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THERMOPLASTIC POLYMER MACHINE GUARDS – EXPLOITATION SAFETY

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Abstract:

The machine construction sector uses from 2 to 5% of thermoplastic polymer production. This material is used to make small elements and big parts of equipment, including guards. The latter have mechanical vibration damping capacity, do not require any maintenance, are cheap and look attractive. Moreover, polymer guards are an essential element of machines as they improve workplace safety. They are used in such machines as lathes, milling machines, drills, extruding machines, presses and grinders. Pursuant to the Ordinance of the Minister of Labour and Social Policy on general provisions for safety and health at work, protective devices used in machines should be strong and durable so as to ensure the appropriate level of occupational safety. This is why the selection of the right material to make such devices is essential. Most frequently guards used in the market are steel frames with a polycarbonate screen or laminated safety glass. Other materials used to manufacture guards are poly(methyl methacrylate) *(PMMA) and polystyrene (PS). Thermoplastics are characterised by high visual light transmittance (even up to 98% in the case of PMMA), easy treatment, possibility to form any shape and resistance to atmospheric factors. However, they are also characterised by limited high temperature resistance, low fire resistance and high speed of fire propagation on their surface which may be dangerous for employees in case of fire. The article discusses the selection of appropriate material for the production of guards in the context of their exploitation in higher temperature conditions and examines threats posed by thermoplastics in fire conditions.*

Keywords:

guards, polymers, thermal resistance, exploitation

INTRODUCTION

At the time of increasing automation machines play a key role in manufacturing processes. Their correct operation is supervised by man without whom continuous and faultless operation quite frequently would be impossible. Machine operators should be provided with comfortable and safe working conditions to operate machines.

The first projects related to ensuring safety during machine operation were developed already in the 40's of the 20th century by Liberty Mutual Insurance Company, an American insurance company. They defined the recommended dimensions of gaps at sample workplaces resulting from the palm size [10]. The accident risk connected with contact with movable machine parts is extremely significant in all industry sectors and all activities performed by workers. The Occupational Safety and Health Administration (OSHA) emphasises that finger or extremity amputations are some of the most serious injuries experienced at work, they frequently lead to permanent disability and exclusion from professional life. Frequent analyses and statistical studies resulted in the development of guidelines and standards, including the latest European Machinery Directive 2006/42/EC. The essence of these standards is occupational safety improvement by the minimisation of contact with movable machine parts thanks to the use of appropriate protective means, mainly guards [1]. Pursuant to the Directive, a guard is a part of a machine which ensures protection in the form of a material barrier.

In Poland mechanical threats concern over 80 000 people every year (Fig. 1).

