demanding production of optical discs.

Most conventional lubricants fail above 300°C because of excessive volatility, cleavage of ester or amide bonds or, in the case of alkyl chains with a lubricating effect, susceptibility to oxidation. In the search for alternatives, completely new structures, e.g. fluorine-substituted groups or organ silicon compounds, are being considered. In addition, the changeover from glycerol to polyols such as pentaerythritol whose esters have a higher thermal stability due to their structure marks the start of progress to provide products for more demanding applications (Gachter and Müller, 1993).

1.5 Solubility Parameters for Polymers

In order to reduce coefficient of friction of a polymer, some polymers or chemicals should be add to the target polymer and therefore, we have to know solubility parameters to select the right polymer or additives for this purpose.

The process of dissolving a polymer in a solvent is governed by the familiar free energy equation given in **Equation1.2**.

$$\Delta G = \Delta H - T\Delta S \qquad \text{Equation 1.2}$$

The change in Gibbs energy is ΔG, ΔH is the heat of mixing, T is the absolute temperature and ΔS is the entropy of mixing. A negative ΔG predicts that a process will occur spontaneously.

Since the dissolution of a polymer is always connected with a large increase in entropy, the magnitude of the heat term ΔH is the deciding factor in determining the sign of the free energy change. Hildebrand and Scott proposed an equation for ΔH (**Equation 1.3**). In this equation, δ values represent the cohesive energy density (**Equation 1.4**).

$$\Delta H_{mix} = V_{mix}(\delta_1 - \delta_2)^2 \phi_1 \phi_2 \qquad \text{Equation 1.3}$$

$$\delta = \sqrt{\frac{\Delta E}{V}} \qquad \text{Equation 1.4}$$

Where ΔH_{mix} is the overall heat of mixing, V_{mix} is the total volume of the mixture, ΔE, V, ϕ are the energy of vaporization, molar volume, and volume fraction of component 1 or 2 in the mixture, respectively.

The expression $(\Delta E / V)$ is known as "cohesive density". If the δ values of two substances are nearly equal, the substances will be miscible. For this reason, Scott proposed the term δ as the solubility parameter [4].

The solubility parameter of a polymer can be calculated from the molar attraction constants and molar volume V_i (cm^3/mol) (Fried, 1995), as given in **Equation 1.5**.

$$\delta_i = \frac{\sum\limits_{i=1} F_i}{V_i}$$
Equation 1.5

$\sum F_i$ is the sum of molar attraction constants for all atoms and groupings in the molecule.

An example to how the solubility parameter is calculated is shown for polycarbonate on the following page. The groups and molar attraction constants have been given in **Table 1.2** for polycarbonate.

Solubility parameter calculation for polycarbonate:

Table 1.2 Groups and molar attraction constants in polycarbonate

Group	$F(cal/cm^3)^{1/2}$	Number of groups	$\sum F_i$
COO	310	1	310
C	-93	1	-93
O	70	1	70
CH_3	214	2	428
Phenyl	735	2	1470
	SUM		2185

Since the density of polycarbonate is 1.2 g/cm^3 and molecular weight, M, is 256 g/mol, the solubility parameter, δ, is found as given below:

$$\delta = 1.2 \times (2185/256) = 10.24 \ (cal/cm^3)^{1/2}$$

The calculation of solubility parameter of pentaerytritol tetrastearate is given below. The chemical formula of pentaerytritol tetrastearate is given in **Figure 1.4.**

$$CH_2OOCC_{17}H_{35}$$
$$|$$
$$C_{17}H_{35}COO\ CH_2 - C - CH_2OOCC_{17}H_{35}$$
$$|$$
$$CH_2OOCC_{17}H_{35}$$
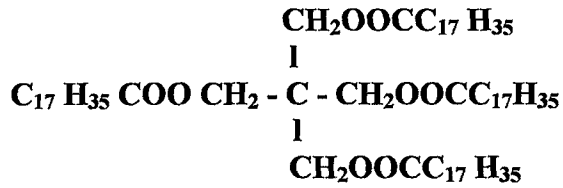
Figure 1.4. Chemical formula of pentaerytritol tetrastearate

Table 1.3. Groups and molar attraction constants in pentaerythritol tetrastearate.

Group	$F(cal/cm^3)^{1/2}$	Number of groups	$\sum F_i$
COO	310	4	1240
C	-93	1	-93
CH_3	214	4	856
CH_2	133	68	9044
	Sum	-	11047

Solubility parameter: $(Density \times \sum F_i)/M$

Since the density of pentaerytritol tetrastearate is 0.94 g/cm^3 and molecular weight, M, is 1156 g/mol, the solubility parameter, δ, is found as given below:

$$\delta = 0.94 \times (11047/1156) = 8.98\ (cal/cm^3)^{1/2}$$

1.6 Annealing

The product made from a crystalline polymer is used at temperatures far below the maximum crystallite growth rate temperature, crystallization can continue. So long as the polymer molecule is mobile, crystallization can proceed, although at an extremely slow rate.

Polymers apparently cannot crystallize at temperatures below their glass transition temperatures. But polypropylene and polyethylene, as examples, have glass transition temperature far below room temperature. Continuing crystallization means continuing decrease in specific volume. Shrinkage and warpage are directly related to local differential changes in specific volume. In many instances, crystallization is deliberately continued by reheating a fixture moulded crystalline polymer part to a temperature above its glass transition temperature and holding it there for several minutes to several hours. This is called annealing (Progelhof and Throne, 1993).

Annealing consists of heating the material and then cooling it very slowly and uniformly; the time and temperatures required in the process are set according to the properties desired. Annealing increases ductility and lessens the possibility of a failure by relieving internal strains. The process, also called hot working, was known to the ancients [5].

1.7 Hardness

"Hardness" is generally used to describe the resistance of a material surface to indentation, scratching of marring. These phenomena are considered to be closely related. The generally accepted definition of hardness as it pertains to plastic is: The resistance to penetration or indentation by another body".

Several different instruments can be used to measure indentation hardness. They differ in the shape and size of the indenter and the magnitude and duration of the applied force. The penetration and deformation of the surface is strongly dependant on the polymer viscoelastic nature (Progelhof and Throne, 1993).

The hardness testing of plastics is most commonly measured by the Shore (Durometer) test or Rockwell hardness test. Both methods measure the resistance of the plastic toward indentation. Both scales provide an empirical hardness value that doesn't correlate to other properties or fundamental characteristics. Shore Hardness, using either the Shore A or Shore D scale, is the preferred method for rubbers/elastomers and is also commonly used for 'softer' plastics such as polyolefins, fluoropolymers, and vinyls. The Shore A scale is used for 'softer' rubbers while the Shore D scale is used for 'harder' ones. The shore A Hardness is the relative hardness of elastic materials such as rubber or soft plastics can be determined with an instrument called a Shore a durometer.

If the indenter completely penetrates the sample, a reading of 0 is obtained, and if no penetration occurs, a reading of 100 results. The reading is dimensionless.

The Shore hardness is measured with an apparatus known as a Durometer and consequently is also known as 'Durometer hardness'. The hardness value is determined by the penetration of the Durometer indenter foot into the sample. Because of the resilience of rubbers and plastics, the hardness reading my change over time - so the indentation time is sometimes reported along with the hardness number [6].

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Hardness comparison scale is shown in **Figure 1.5**.
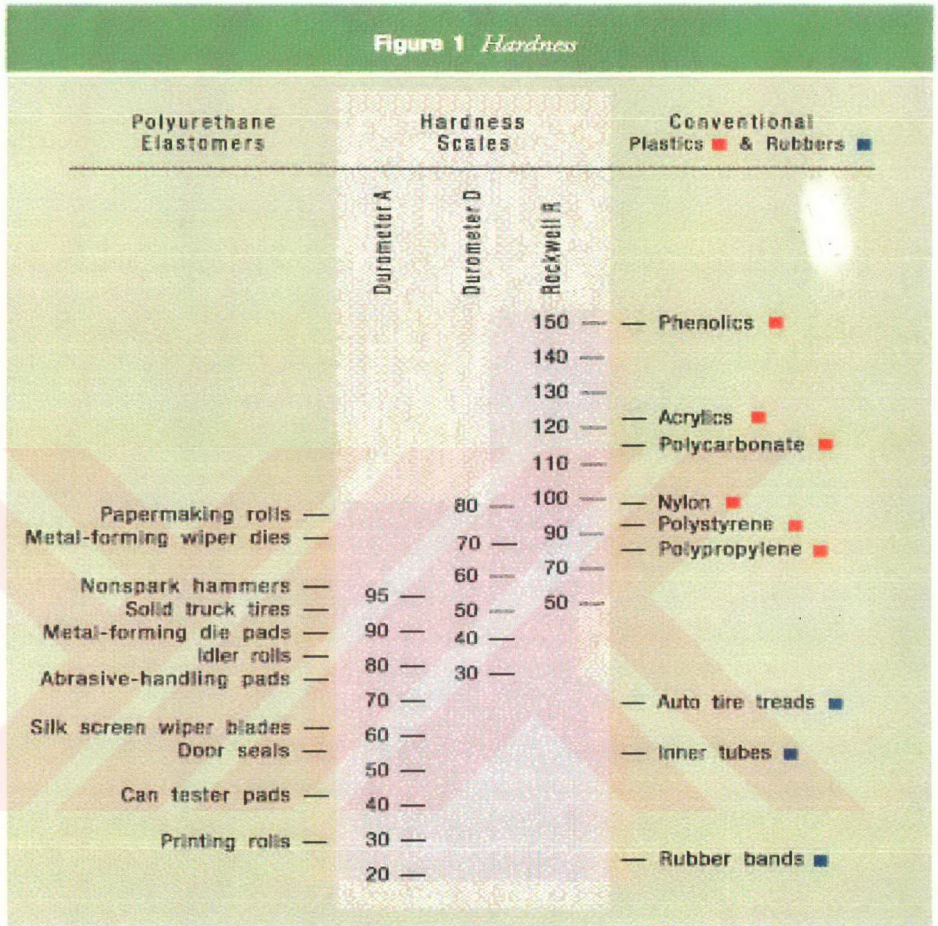
Figure 1.5. Hardness comparison scales of some materials. (6)

1.8. Present study

In the present study, coefficient of friction (COF) of PC (polycarbonate) has been studied. The COF of PC has been studied to reduce by using two different methods.

