IOSUD - Universitatea Politehnica Timişoara
Şcoala Doctorală de Studii Inginereşti

RESEARCH ON ALTERNATIVE METHODS OF MANUFACTURING ROLL ON BALLS

PhD Thesis - Abstract

for the award of the scientific title of Doctor of
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in the field of Mechanical Engineering

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1. Introduction

Polymeric materials are used in a wide range of industrial applications [1, 2, 3], with packaging accounting for 39.6% of the total, followed by construction with 20.4% and the automotive industry with 9.6% [5]. However, the widespread use of products made of polymeric materials is generating more and more environmental problems. In this regard, the European Parliament issued Directive 2019/904, which is mandatory to be implemented in all EU countries [7]. The Directive regulates the concept of Circular Economy and gives priority to recyclable, reusable, sustainable and non-toxic products. The Directive recommends the introduction of systems to reuse and reduce the quantities of waste. The European legislation also promotes alternative technologies that generate reductions in specific raw material and energy consumption. In this paper, alternative methods of making roll on balls that meet the above requirements are researched.

2. Theoretical considerations on polymeric materials and processing technologies

Polymers are macromolecular compounds obtained from monomers by polymerisation reactions. The degree of polymerisation "n" represents the number of monomer molecules that join to form a macromolecule [1,2,8].
The main sources of polymeric materials are hydrocarbs (fossil or gaseous fuels) [1,2,8]. In recent years, these sources have diversified with the implementation of mechanical and chemical recycling technologies and the development of bio-polymers. The most widely used polymeric materials derived from hydrocarbons are polyolefins. This category includes polyethylene and polypropylene [1].
Polyethylene is a white or semi-transparent, semi-crystalline, thermoplastic polymer obtained by the polymerisation of ethylene. The macromolecular structure is linear with a small or large number of branches.

Polypropylene is a thermoplastic, semi-crystalline material obtained by polymerisation of propylene. Polypropylenes have different chemical compositions and are available as homopolymers or copolymers.

Polymeric materials are widely used in the production of packaging for the cosmetics industry. In recent times, modern manufacturing technologies have been developed and new polymeric material recipes have emerged [3]. Newly developed polymeric materials are successfully replacing materials such as glass, metal and wood.

Globally, there is a steady increase in the consumption of cosmetics: creams, deodorants and antiperspirants. The publication "Statista" presents an overview of the global deodorants market starting with 2012 as well as the forecasts up until 2025. According to the publication, the average annual growth rate of this market is estimated at 3.5-4% [12].

Roll on products are common on the shelves of convenience stores. The parts that make up these products can be made of polymeric materials such as polypropylene (PP), high density polyethylene (HDPE), low density polyethylene (LDPE), polyethylene terephthalate (PET).

3. Presentation of the research topic and objectives of the PhD thesis

The research topic refers to alternative methods of manufacturing roll on balls.
Definition of roll on ball: *a spherical, thin-walled polymeric material object which, through rotational movement in the dosing device, ensures the transfer of liquid (deodorant) from a container onto the human body* [13,14].

The classical method of manufacturing roll on balls involves the use of extrusion-blow moulding technology and the raw spherical balls are produced in one piece [15, 33, 35].

The major drawbacks of the classical technology are :

- the large amount of technological waste, which can reach up to 40% of the processed material. This waste has to be regrinded and fed back into the process, which leads to additional material and energy consumption (Figure 3.2);
- the inconsistent thickness of the walls, leading to additional material consumption.