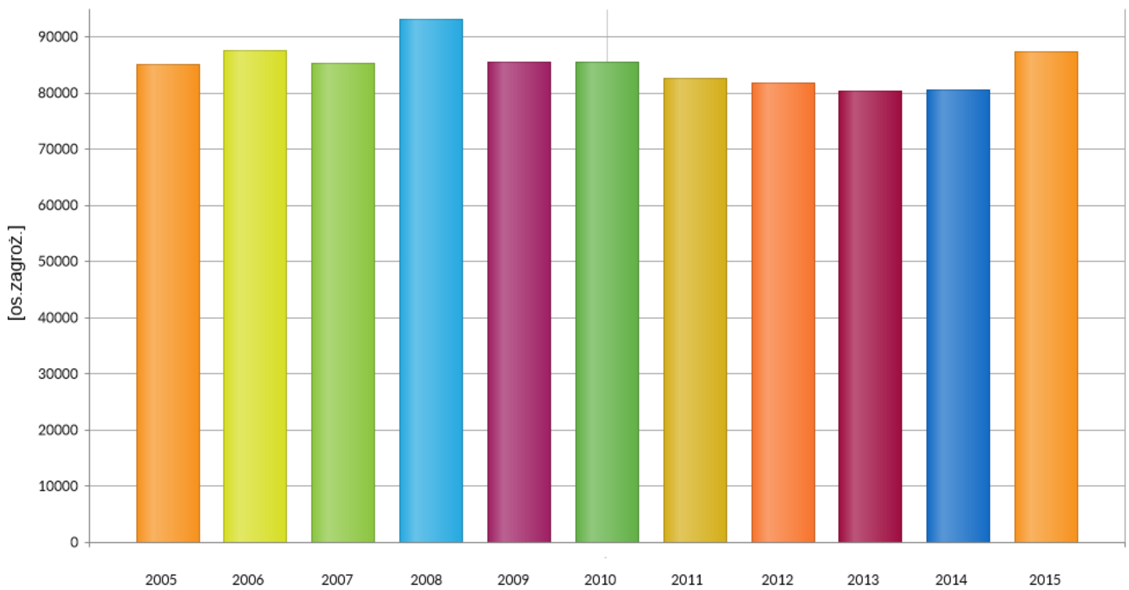

Fig. 1. Working conditions in Poland in the years 2005 – 2015: threats related to mechanical factors [No. of people at risk]

Source: Local data Bank https://bdl.stat.gov.pl

Only in industrial processing (Section C; Ordinance of the Council of Ministers on the Polish Classification of Activities of December 24, 2007), over the last six years about

30,000 people have been injured every year (Fig. 2), which makes over 30% of all occupational injuries.

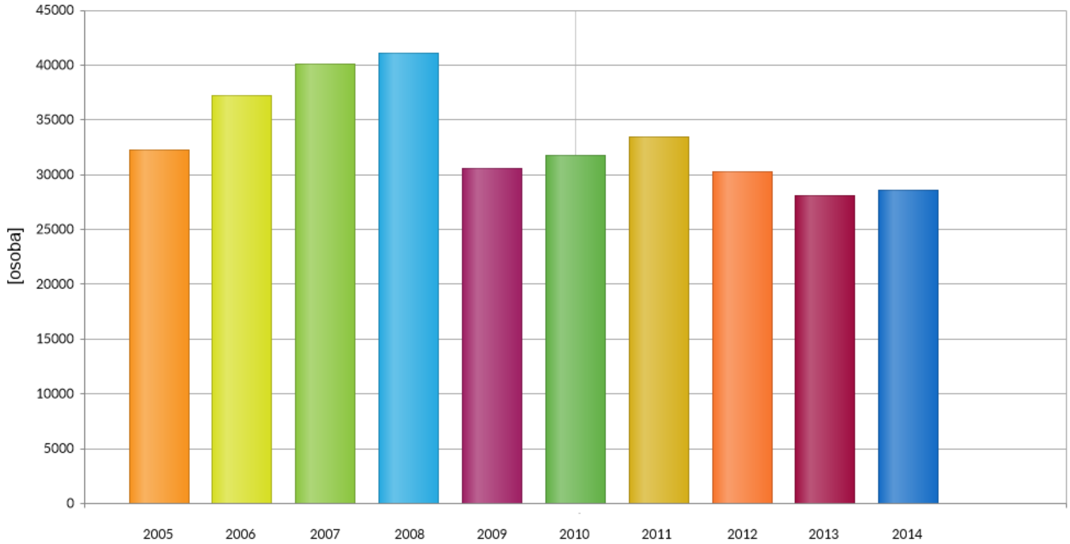

Fig. 2. The injured in occupational accidents in Poland in the years 2005 – 2014, employed in Section C jobs of the Classification, 2007 [person]

Source: Local data Bank https://bdl.stat.gov.pl

Hence, it is essential to protect workplaces accordingly to the threat. One of the elements which allow to supervise equipment operation are fixed or movable protecting staff from any negative effects (Fig. 3). They prevent contact with moving machine parts, ejected moving elements, being caught by rotating machine parts and at the same time allow for constant process or operation supervision.