1) Addition of pentaerytritol tetrastearate and montanic ester / wax. slip agents,
2) Annealing at the temperatures close to glass transition temperature, T_g, of the material.

The dynamic friction by using pin on plate method at a velocity of the plate 80mm/s and 50 N constant load has been measured

2.0 MATERIALS AND METHODS

2.1 Description of Material

The raw material is PC (polycarbonate), (Dow, USA), coded as 200-15 which is sold with the commercial name of "CALIBRE".

CALIBRE 200 series Polycarbonate resins are general purpose, UL listed resins formulated to comply with the FDA (Food and Drug Administration) and European regulations governing food contact. CALIBRE 200 series resins exhibit an excellent physical property balance of heat resistance, transparency and impact strength. CALIBRE 200 series can be supplied with a mould release package, a UV stabilizer package or both [2].

Two slip agents (lubricants) as Lucawax E-BASF-GERMANY (Montanic Ester Wax) and FINALUX-G 748 FINE ORGANICS-INDIA (Pentaerytritol Tetrastearate) were used.

Lucawax can be used as a lubricant for rigid PVC and plasticized PVC during calendaring, extrusion or injection molding. Only small amount are required to provide a significant increase in internal and external lubrication.

FINALUX-G 748 is an effective lubricant (pentaerythritol tetrastearate) for many polymer compounds in both extrusion and moulding processes. It is recommended for use as a mould release agent in Polycarbonate and other engineering thermoplastics.It is a preferred product for such applications because of its outstanding thermal stability which allows its use in these systems without fear of degradation at high processing temperatures.

FINALUX-G 748 also has a favourable influence on the filling speed, which results in finished parts, which display good surface properties. Polycarbonate and PMMA containing an amount between 0.1 to 0.5 % of it's remained transparent and colour stable.

2.2 Experimental Method

It has been added some slip agents into the Polycarbonate powder and moulded in Akçim company vertical hand press injection. Besides, some samples injection moulded in Inelli plastic company have been annealed in an oven at Ege University Chemical Engineering Department. The samples were brought into appropriate size for frictional coefficient measurement. Organization of Experiments, which are explained below, is shown in **Figure 2.1**
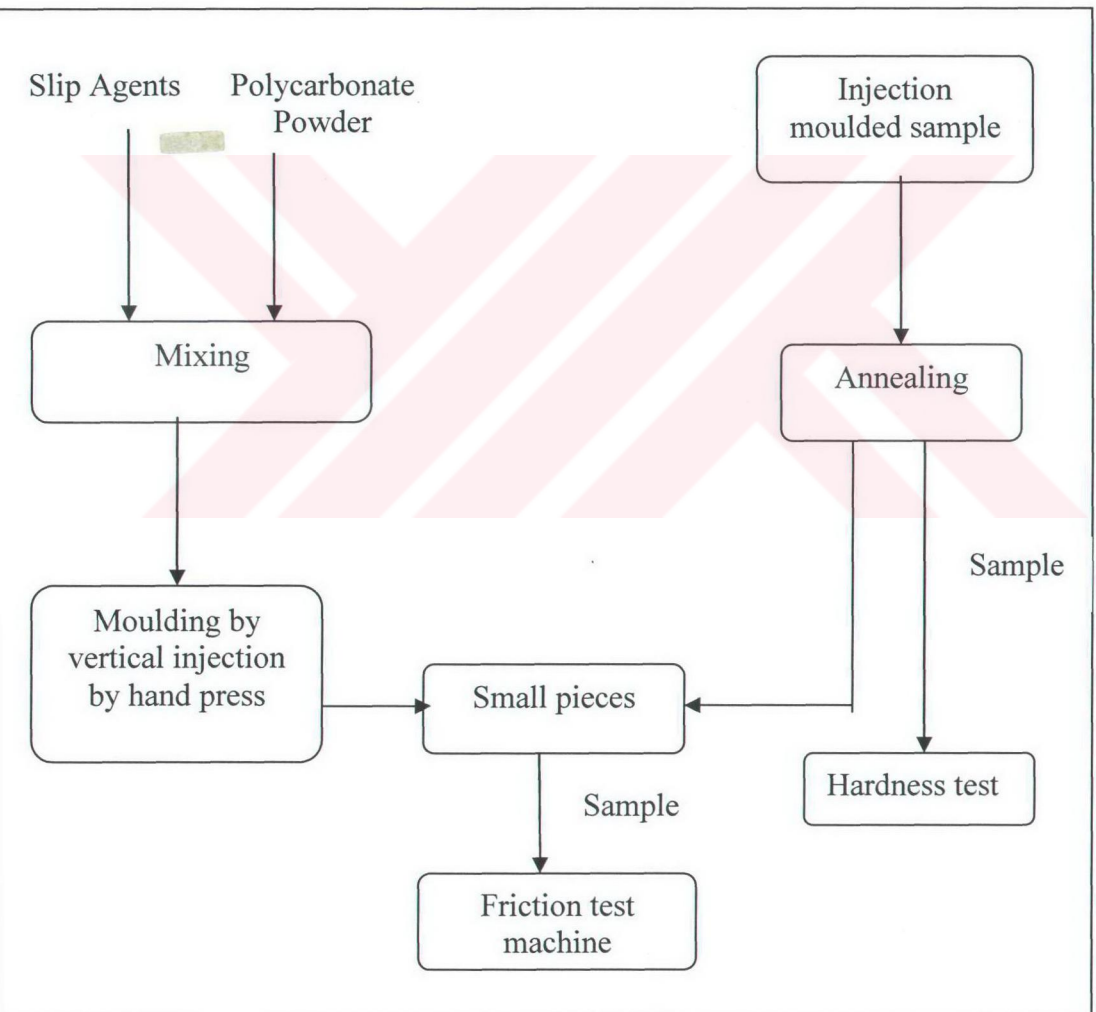
Figure 2.1, Organization of Experiments.

2.2.1 Sample preparation

Annealing samples: The sample of Polycarbonate as seen in **Figure 2.2** is moulded in injection moulding machine. The sample has been subjected to annealing keeping in oven for 15, 30 and 45 hours in three different annealing temperatures as 130, 140 and 145°C. Then the samples were subjected to the hardness tests in an "Equa Tip" hardness tester working in Brinell range 100-730 HB. The instrument was calibrated against a certain metallic surface (Topağaç, 2005).

Figure 2.2. Polycarbonate sample plates

Slip Agent Added Samples: Polycarbonate samples ring shaped as seen in **Figure 2.3** have been subjected directly to the friction tests. The samples were prepared by mixing slip agents in different concentrations (0.0-1.5 %) with powder polycarbonate homogenously.

Figure 2.3. Polycarbonate samples in ring shape

2.2.2. **Apparatus and methods**

In this study, all friction tests have been made by TE 88 Multi-Station Friction and Wear Test Machine at room temperature (23° C). The cylindrical pin on plate method is used during the tests. The pin made of stainless steel with 5 mm of diameter is constant, while the sample is mobile. The sliding velocity constant load values were 80 mm/s and 50 N, respectively. The total test duration was 16000 seconds.

The Multi-Station Friction and Wear Test Machine is design for wear testing of materials under high contact pressures in pin on disc, block on ring or reciprocating pin on plate modes. In reciprocating mode the machine can perform tests in the ASTM F 732 geometry, in Pin on Disc mode according to ASTM G 99, and in Block on Ring Mode according to ASTM G 77.