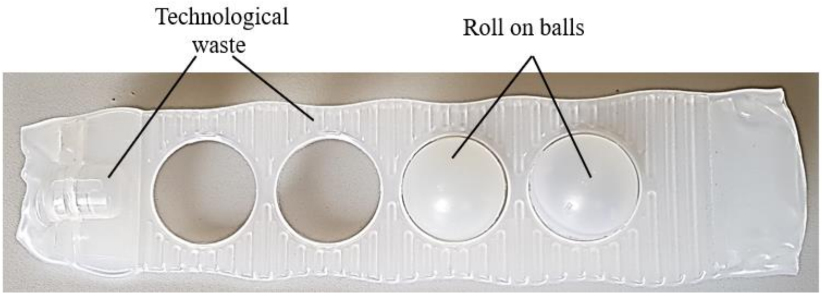
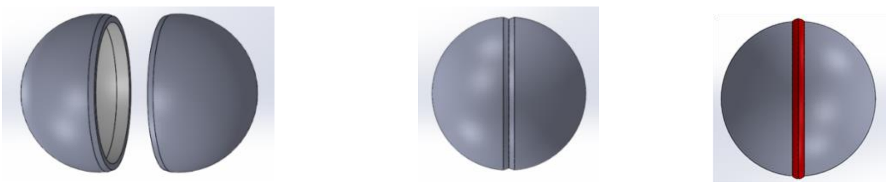


Figure 3.2. Technological waste from conventional extrusion-blow moulding technology.

Afterwards, the raw balls having the nominal diameter D_B = 25.7 mm are polished/grinded and calibrated to the diameters required by the specification D_N = 25.4 mm.

The PhD thesis proposes alternative methods of manufacturing roll on balls produced by welding two hemispheres/ball halves (Figure 3.5). These methods allow to control more precisely the thickness of the walls of the balls and hence their mass.



Hemispheres before welding | Hemispheres in contact | Roll on ball

Figure 3.5. Alternative technology for manufacturing balls by welding two hemispheres.

Conventional roll on technology is stable but characterised by low productivity and high raw material and energy consumption. Given the considerable volumes of cosmetic products on the global market, it is very important that alternative techniques offer higher productivities. Equipment for manufacturing roll on balls by alternative methods has started to appear on the market [37], but the number is still very small, the technological processes are unstable and the volumes produced are limited. Therefore, there is still great potential for the development of alternative technologies. Studies so far show that a manufacturing line should be developed to ensure a productivity of 60-80 million roll on balls per year.

The main objectives of the PhD thesis were the following:

1. Reducing raw material and energy consumption in the production of roll on balls, in the current context of a general increase in world prices;
2. Ensuring the recyclability of the balls in the context of Sustainability requirements and the transition to a Circular Economy;
4. Identifying roll on manufacturing technologies that ensure higher productivity compared to conventional technology;
5. Setting up a high speed roll on production line;
6. Exploiting the research results in industries using spherical shaped parts (automotive, toys, leisure, medicine, etc.).

4. Alternative methods of manufacturing roll on balls.

From the design phase of polymer products, there is a natural tendency to make them from a single component. Very often, however, the shape of these products is too complex to be injected into moulds. As a result, inevitably they have to be made out of two or more subcomponents, which will then be assembled to obtain the finished product [18,38].

Welding methods of polymeric materials fall into several categories: thermal welding, mechanical welding and electromagnetic welding (Figure 4.2).

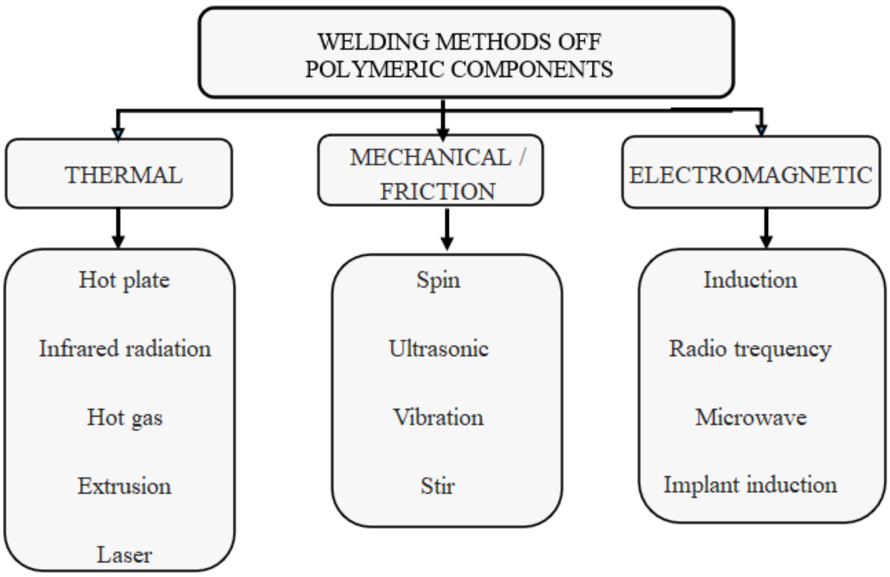
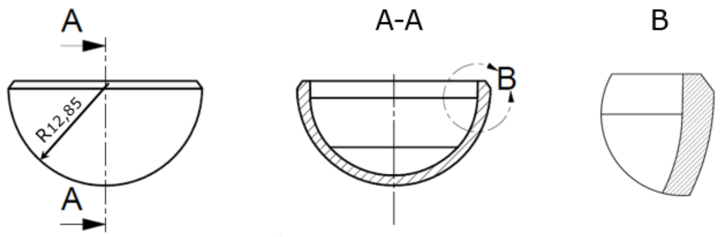