Fig. 3. Vertical machining centre with a guard

Source: http://foter.com

1. MACHINE GUARDS IN THE LIGHT OF BINDING LEGAL REGULATIONS

Pursuant to the Ordinance of the Minister of Labour and Social Policy on general provisions for safety and health at work of September 26, 1997 (Section IV, Chapter 1, § 39.1) an employer is obliged to "organise work and provide workplaces in a way which protects employees from injuries or conditions which are harmful for health and other nuisance, taking into consideration the psychological and physical abilities of staff". Guards used at workplaces should prevent direct access to a danger zone. Protective devices used in machines should:

- ensure the safety of machine operators and people who are near machinery;
- operate in a reliable manner, be durable and strong;
- be able to self-activate regardless of the operator's will (when it is purposive and possible);
- be hard to remove or disconnected without any tools;
- not hinder technical operations or limit the possibility of its supervision;
- be safe for staff not cause physical or psychological or physical encumbrance.

Apart from this, "machines and other technical equipment (…) should meet the requirements of the occupational health and safety regulations defined in separate legal provisions throughout the whole period of their use" (Chapter 3, § 51) [6]. These requirements were specified in the Ordinance of the Minister of Economy on the minimum requirements concerning the use of machinery by employees during work of October 30, 2002. Pursuant to this regulation "Machines are equipped with protective devices which prevent threats related to the emission or ejection of substances, materials or objects". Guards are used also when there is a risk of direct contact with movable machine parts. In Chapter 3, item 4 (minimum requirements concerning the use of machinery) the legislators defined the characteristics of guards and protective devices, namely they [7]:

- "should have a strong (durable) structure;
- cannot constitute a threat;
- cannot be easily removed or excluded from use;
- should be located at appropriate distance from the danger zone;
- should not restrict the visual field of the machine operating cycle;
- should allow to perform activities related to fixing or replacing machine parts and also to conduct maintenance activities leaving only limited access to the area where these activities are performed, as much as it is possible without taking off protective devices;
- should restrict access only to the danger zone of machine operation".

General requirements related to the design, construction and selection of guards used to protect people from mechanical threats are defined in the harmonised Polish standard PN-EN ISO 14120:2016-03 ("Safety of machinery – Guards – General requirements for the design and construction of movable and fixed guards"). Guards must be designed and constructed in such a way that they can ensure sufficient visibility of a process. Protective devices used in machines can be made from various materials. It is designer's task to make a product which not only will meet the requirements of regulations and standards, but also will be user friendly, cost-effective and will look good. The main solutions offered in the market are steel guards with a wire lattice screen, laminated glass or plastic. The most frequently used polymers in the production of guards are: polycarbonate (PC), polyethylene terephthalate glycol (PET-G), acrylate polymers and transparent polyvinyl chloride (PVC).

2. THERMOPLASTIC POLMERS USED IN GUARD SCREENS

From among thermoplastic polymer used to manufacture guards the most significant one is polycarbonate. It is easy to process, transparent and strong, which makes it an ideal material for machine guards. On the market some of the available PCs are intended for general use and there are also those dedicated to contact with food (machine guards in food industry). Other thermoplastic polymers which can be used as guard screens due to their high transparency are poly(methyl methacrylate) (PMMA) and polystyrene (PS).

Because of their strength and transparency polycarbonate and poly(methyl methacrylate) slabs are widely used both in the arms and civilian industries, e.g. as machine and cockpit guards, motorcycle deflectors, safe glazed surfaces, entrance enclosures, bus stop shelters**,** interior decoration elements, smoke dampers, acoustic screens, advertising boards and signboards, anti-burglary shields, visors and protective shields. Polystyrene has similar applications, it is used to make small-size objects with complex shapes and also for packaging, signboards or bath screens. These polymers are widely available in the market. The process of PC and PMMA pellets are similar (about PLN 12/kg), while the price of PS is 50% lower [12].