The base unit comprises an A.C. variable speed gear-motor and a control and data acquisition system. These are transferred between the Pin on Disc, Block on Ring and Pin on Plate modules, depending on the tests configurations [7]. The picture of the machine is shown in **Figure 2.4** and the scheme of working in **Figure 2.5**, respectively.
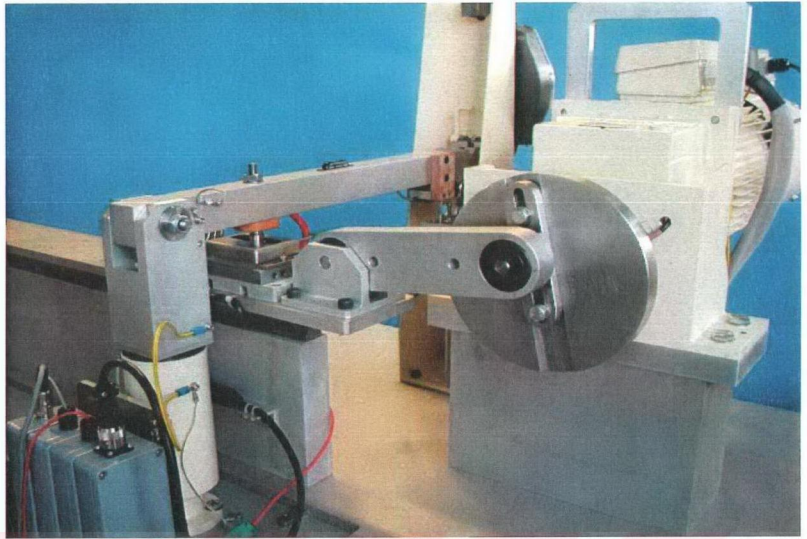
Figure 2.4. TE 88 Multi station friction and wear test machine
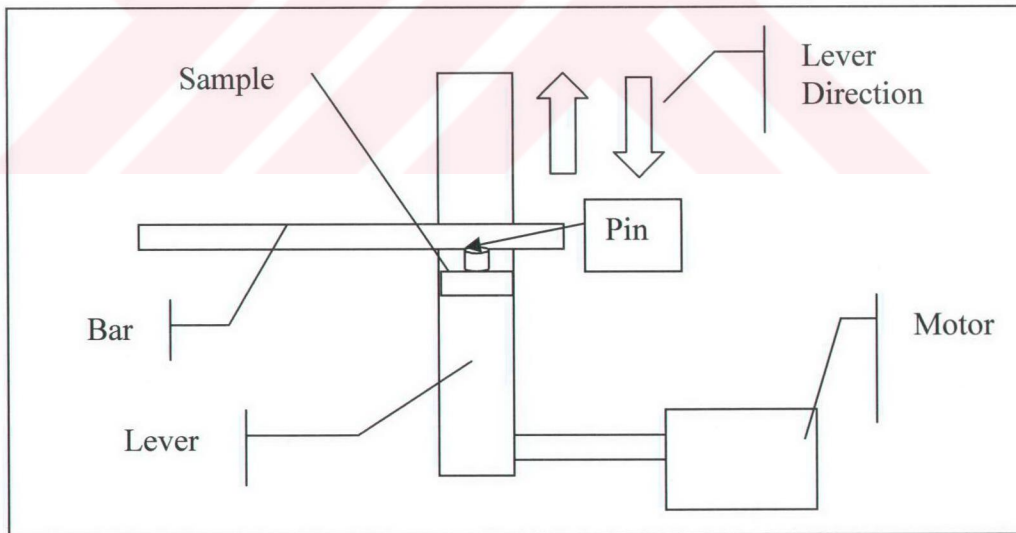
Figure 2.5. Working scheme of the friction machine

3.0 RESULTS AND DISCUSSION

Coefficient of friction (COF) has been determined for unfilled polycarbonate sample as a function of time to compare the effect of slip agent and annealing method. COF graph for unfilled sample has been shown in **Figure 3.1.**

PC-C.O.F
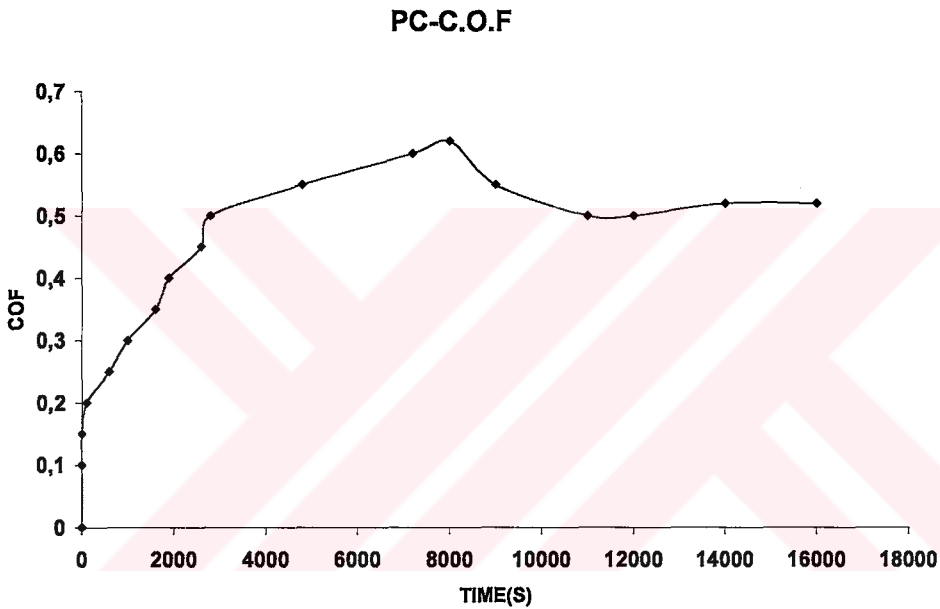
Figure 3.1. Coefficient of friction between polycarbonate and metal surface as a function of time

Static and dynamic coefficients of friction of unfilled polycarbonate found as 0.58 and 0.52 respectively, which comply with literature values **(Table 1.1).**

3.1. Effect of Slip Agent Addition

In order to reduce the coefficient of friction which cause problems in some industrial applications, montanic ester wax and pentaerythritol tetrastearate were added into polycarbonate as slip agents.

Montanic ester wax was added in concentrations of 0.5, 1.0 and 1.5 % of total weight of polycarbonate. Coefficients of friction versus time graphs for each sample were given on the following pages in **Figure 3.2, Figure 3.3,** and **Figure 3.4.**

MONTANIC ESTER WAX ADDED 0,5 %
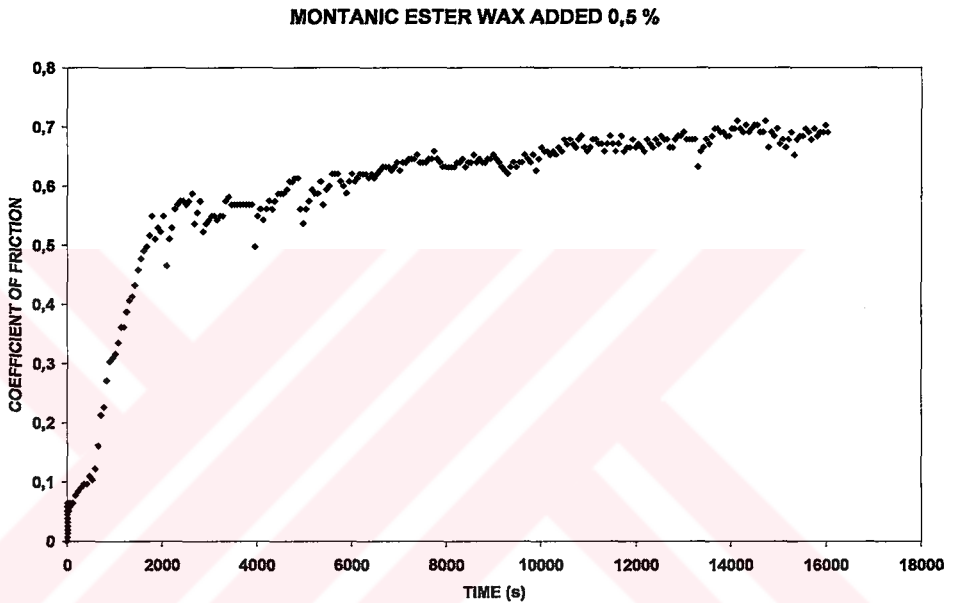
Figure 3.2. Coefficient of friction vs. time of polycarbonate + 0.5 % montanic ester wax

However, it was expected to be reduced, dynamic coefficient of friction increased from 0.52 to 0.68 as it is seen on **Figure 3.2.**

MONTANIC ESTER WAX ADDED 1%
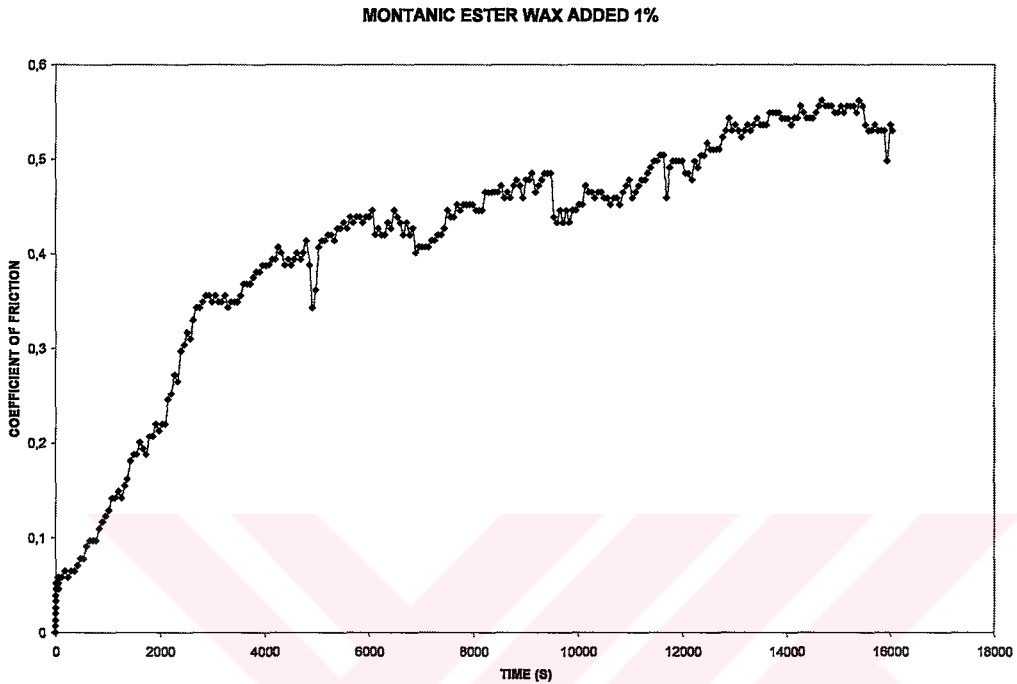
Figure 3.3. Coefficient of friction vs. time of polycarbonate + 1.0 % montanic ester wax

The dynamic coefficient of friction is found as 0.58 for 1 % montanic ester wax added to polycarbonate, which is not the desired value (**Figure 3.3**). Unfortunately, the value as 0.7 with montanic ester wax of % 1.5 (**Figure 3.4**) is noted high.