Figure 4.2. Welding methods of polymeric materials [38].

The following are the roll on ball welding processes that have given the best results.

Welding roll on balls with heating element

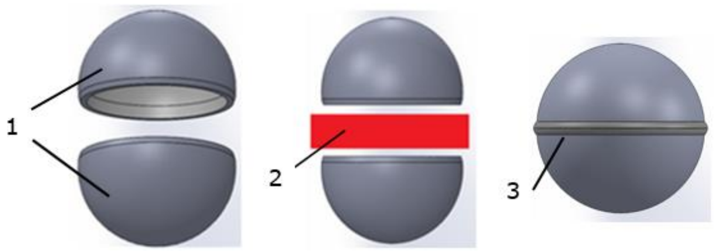
The outline of the hemisphere underlying the roll on ball by hot plate welding is shown in Figure 4.9.



hemisphere-view hemisphere-section detail of joint area

Figure 4.9. Sketch of the hemisphere underlying the roll on ball by hot plate welding.

The heating element used in this process is a hot plate [44, 67]. Heat transfer from the hot plate to the hemispheres to be welded is achieved by bringing the hemispheres (1) into contact with the hot plate (2), followed by withdrawing the plate, pressing the hemispheres together and obtaining the welded ball (3). The schematic of hot plate welding operations is shown in Figure 4.8.



1 - hemisphere
2 - hot plate
3 – welded ball

hemisphere alignment heating welding

Figure 4.8. Schematic diagram of the hot plate hemisphere welding operations.

Welding roll on balls with infrared radiation

Welding roll on balls with infrared radiation is similar to hot plate welding. The difference between the two processes is that the heating of the hemispheres is achieved by bringing them in close proximity to the radiant source and not by direct contact with the source [45, 46, 48].

Ultrasonic welding of roll on balls

The typical technological phases of the ultrasonic welding process [74,78] of roll on balls, described in Figure 4.66, are:

A. Positioning and fixing the upper ball halve in the sonotrode and the lower ball halve in the anvil;
B. Contacting the two hemispheres/ball halves by lowering the sonotrode;
C. Welding the two hemispheres by activating the ultrasonic block;
D. Ejection the welded ball.