2.1. Chemical structure and basic properties

Polycarbonates are linear polyesters of carbonic acid and diols which include -R-O-CO-O- bond (R is to alkyl or acrylic). Usually it is obtained as a result of phosgene polycondensation with dihydroxy compounds. The most significant group of polycarbonates from a practical perspective are aromatic polycarbonates obtained from Bisphenol A. They have very good mechanical, thermal, electrical and optical properties. They transmit 90% of visual light. They are resistant to water, diluted acids and base solutions, alcohols (except methanol), fats, oils, milk, fruit juice. Their disadvantage is limited chemical resistance (no resistance to benzene, toluene, xylene, chlorinated hydrocarbons, methanol, concentrated acids and bases, constant water exposure) and sensitivity to stress corrosion [8].

Ppoly(methyl methacrylate) is obtained as a result of free radical polymerisation of methyl methacrylate. Depending on the process conditions, it is possible to obtain an atactic, syndiotactic or isotactic polymer. In addition to this the industrial methods of obtaining PMMA concern only the atactic polymer obtained in mass, suspension, emulsion or solution. PMMA is characterised by very good optical properties, resistance to atmospheric factors and low temperature as well as water absorbency. It has good mechanical and electrical insulating. It also shows high chemical resistance (it is resistant to weak acids, weak base solutions, salt solutions, aliphatic hydrocarbons, nonpolar solvents, lubricants, oils, water, detergents). It is not resistant to strong acids and bases, benzene, polar solvents, such as ketones, esters, ethers and aromatic and chlorinated hydrocarbons [8].

Polystyrene is obtained by styrene polymerisation. In industry the reaction is conducted in mass, suspension, emulsion and solution. PS is a linear amorphous polymer characterised by relatively high hardness and transparency as well as very good dielectric properties. Polystyrene undergoes yellowing and accelerated aging under the influence of visual light (especially UV radiation). As a result it becomes brittle and breakable. Its mechanical properties depend on its molecular weight and temperature in which it is used (they deteriorate when temperature approaches the softening point). Polystyrene dissolves in aromatic and chlorinated hydrocarbons, esters, ketones, carbon disulphide, pyridine. It does not dissolve in aliphatic hydrocarbons**,** lower alcohols, ether, phenol, acetic acid and water [8].

Figure 4 presents the structural formulae of PC, PMMA and PS and Table 1 their basic properties.

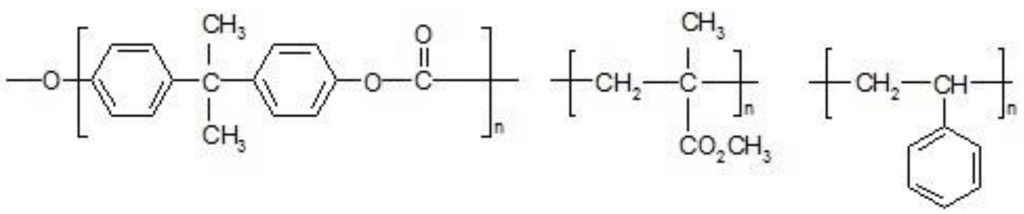

Fig. 4. Structural formulae (left to right): polycarbonate, poly (methyl methacrylate),polystyrene

Source: own elaboration

Among the discussed polymers polycarbonate has the best thermal characteristics. It can be used for a long time on both low and high temperatures. It is a strong material with exceptionally high impact resistance, over 15-fold higher than in the case of other polymers. It is also characterised by much bigger elongation at break. Both polycarbonate and poly(methyl methacrylate) have similar tensile strength. The parameter which distinguishes polystyrene is the value of dielectric breakdown voltage. In the case of this polymer it is twice as high as in the case of PC and significantly higher than the dielectric strength of electrotechnical ceramic materials (10 ÷ 50 kV/mm). PS also has high resistivity and, hence the ability to limit the electrical current intensity.