The increase in COF is thought to be due to the degradation of montanic ester wax at the processing temperature of polycarbonate. This slip agent is recommended for PVC and its processing temperature is higher than 180°C. However, processing temperature of polycarbonate is 300°C.

MONTANIC ESTER WAX ADDED 1,5 %
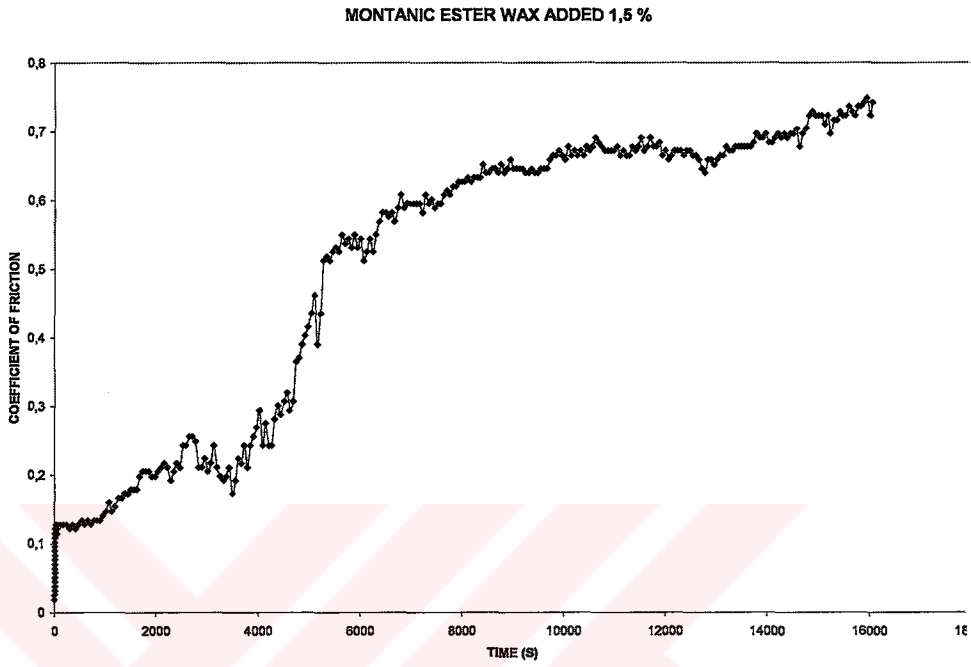
Figure 3.4. Coefficient of friction vs. time of polycarbonate + 1.5 % montanic ester wax

Static and dynamic coefficient of frictions (μ_s and μ_k, respectively) have been given in **Table 3.1** for montanic ester wax added to polycarbonate in different concentrations. In addition, Coefficients of friction measured on dynamic mode for montanic ester wax containing Polycarbonate have been shown on **Figure 3.5**.

In spite of a decrease has been expected, montanic ester wax resulted in a slight increase in COF value of Polycarbonate, as can be seen on **Table 3.1**.

Table 3.1. Static and Dynamic Coefficient of Frictions of PC+ Montanic Ester Wax

Additive %	μ_s	μ_k
PC + MW 0.0	0.52	0.58
PC + MW 0.5	0.58	0.63
PC + MW 1.0	0.45	052
PC + MW 1.5	0.55	0.63

COF- MW %
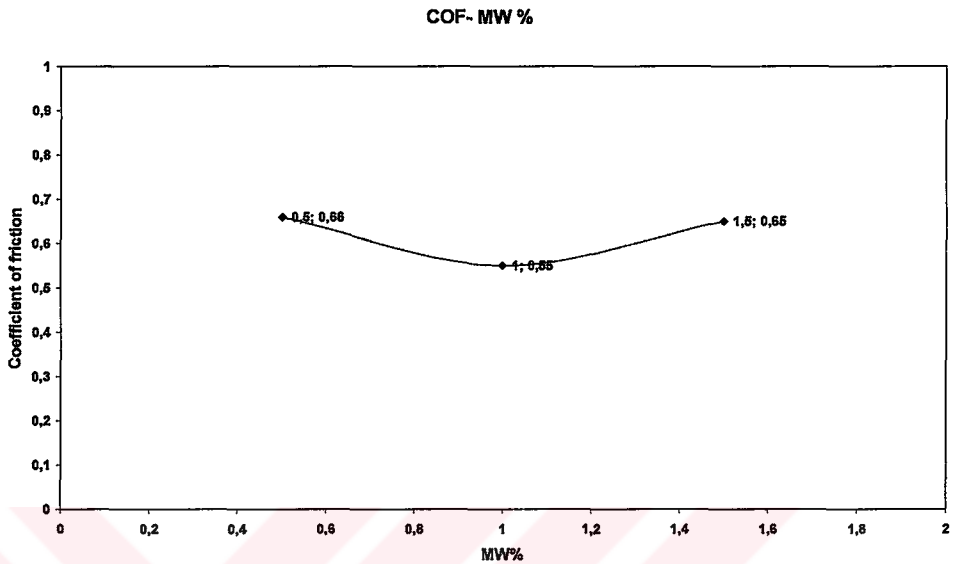
Figure 3.5, Coefficient of friction vs. montanic ester wax (MW) % concentration ratios added to polycarbonate

The other slip agent to be tested is pentaerytritol tetrastearate. When compared the solubility parameters of pentaerytritol tetrastearate and polycarbonate, it is seen that the two materials could be miscible.

Pentaerythritol tetrastearate was added in concentrations of 0.5, 1.0 and 1.5 % of total weight of polycarbonate. Coefficients of friction versus time graphs for each sample were given on the following pages in **Figure 3.6, Figure 3.7,** and **Figure 3.8**.

It is achieved to reduce the friction from 0.52 to 0.35 by adding 0.5 % of pentaerytritol tetrastearate. The intermittent points on the graph at about 5000s in **Figure 3.6** are due to the slipping out of the sample plate during the sliding of the pin on it. Such slipping is generally caused by some scratches on the sample.

PENTAERYTRITOL STEARATE ADDED 0,5 %
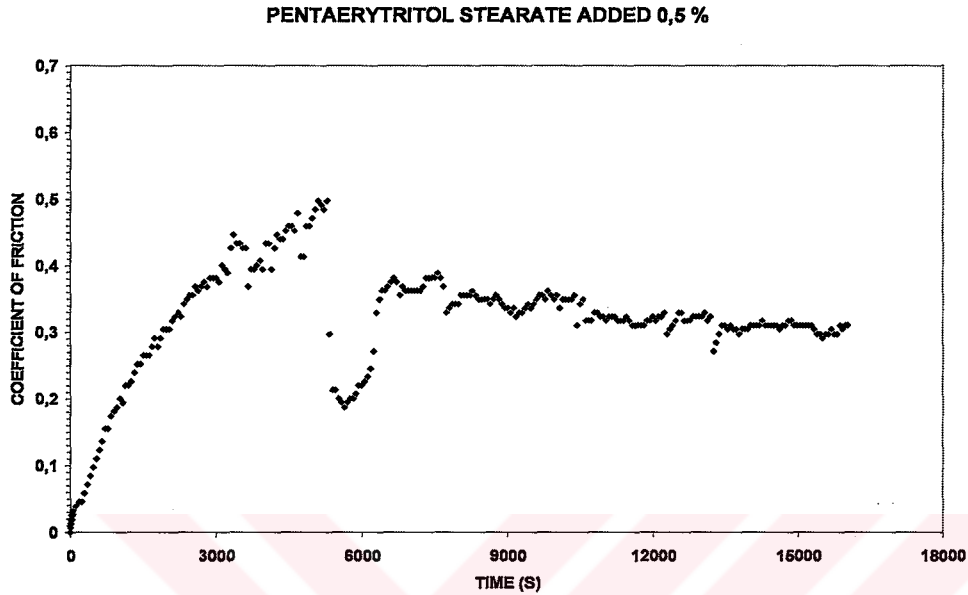
Figure 3.6. Coefficient of friction vs. time of polycarbonate + 0.5 % pentaerythritol tetrastaerate

The dynamic coefficient of frictions for 1.0 % and 1.5 % (by weight) pentaerythritol tetrastearate having polycarbonate samples have been found as 0.33 and 0.35, respectively (**Figure 3.7, Figure 3.8**).