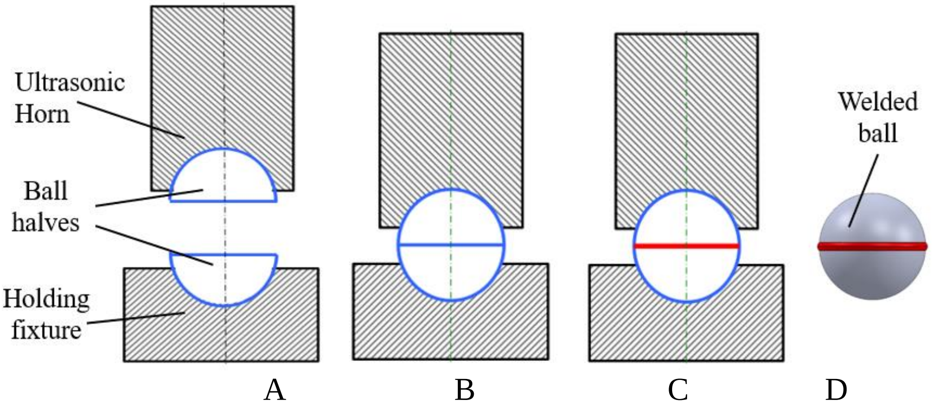


Figure 4.66. Technological phases of the ultrasonic roll on ball welding process.

Ultrasonic welding experiments were carried out using two welding equipments with different frequencies: 20 kHz and 35 kHz, respectively [79, 80].

A specialised ultrasonic welding equipment of Stapla Ultraschal brand, equipped with a sonotrode adapted for welding roll on balls was used at 20 kHz frequency in the ultrasonic welding experimental programme (Figure 4.67).

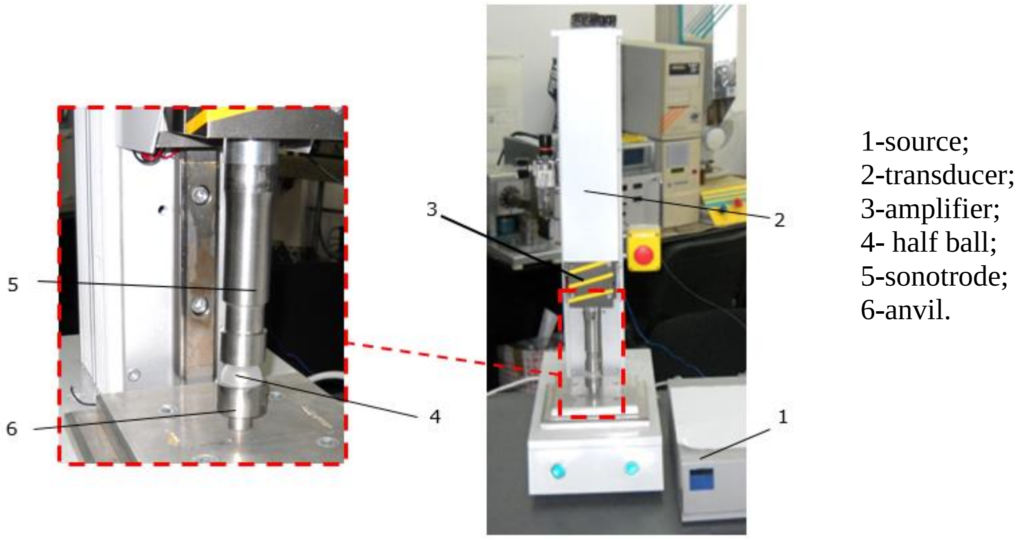


Figure 4.67. Experimental ultrasonic roll on ball welding stand at 20 kHz frequency.

Welding experiments of roll om balls at 35 kHz frequency were performed on an ultrasonic welding stand of Herman Ultrasonics brand [80]. The optimization of the sonotrode was carried out using a specialized finite element simulation software.

5. Quality determinations of roll on balls

Methods for determining the quality of roll on balls.

There are two main methods for determining the quality of roll on balls: destructive and non-destructive methods.

Non-destructive control methods for roll on balls.

The simplest non-destructive control method is the visual control method [81]. It is the quickest method that allows immediate observation of defects in the balls produced by welding the hemispheres (burrs, cracks, opacities, deviations from the spherical shape, etc).

Another non-destructive control method applicable to roll on balls is the penetrating liquid method. The method is based on immersing the welded balls in isopropylic alcohol pigmented with a dye that highlights defects that are difficult to detect with the naked eye (pores, microcracks, etc.).

Destructive control methods of roll on balls

The most common destructive control methods are performed:

- by sectioning the balls [81];
- by determining the mechanical properties [81, 87, 93].