Table 1. Collation of the basic properties of polycarbonate (PC), poly(methyl methacrylate) (PMMA) and polystyrene (PS)

Properties	PC (standard)	PMMA	PS
Density [g/cm^3]	1.2	1.18	1.05
MFR* [g/10 min]	9 ÷ 13	11 ÷ 0,8	5

Properties	PC (standard)	PMMA	PS
Tensile strength [MPa]	> 65	68 - 75	50
Elongation at break [%]	110	4.5 ÷ 3.0	3
Modulus of elasticity [MPa]	2300	3300	3300
Notched impact strength [kJ/m^2]	> 30	2	2
Thermal stability [°C] Short-term Long-term	 -115 ÷ +150 -115 ÷ +130	 92 ÷ 108 82 ÷ 98	 80 ÷ 85 65 ÷ 75
Glass transition temperature [°C]	150	106	90
Vicat softening temperature [°C]	148	92 - 108	88
Heat distortion temperature [°C]	138	82 - 98	85
Cross-resistance [Ω cm]	> 10^{16}	> 10^{15}	> 10^{18}
Surface resistance [Ω]	> 10^{15}	5×10^{13}	10^{15}
Breakdown strength [kV/mm]	> 80	30	200
Refraction index n_D^{20}	1.585	1.491	1.5916– 1.5927
Transparency	92	92	90

* Melt Mass-Flow Rate

Source: own elaboration based on [8]

Among the discussed polymers, polycarbonate is characterised by the best thermal stability. It can be used for a long time in both low and high temperatures. It is a strong material with high impact toughness which is over 15-fold higher than in the case of the other two polymers. It is also characterised by much bigger elongation at break. Polycarbonate and poly(methyl methacrylate) have similar tensile resistance. The parameter which distinguishes polystyrene is the value of dielectric breakdown voltage. In the case of this polymer it is over two-fold higher than in the case of PC and significantly higher than the dielectric strength of electrotechnical ceramic materials (10 ÷ 50 kV/mm). PS also has high resistivity and, hence the ability to limit the electrical current intensity.

2.2. Processing parameters

Polycarbonate is processed in the melted state using injection moulding, extrusion, vacuum moulding, etc. Injection moulding is conducted at a temperature of 280 ÷ 320°C and pressure not higher than 220 MPa, while extrusion requires a temperature of 240 ÷ 280°C. PC processing shrinkage for PC is 0.7 ÷ 0.8 %. Semi-products can be mechanically processed by machining, milling and spot drilling.

Poly(methyl methacrylate) can be processed using injection moulding, extrusion and compression moulding after prior drying of pellets. Its processing can be conducted at lower temperatures than PC. Injection moulding is conducted at a temperature of 210 ÷ 220°C, pressure of 50 ÷ 120 MPa, extrusion – 200 ÷ 230°C, compression moulding – 160 ÷ 180°C. PMMA processing shrinkage is 0,1 ÷ 0,8%. Semi-products are processed mechanically by milling, turning, drilling, polishing and heat bending.

Polystyrene is processed mainly using injection moulding: Low impact PS at a temperature of 160 ÷ 260°C, pressure 80 ÷ 140 MPa (shrinkage 0.3 ÷ 0.8 %) while high-impact PS at a temperature of 200 ÷ 260°C, pressure 100 ÷ 130 MPa (shrinkage 0.2 ÷ 0.6 %). Semi-products can be polished, drilled and painted.

Thermoplastic products can be easily metallised and join by welding, pressure welding and gluing [8].

2.3. Flammability and thermal stability of thermoplastic polymers

The flammability and thermal stability of materials are characterised by, inter alia, oxygen index (LOI), ignition and breakdown temperature (Table 2). Initial breakdown temperature (T_d) is determined on the basis of formula 1:

$$T_d = 0{,}9 T_{d,1/2} \tag{1}$$

where:

$T_{d,1/2}$ –50% mass loss temperature.