PENTAERYTRITOL STEARATE ADDED 1%
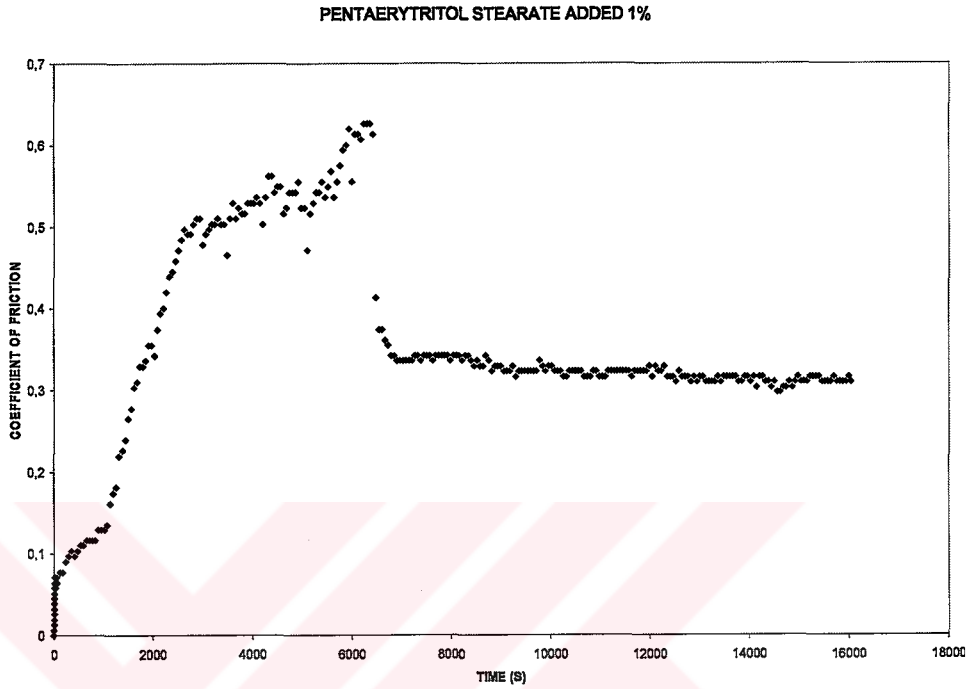
Figure 3.7. Coefficient of friction vs. time of polycarbonate + 1.0 % pentaerythritol tetrastearate

PENTAERYTRITOL STEARATE ADDED 1,5 %
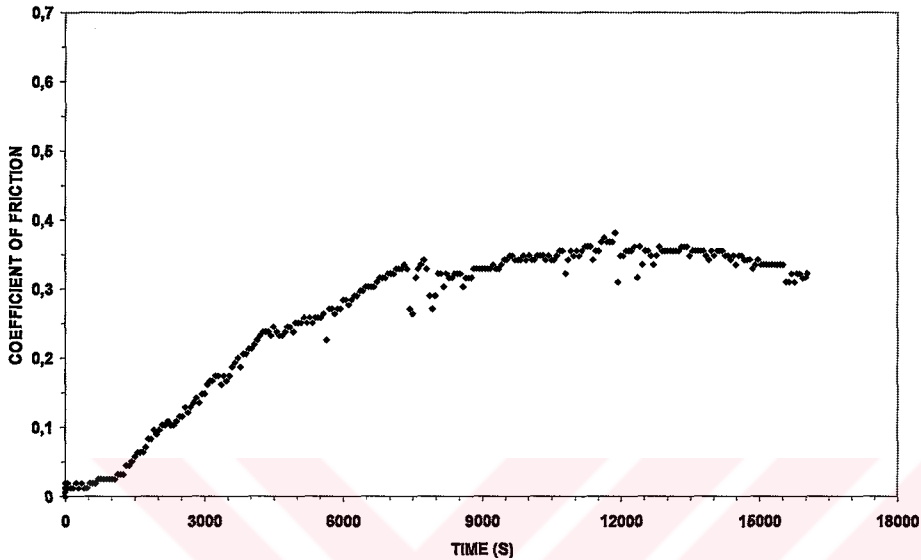
Figure 3.8. Coefficient friction vs. time of polycarbonate + 1.5 % pentaerythritol tetrastaerate

The static and dynamic coefficient of frictions (μ_s and μ_k, respectively) for Polycarbonate samples having pentaerytritol tetrastearate in different concentrations (by weight) could be seen in **Table 3.2.** In addition, COF measured on dynamic mode for montanic ester wax containing Polycarbonate have been shown on **Figure 3.9**.

Pentaerytritol tetrastearate resulted in a slight decrease in COF value of Polycarbonate measured on the static mode, however a considerable decrease of COF was obtained in dynamic measurement, as can be seen on **Table 3.2.** In fact, this slip agent is recommended one for polycarbonate, that is, no degradation at the processing temperature of polycarbonate is expected.

Table 3.2. Static and dynamic coefficient of frictions of PC+ pentaerytritol tetrastearate

Additive %	μ_s	μ_k
PC + PS 0,0	0,52	0,58
PC + PS 0,5	0,42	0,35
PC + PS 1,0	0,52	0,35
PC + PS 1,5	0,35	0,35
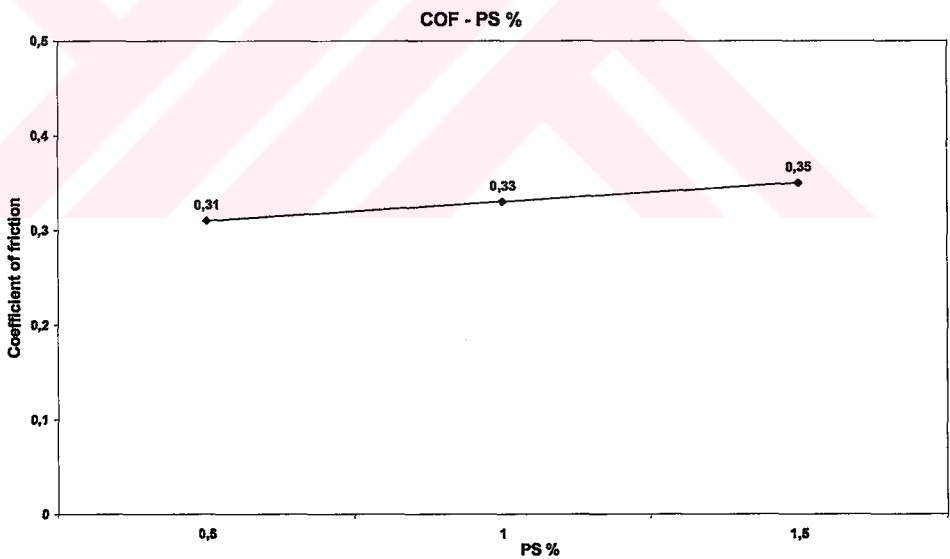
Figure 3.9. Coefficient of friction vs. pentaerythritol tetrastearate concentration rates added to polycarbonate

3.2 Effect of Annealing Process

Hardness is a crucial parameter in surface friction. Zhang (1998) reported that the spherulite size and hardness play and important role in friction performance for the PEEK, poly (ether ether ketone).

Polycarbonate has a glass transition temperature (T_g) value of 148°C. It is considered that by annealing polycarbonate sample near to its T_g value, a compact chemical structure which has improved hardness could be created.

The hardness values of polycarbonate plates annealed in oven at 130, 140 and 145°C were plotted as a function of annealing time (15, 30 and 45 hours). As can be seen in **Figure 3.10**, as the annealing temperature gets closer to the glass transition temperature, the higher hardness values were obtained. Considering the annealing temperature, 130°C gave lower hardness however 140 and 145°C temperatures show higher hardness values.

The annealed polycarbonate samples together with the unannealed one were subjected to coefficient of friction tests. COF versus time relationship of these samples have been shown in **Figure 3.11**. These tests that were carried out for 3600 s exhibited that best results would be taken in between 140 and 145 °C annealing temperatures for not more than 30 hours annealing period.
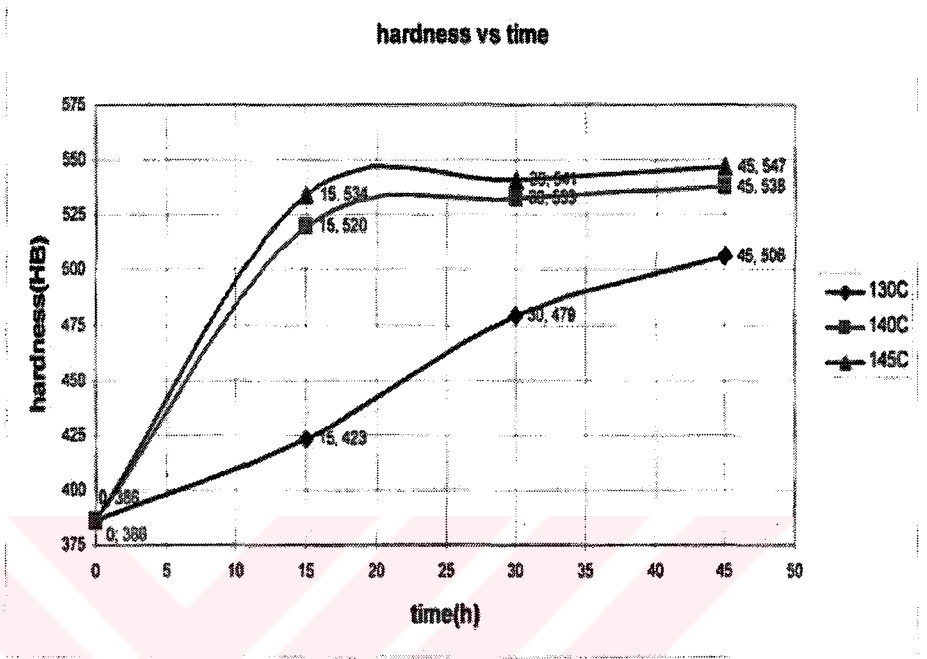
Figure 3.10. Relationship between hardness vs. annealing time (Topağaç, 2005).