The destructive control method by sectioning the balls allows a visual analysis of defects inside the balls. The most common defects detected by this control method are:

- excessive material flow inside the ball;
- discontinuities or cracks in the weld bead.

The mechanical properties testing method consists of applying a compressive force to the ball in two directions: equatorial and polar direction (see Figure 5.2).

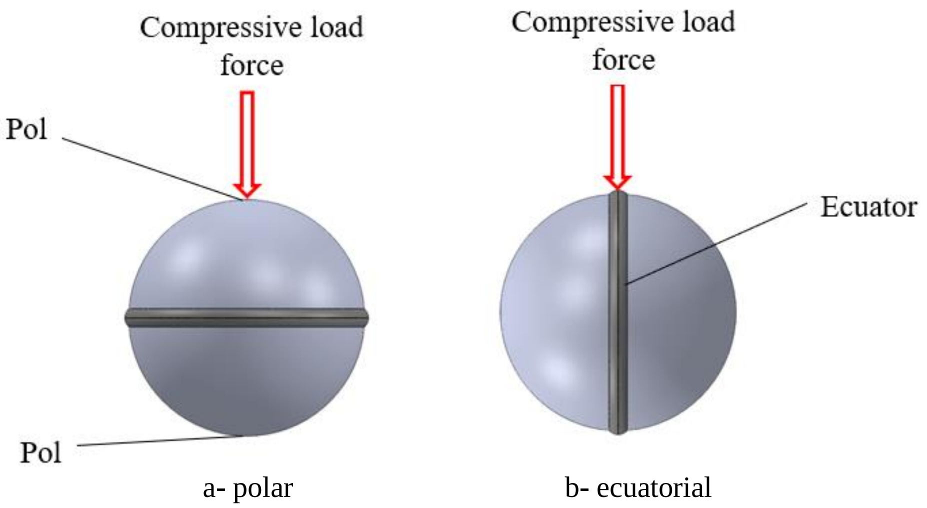
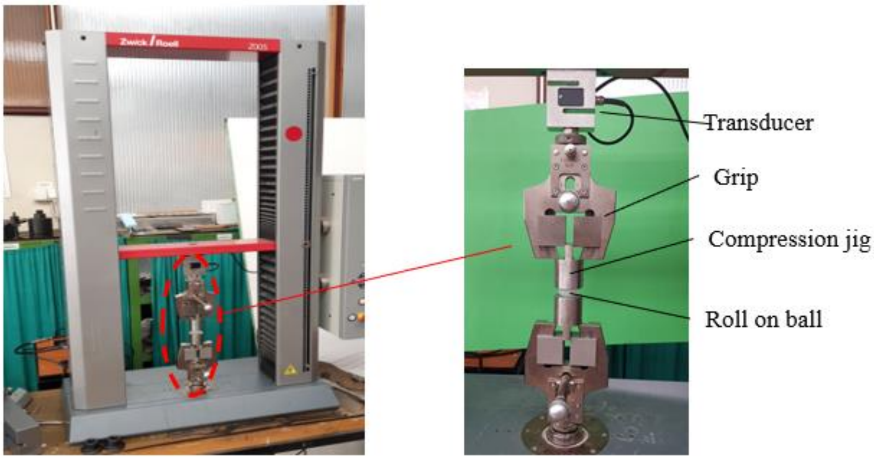


Figure 5.2. Compressive force application directions.

A Zwick /Roell measuring stand (Figure 5.4-a), equipped with a KAP-TC/ KI 0.05/ Fnr 06 6716/ 2.0 mV/V =5Kg transducer compression system, AST Germany Dresden brand, was used for the measurements (Figure 5.4-b).



a-overview b-detail: compression system with transducer

Figure 5.4. Zwick/Roell force and strain measurement stand.

Graphical representation of all compression curves obtained by using the Zwick/Roell software program is shown in Figure 5.20.