Table 2. Initial breakdown temperature (average temperature value ± 10°C) and ignition temperature of polycarbonate, poly(methyl methacrylate) and polystyrene

Polymer	LOI [%]	T_d [°C]	$T_{ignition}$ [°C]	$T_{self\text{-}ignition}$ [°C]
Polycarbonate	25	476	520	-
Poly(methyl methacrylate)	17	354	300	430
Polystyrene	18	319	350	490

Source: [5,9]

Among the discussed polymers, polystyrene is characterised by the lowest thermal stability, its initial breakdown temperature and ignition temperature is as much as about 150°C lower than for PC. Polycarbonate is a self-extinguishing material which is self-ignited at a temperature above 500°C. It is a flammable material (LOI <26%) contrary to PMMA and PS which are inflammable in air and pose the biggest fire threat (oxygen index 21%). A factor which has a significant influence on fire threat is ignition timing (Table 3), the amount of generated heat (Table 4), smoke thickness and toxicity of combustion products (Table 5).

Table 3. Ignition timing for selected values of heat flux for polycarbonate, poly(methyl methacrylate) and polystyrene

Polymer	Ignition timing [s] / heat flux		
	20 kW/m^2	40 kW/m^2	70 kW/m^2
Polycarbonate	10000	182	75
Poly(methyl methacrylate)	176	36	11
Polystyrene	417	95	50

Source: [11]

Regardless of thermal radiation, polycarbonate has the longest ignition timing, while poly(methyl methacrylate) the shortest.

Table 4. Heat generation for selected heat flux values for polycarbonate, poly (methyl methacrylate) and polystyrene

Polymer	20 kW/m^2		40 kW/m^2		70 kW/m^2	
	Heat generation maximum speed [kW/m^2]	Total heat release, THR [MJ/m^2]	Heat generation maximum speed, [kW/m^2]	Total heat release, THR [MJ/m^2]	Heat generation maximum speed, [kW/m^2]	Total heat release, THR [MJ/m^2]
PC	16	0.1	429	119.2	342	121.7
PMMA	409	691.5	665	827.9	988	757.1
PS	723	202.6	1101	210.1	1555	197.8

Source: [11]

Table 5. Mass optical density of smoke (D_m) and combustion products of polycarbonate, poly(methyl methacrylate) and polystyrene

Polymer	D_m [m^2/kg]	Combustion products
Polycarbonate	891	CO, CO_2
Poly(methyl methacrylate)	100	CO, CO_2
Polystyrene	1150	CO, CO_2, NO_2

Source: [9]

Polycarbonate is the only polymer in the discussed group which makes a carbonized layer. As a result its total heat release is the lowest because a foam coke layer prevents free heat exchange and oxygen transport to deeper layers of the material during a fire. However, thermal radiation released from each of the discussed materials during a fire poses a threat to people staying nearby (4.7 kW/m^2 causes pain after 15-20 s and burns after 30s). Polystyrene decisively releases the largest amount of smoke during a fire. Thick smoke hinders breathing and affects visibility which is extremely important during emergency evacuation.

At the West Pomeranian University of Technology in Szczecin a new method of polystyrene and poly(methyl methacrylate) modification has been developed so as to decrease their flammability and ensure high thermal stability [2-4]. The polymers are modified by extrusion with 9,10-dihydro-9-oxa-10-fosfat phenanthrene 10-oxide (flame retardant available on the market). Polymers obtained in this way are characterised by higher thermal decomposition temperature and lower flammability in comparison with non-modifies polymers. The use of this type of materials to make guards would improve safety during operation in higher temperatures.

CONCLUSIONS

The materials discussed in this article are thermoplastic polymers which allow to obtain products in any shape. Used as guards, thanks to their high transparency, they allow to continuously observe a process. In the discussed group polycarbonate is characterised by the best strength parameters, which is essential in all sectors where ejection of elements during machine operation is possible. In this group of materials it is also characterised by the highest thermal stability. Unfortunately all the discussed polymers pose a threat during a fire. The largest amount of heat is released during the combustion of poly(methyl methacrylate). On the other hand in fire conditions, it releases not so much smoke as PC and PS. This is why it is essential to modify this material to decrease its flammability and improve thermal stability while maintaining its strength parameters.

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BIOGRAPHICAL NOTE

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