COF- ANNEALING TIME
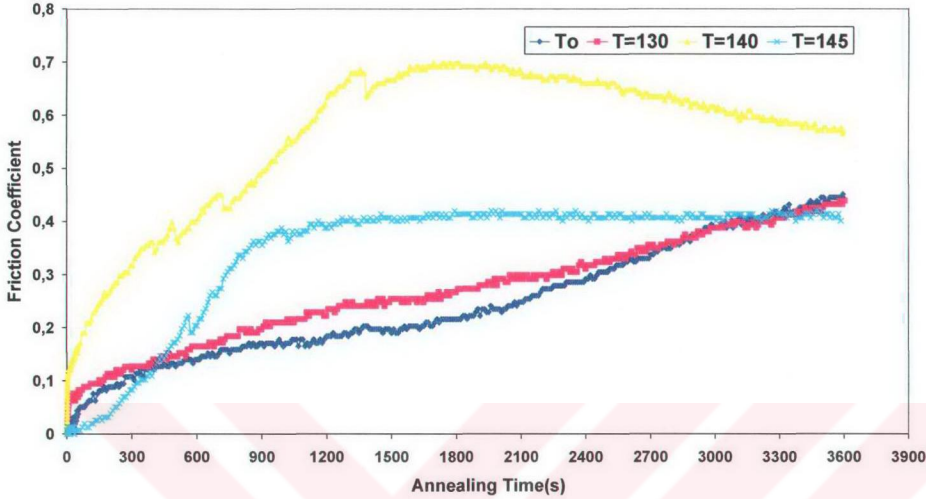
Figure 3.11. Coefficient of friction vs. annealing time of three different annealing temperatures (Topağaç, 2005). (**T₀** stands for the sample before annealing, the other **T** values give the annealing temperature of each sample).

3.3 Optimization of the Annealing Results

A new set of experiment have been performed annealing the polycarbonate at 142° C for 7.5, 15 and 30 hours, since the best results in terms of reduced COF value were expected under these conditions. Then the samples were subjected to friction tests under the same test conditions as those with the slip agent having ones.

COF graphs of the polycarbonate samples for different annealing times as 7.5, 15 and 30 hours at 142° C have been given in **Figure 3.12**, **Figure 3.13**, and **Figure 3.14**. The dynamic coefficient of friction values were found as 0.58, 0.56, and 0.53 for the samples annealed for 7.5, 15 and 30 hours, respectively. The values were far beyond the expected values since unannealed polycarbonate has a COF value of 0.52.

ANNEALING : 142 C - 7,5 HRS
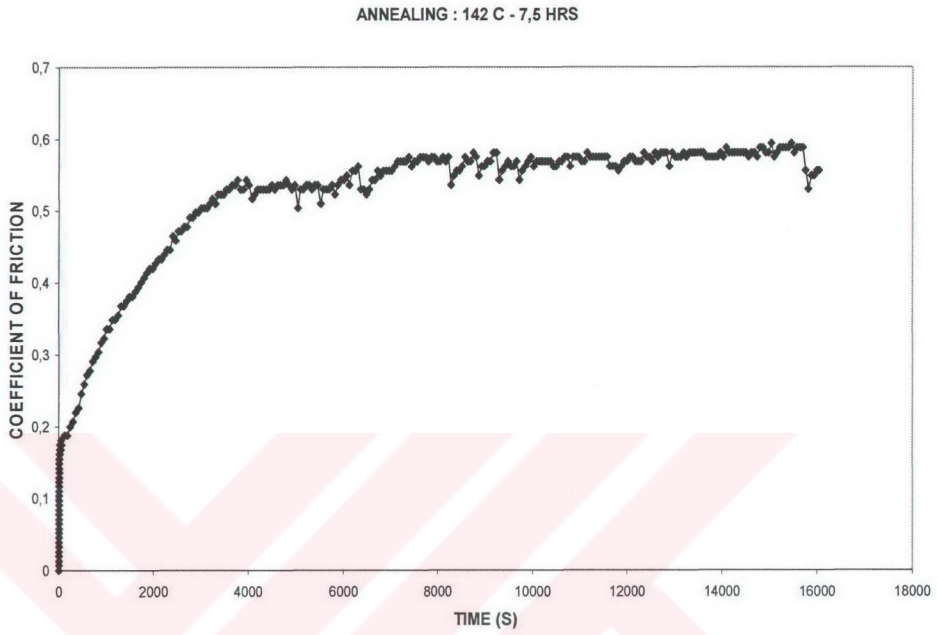
Figure 3.12. Coefficient of fiction vs. time for annealing method 142° C and 7.5 Hours
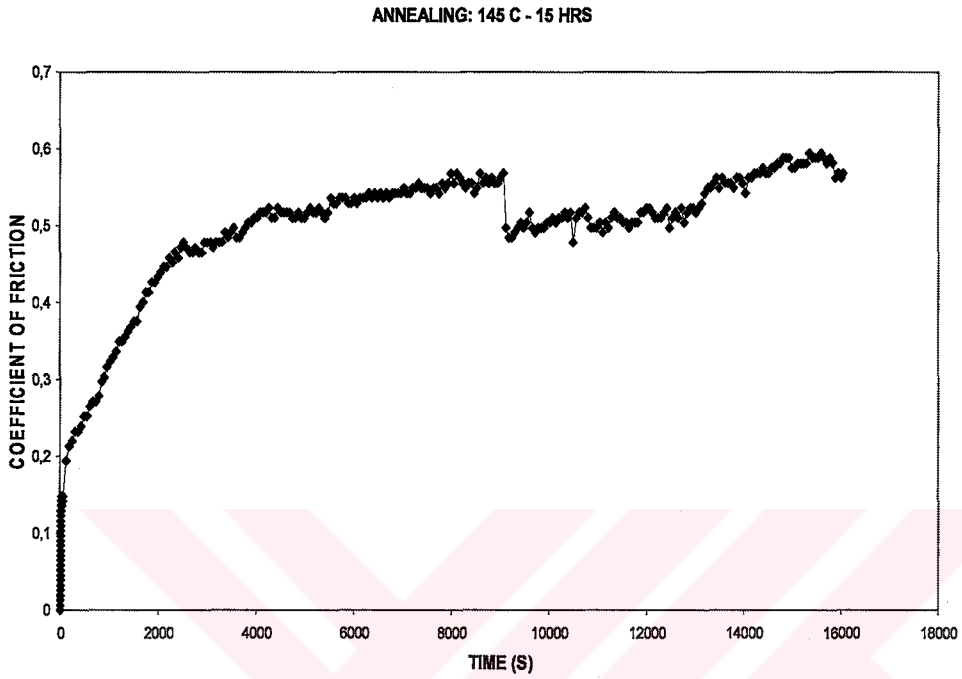
Figure 3.13. Coefficient of friction vs. time for annealing method 142° C and 15 hours

ANNEALING: 142 C - 30 HRS
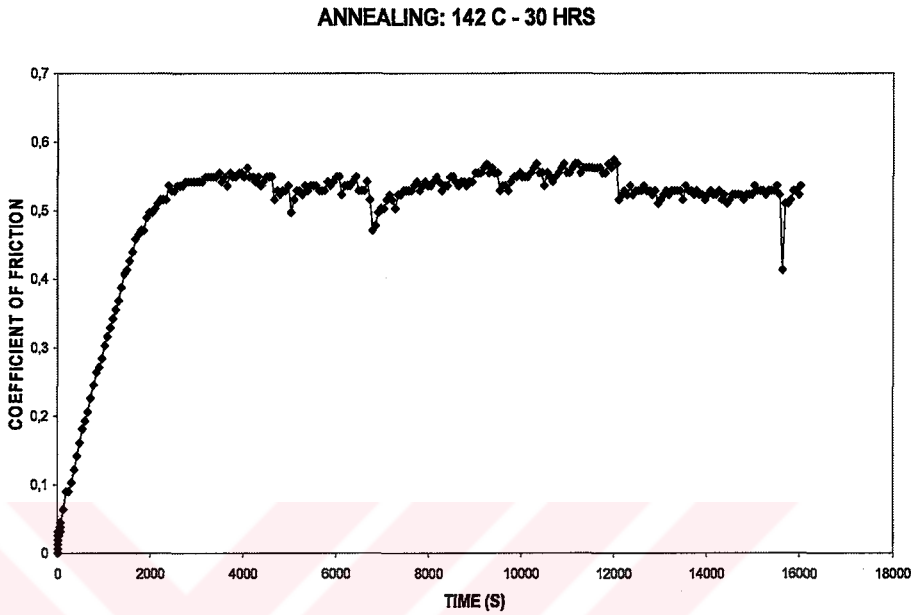
Figure 3.14 Coefficient of friction vs. time for annealing method 142° C and 30 hours

In **Table 3.3**, the dynamic and static coefficient of friction of polycarbonate samples subjected to the annealing tests have been given. In addition, dynamic coefficient of friction as a function of annealing period has been given in **Figure 3.15**.