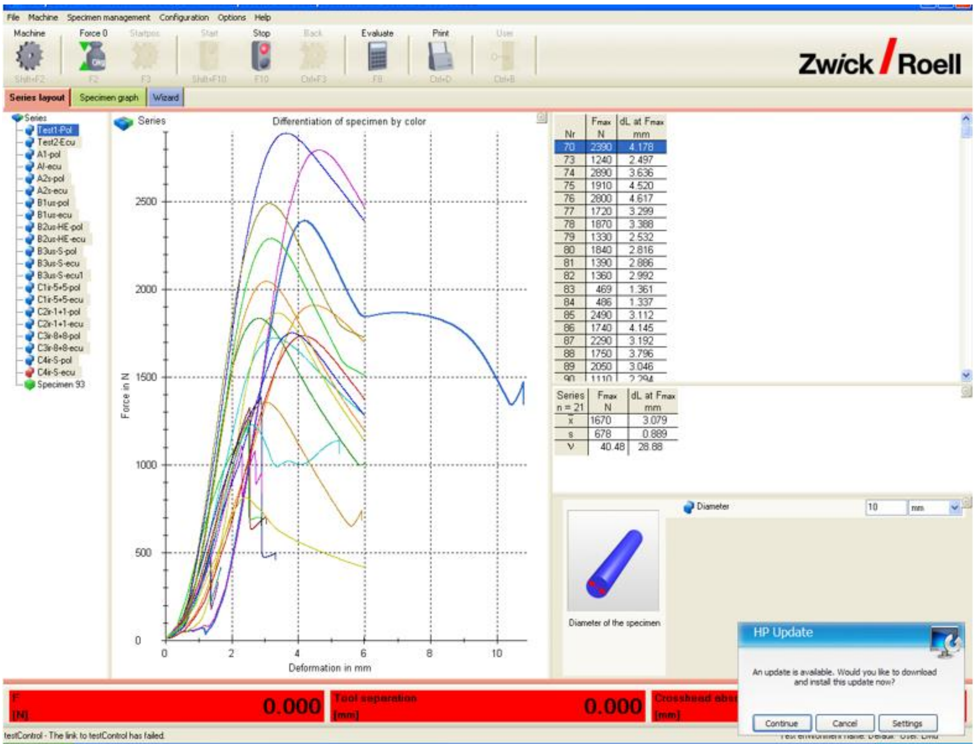


Figure 5.20. Graphical representation of compression curves (Force-Deformation) obtained by using the Zwick/Roell software program for all roll on ball manufacturing technologies.

In order to summarize the results from the measurements carried out for all the technologies studied, the average compressive forces were analyzed. The graph of the average compressive forces for all batches of roll on balls is shown in Figure 5.21.

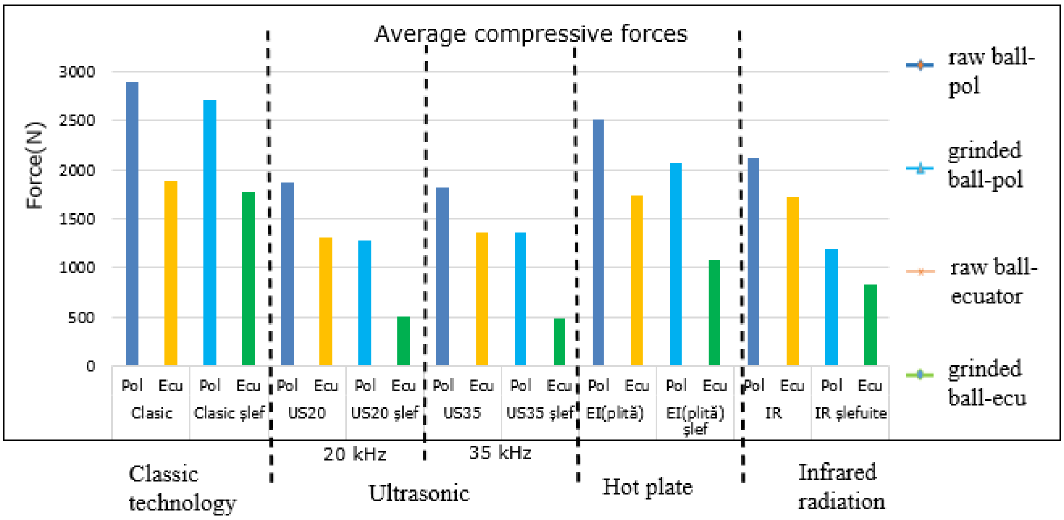


Figure 5.21. Average compressive forces for all batches of balls.