Table 3.3. Static and dynamic coefficient of frictions of Polycarbonate samples subjected to annealing method

Annealing 142°C	μs	μk
PC (No Annealing)	0.52	0.58
142° C 7.5 H	0.55	0.58
142° C 15 H	0.52	0.56
142° C 30 H	0.55	0.53

COF - ANNEALING TIME 142 C
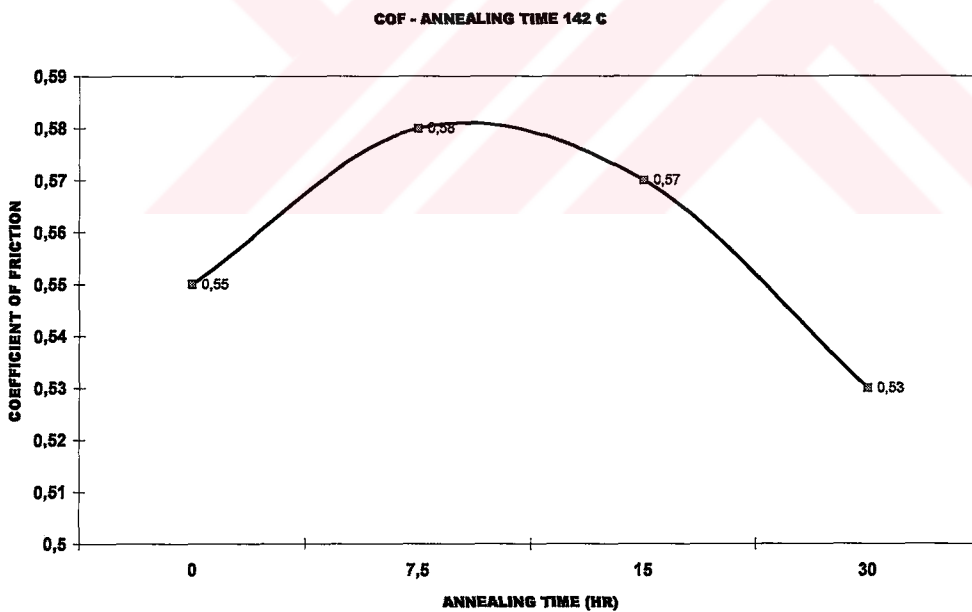
Figure 3.15. Dynamic coefficient of frictions vs. annealing times

4. CONCLUSIONS

In this project, two methods, namely the slip agent addition and annealing, were studied to reduce the friction of polycarbonate (PC) on metal surface.

Two different types of slip agent, pentaerytritol tetrastearate and montanic ester wax have been studied. When pentaerytritol tetrastearate is used as a slip agent, it is achieved to reduce the coefficient of friction of polycarbonate on metal surface from 0.55 to 0.35 which corresponds to 40 % of reduction of the initial value.

It is not succeeded in reducing the coefficient of friction by using montanic ester wax. Since it is commercial product, we were unable to predict the compatibility with PC by calculating its solubility parameter. This material is used mostly for PVC application.

Another method applied in the present study was annealing of polycarbonate at temperatures near to its T_g, below 148° C. However, no significant of reduction of coefficient of friction could be achieved.

Teflon, known for friction reduction, could be an alternative additive, but it is a high-cost material. As a recommendation for the further studies, montanic acid ester can be possibly an alternative to pentaerythritol tetrastearate.

In conclusion, the present study offers a slip agent additive to reduce the frictional coefficient between polycarbonate bobbin and metal spindle used in the textile industry.

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APPENDIX

Specifications of LUCAWAX E (montanic ester wax)

	DIN	ASTM
Physical form		Pale yellow powder
Melting point (DSC)	51007 D-3418	75-85°C
Recrystallization point (DSC)	51007	70-77°C
Dropping point	51801 D-3954	80-85°C
Penetrometer hardness (23°C)	51579D-1321	approx. 1dmm
Acid number	ISO3682 D-1386	15-20mgKOH/g
Melt viscosity (120°C)	51562 D-2162	approx.15mm/s
Density (23°C)	53479 D-792	0.98-1.00 g/cm3

AISI and ACI Standard Composition Ranges for Wrought and Cast Chromium-Nickel Stainless Steels
American Iron and Steel Institute Classification of Chromium-Nickel Stainless Steels

AISI Type	Composition, %								
	C max	Mn max	P max	S max	Si max	Cr	Ni	Mo	Other
201	0.15	5.50-7.50	.060	.030	1.00	16.00-18.00	3.50-5.50	—	N 0.25 max
202	0.15	7.50-10.00	.060	.030	1.00	17.00-19.00	4.00-6.00	—	N 0.25 max
301	0.15	2.00	.045	.030	1.00	16.00-18.00	6.00-8.00	—	—
302	0.15	2.00	.045	.030	1.00	17.00-19.00	8.00-10.00	—	—
302B	0.15	2.00	.045	.030	2.00-3.00	17.00-19.00	8.00-10.00	—	—
303	0.15	2.00	0.20	0.15 min	1.00	17.00-19.00	8.00-10.00	0.60 max	—
303Se	0.15	2.00	0.20	.06	1.00	17.00-19.00	8.00-10.00	—	Se 0.15 min
304	.08	2.00	.045	.030	1.00	18.00-20.00	8.00-12.00	—	—
304L	.03	2.00	.045	.030	1.00	18.00-20.00	8.00-12.00	—	—
305	0.12	2.00	.045	.030	1.00	17.00-19.00	10.00-13.00	—	—
308	.08	2.00	.045	.030	1.00	19.00-21.00	10.00-12.00	—	—
309	0.20	2.00	.045	.030	1.00	22.00-24.00	12.00-15.00	—	—
309S	.08	2.00	.045	.030	1.00	22.00-24.00	12.00-15.00	—	—
310	0.25	2.00	.045	.030	1.50	24.00-26.00	19.00-22.00	—	—
310S	.08	2.00	.045	.030	1.50	24.00-26.00	19.00-22.00	—	—
314	0.25	2.00	.045	.030	1.50-3.00	23.00-26.00	19.00-22.00	—	—
316	.08	2.00	.045	.030	1.00	16.00-18.00	10.00-14.00	2.00-3.00	—
316L	.03	2.00	.045	.030	1.00	16.00-18.00	10.00-14.00	2.00-3.00	—
317	.08	2.00	.045	.030	1.00	18.00-20.00	11.00-15.00	3.00-4.00	—
D319	.07	2.00	.045	.030	1.00	17.50-19.50	11.00-15.00	2.25-3.00	—
321	.08	2.00	.045	.030	1.00	17.00-19.00	9.00-12.00	—	Ti 5 x C min
347	.08	2.00	.045	.030	1.00	17.00-19.00	9.00-13.00	—	Cb-Ta 10 x C mi
348	.08	2.00	.045	.030	1.00	17.00-19.00	9.00-13.00	—	Cb-Ta 10 x C mi; 0.10 max; Co 0.2
384	.08	2.00	.045	.030	1.00	15.00-17.00	17.00-19.00	—	—
385	.08	2.00	.045	.030	1.00	11.50-13.50	14.00-16.00	—	—

Alloy Casting Institute Division (SFSA) Classification of Chromium-Nickel Stainless Steel Castings

Cast Alloy Designation	Wrought Alloy Type[a]	Composition, %								
		C max	Mn max	P max	S max	Si max	Cr	Ni	Mo	Other
CA-6NM	—	.06	1.00	.04	.04	1.00	11.5-14	3.5-4.5	0.40-1.0	—
CD-4MCu	—	.04	1.00	.04	.04	1.00	25-26.5	4.75-6.00	1.75-2.25	Cu 2.75-3.25
CE-30	—	0.30	1.50	.04	.04	2.00	26-30	8-11	—	—
CF-3	304L	.03	1.50	.04	.04	2.00	17-21	8-12	—	—
CF-8	304	.08	1.50	.04	.04	2.00	18-21	8-11	—	—
CF-20	302	0.20	1.50	.04	.04	2.00	18-21	8-11	—	—
CF-3M	316L	.03	1.50	.04	.04	1.50	17-21	9-13	2.0-3.0	—
CF-8M	316	.08	1.50	.04	.04	1.50	18-21	9-12	2.0-3.0	—
CF-12M	316	0.12	1.50	.04	.04	1.50	18-21	9-12	2.0-3.0	—
CF-8C	347	.08	1.50	.04	.04	2.00	18-21	9-12	—	Cb 8 x C min, 1.0 or Cb-Ta 10 x C; 1.35 max
CF-16F	303	0.16	1.50	0.17	.04	2.00	18-21	9-12	1.5 max	Se 0.20-0.35
CG-8M	317	.08	1.50	.04	.04	1.50	18-21	9-13	3.0-4.0	—
CH-20	309	0.20	1.50	.04	.04	2.00	22-26	12-15	—	—
CK-20	310	0.20	1.50	.04	.04	2.00	23-27	19-22	—	—
CN-7M	—	.07	1.50	.04	.04	1.50	18-22	27.5-30.5	2.0-3.0	Cu 3-4

[a] Wrought alloy type numbers are included only for the convenience of those who wish to determine corresponding wrought grades. The chemical composition ranges of the wrought materials differ from those of the cast grades.

Solubility parameters of some polymers

Polymer	δ_2	Polymer	δ_2
	$(cal/cm^3)1/2$		$(cal/cm^3)1/2$
Cellulose derivatives:		Poly (vinyl chloride)	9.7
C.dinitrate	10.6	Poly (vinyldene chloride)	12.2
C.laqueur nitrate	11.5	Polystyrene	9.1
C.diacetate	10.0	Poly (tetrafluoroetylene)	6.2
		Rubbers:	
Ester gum	9.0	Butadiene-acrylonitrile (70:30)	9.4
Nylon 66	13.6	Butadiene-styrene (71.5:28.5)	8.1
Polyacrylonitrile	15.4	Cis-polyisoprene	8.3
Polyetylene	7.9	Polychloroprene	9.2
Polypropylene	8.1	Polybutadiene	8.6
Poly (ethylene terephtalate)	10.7	Polyisobutylene	8.1
Poly (metyl methacrylate)	9.5	Etylene-propylene	8.0
Poly (vinyl acetate)	9.4	Poly (dimetylsiloxane)	7.3

Lubricants and Related Additives

Table 3. Types of chemical compounds.

Chemical name	Structure
Fatty alcohols	C_{12} to C_{22} ⊢——— OH
Fatty alcohol dicarboxylic acid esters	C_{13} to C_{17} ⊢——— O—C—(CH$_2$)$_x$—C—O ———⊣ C_{13} to C_{17} (‖O below each C)
Fatty acid esters	C_{13} to C_{17} ⊢——— C—OR (‖O)
Fatty acids	C_{13} to C_{17} ⊢——— C〈OH···O〉 C ———⊣ C_{13} to C_{17} 〈O···HO〉 (OH) (OH)
Fatty acid monoamides	C_{15} to C_{17} ⊢——— C—NH$_2$ (‖O)
Fatty acid diamides (amide wax)	C_{15} to C_{17} ⊢——— C—NH—CH$_2$—CH$_2$—NH—C ———⊣ C_{15} to C (‖O)
Metallic soaps	C_{13} to C_{17} ⊢——— C—O$^⊖$ Me$^{+⊕}$ $^⊖$O—C ———⊣ C_{13} to C (‖O)
Oligomeric fatty acid esters (fatty acid complex esters)	adipic acid / pentaerythritol — C_{17} to C_{21} ⊢——— C—O —·— C—O ———⊣ C_{17} to C (‖O)
Fatty alcohol fatty acid esters	C_{13} to C_{17} ⊢——— C—O ———⊣ C_{13} to C_{17} (‖O)
Wax acids	C_{21} to C_{31} ⊢——— C〈OH···O〉 C ———⊣ C_{21} to C_{31} 〈O···HO〉
Wax acid esters	C_{21} to C_{31} ⊢——— C—O—(CH$_2$)$_x$—O—C ———⊣ C_{21} to C_{31} (‖O)
Polar polyethylene waxes	C_{128} to C_{-400} ⊢——— (‖) (OH) (OR) ———〈O〉 OH
Nonpolar polyethylene waxes	C_{128} to C_{-400} ⊢——— (‖) ———⊣
Paraffin waxes	C_{20} to C_{40} ⊢——— (‖) ———⊣

⊢——— aliphatic chain

Lubricants and Related Additives

Plasticizing

Viscosity reduction

Reduction of
heat dissipation

Release effect

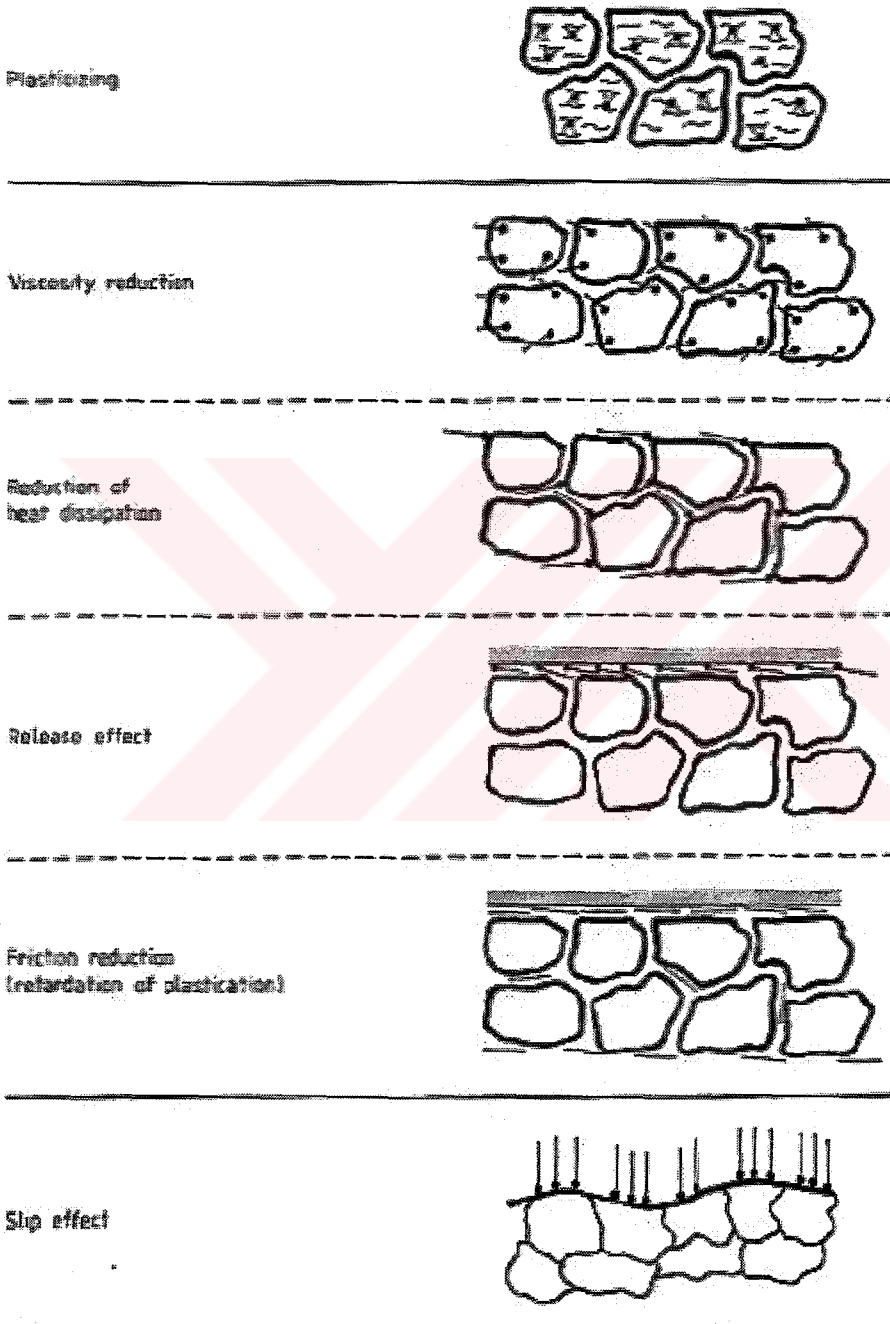Friction reduction
(retardation of plastication)

Slip effect

Fig. 4. Models illustrating theories of lubricant action (idealized individual effects; direction of movement from left to right).

Specifications of PC (200-15 Dow, Europe)

Rheological properties	Value	Unit	Test Standard
Melt volume-flow rate	12	cm³/10min	ISO 1133
Temperature	300	°C	ISO 1133
Load	1.2	kg	ISO 1133
Density	1200	kg/m³	ISO 1183

Mechanical properties	Value	Unit	Test Standard
Tensile Modulus	2300	mPa	ISO 527-1/-2
Yield stress	60	mPa	ISO 527-1/-2
Yield strain	6	%	ISO 527-1/-2
Nominal strain at break	>50	%	ISO 527-1/-2
Charpy impact strength (+23°C)	N	KJ/m²	ISO 179/1eU
Charpy impact strength (-30°C)	N	KJ/m²	ISO 179/1eU
Charpy notched impact strength (+23°C)	80	KJ/m²	ISO 179/1eA
Charpy notched impact strength (-30°C)	-12	KJ/m²	ISO 179/1eA

Thermal properties	Value	Unit	Test Standard
Temp. of deflection under load (1.80 MPa)	130	°C	ISO 75-1/-2
Temp. of deflection under load (0.45 MPa)	144	°C	ISO 75-1/-2
Vicat softening temperature (50°C/h 50N)	148	°C	ISO 306
Coeff. of linear therm. expansion (parallel)	0.7	E-4/°C	ISO 11359-1/-2
Burning Behav. at 1.6 mm nom. thickn.	HB	class	IEC 60695-11-
Thickness tested	1.6	mm	IEC 60695-11-
UL recognition	UL	-	-
Burning Behav. at thickness h	HB	class	IEC 60695-11-
Thickness tested	3.2	mm	IEC 60695-11-
UL recognition	UL	-	-
Oxygen index	26	%	ISO 4589-1/-2

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Ural Huseyin Aksoy

Experience

1997–   Benak Pazarlama
General Manager

- Marketing thermoplastic raw materials in Turkey
- Finding foreign partners and making contract
- Looking for new investment sectors
- Visiting plastic fairs in the world

1995–1997   Raks Elektrikli Ev Aletleri
Purchasing Chief

- Purchasing 2000 tons/year of thermoplastic raw materials
- Procurement different goods from domestic market
- Providing new skills to reach the most competitive price in the market and making purchasing contracts

1993–1995   Teba/Ente
Purchasing Executive

- Purchasing components for Heating Ventilating Air Conditioning Systems
- Following and making daily correspondence
- Making research to find suitable component provider

1993–1992   Safir Tekstil
Technical Responsible

- Working as a shift supervisor.
- Dying fabric
- Developing new dying recipe

Education

2004   Ege University

- Started in 2004 for obtaining master degree in polymer field in Chemical Engineering faculty
- Preparing master thesis (reducing the coefficient of friction of polycarbonate material) and will be graduated by end of 2005, the latest

1984–1990   Yıldız Technical University

- Graduate Chemical Engineering faculty
- Industrial training in detergent and olive oil factories

Skills

Knowing French and English as foreign languages in advance level, making search in internet, and using office and power point programs.