There is a very large variability in the values of the compressive forces depending on: the technology used, the direction of application of the compressive force and the grinding/calibration operation.

Comments and discussions

1. The highest compressive strength corresponds to the balls produced by the classical method, followed by the hot plate method. The lowest strength is measured for balls produced by ultrasonic welding at both 20 kHz and 35 kHz.
2. In all technologies, an anisotropic behaviour is seen in the compressive stress, by which the lowest compressive strength was measured in the equatorial direction in both raw (unpolished) and especially finished (polished/grinded) balls;
3. The lower compressive strength in the equatorial direction is primarily determined by the quality of the welds but also by the parameters of the polishing process.
4. The measurement of the compressive strength in the equatorial direction should be the basis for the quality control plan of the polished and raw/unpolished balls;
5. Currently there is no clear information that requires specific compressive strength values for roll on balls. The specifications imposed by cosmetics manufacturers generally require dimensional, functional and visual aesthetic aspects.
6. The fact that the mechanical strength has lower values does not automatically restrict alternative methods of manufacturing roll on balls;
7. Optimisation of current roll on polishing technology is necessary.

Following the quality determinations, the results obtained for each roll on ball manufacturing technology has been centralized (Table 5.10).

Table 5.10. Synthetic centraliser with the results obtained for each technology.

No	Indicator	Classic technology	Alternative technology				
			US	F	EI	IR	L
1	Cycle time (s)	16 -18	6-9	NE	10-12	13 - 15	NE
2	Material consumption/unit (g)	2,8	2,2	2,2	2,2	2,2	2,2
3	Weld quality	No welding	poor	poor	good	good	poor
4	Productivity ('000 balls/hour)	3-5	NE	NE	10 - 12	6-8	NE
5	Compressive force (N)	1766	494	NE	1075	831	NE
6	Process capability (Cpk) (Cpk>1)	0,56	4,47	NE	1,9	3,24	NE
7	Know how	high	low	low	low	low	low

Caption:
US - ultrasonic welding;
F - friction/spin welding;
EI - thermal welding with hot plate;
IR- infrared welding ;
L - laser welding ;
NE - not evaluated.

6. Configuration of a manufacturing line for roll on balls

After analyzing the results in Table 5.10, it is possible to identify the technologies that allow their transposition into large-scale production lines. Each evaluated parameter was assigned a score from 0 to 3 (0- not evaluated, 1- poor/low, 2- medium, 3- good). By summing up the scores of the evaluated indicators, a performance indicator was obtained for each individual technology. A *performance indicat*or expressed in *percentage* values, compared to the classical (current) technology, was also calculated.

The quantification of the welding processes in terms of the transposition in the roll ball manufacturing lines is presented in Table 6.1.

Table 6.1. Quantification of roll on balls welding technologies

No	Indicator	Classic technology	Alternative technology				
			US	F	EI	IR	L
1	Cycle time	1	3	0	2	1	0
2	Material consumption	1	3	3	3	3	3
3	Weld quality	3	1	1	2	2	1
4	Productivity	1	0	0	2	2	0
5	Compression force (N)	3	1	0	2	1	0
6	Process capability	2	3	0	3	3	0
7	Know how	3	1	1	1	1	1
Performance indicator (total score)		**14**	**12**	**5**	**15**	**13**	**5**
Performance indicator (%)		**100**	**85**	**36**	**107**	**93**	**36**
Estimated probability of using the technological process in a manufacturing line		**in use**	low	low	**high**	**medium**	small

Alternative welding manufacturing technologies for roll on balls considered suitable for large series production are:

- welding with a heating element;
- welding with infrared radiation.

The presented research shows that the heating element welding method is the most feasible alternative method for the large-scale production of roll on balls, followed by infrared radiation welding. The ultrasonic welding method has a high potential for implementation, but requires further research to improve the quality of welds and increase productivity.

Configuration of a manufacturing line for roll on balls by welding hemispheres with heating element

The experimental results obtained allow the configuration of an integrated system for the production and assembly of polypropylene roll on balls at a rate of about 100-150 welded parts/min. The schematic diagram of a high productivity manufacturing line, based on hemisphere welding with heating element, is shown in Figure 6.1 [67].

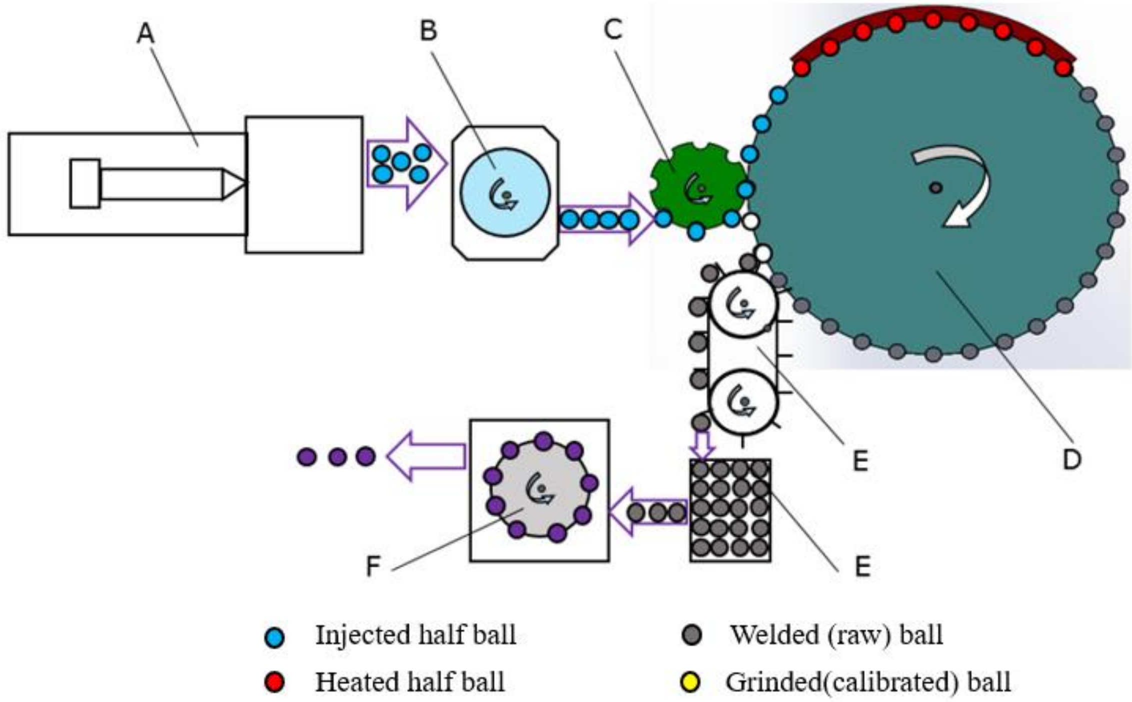


Figure 6.1: Schematic diagram of a high productivity manufacturing line for the production and assembly of roll on balls.

The manufacturing line consists of the following equipment:

A- polypropylene production system of the hemispheres
B- feeding and orienting system of the hemispheres
C- insertion unit of the hemispheres
D- roll on ball welding assembly equipment
E- welded ball evacuation system
F- roll on ball accumulation station
G- roll on ball polishing and calibration equipment

Design of cylindrical cam mechanisms

The equipment for assembling roll on balls by welding, shown in Figure 6.1-pos G, representing the inovative part of the thesis and contains two mechanisms with a cylindrical cam, in the version with fixed cams and synchronous rotating cam follower supports (Figure 6.10)[94, 95, 98]. The two fixed cylindrical cams are symmetrical cams (upper and lower). Permanent contact between the cam and the cam follower is ensured by means of the groove made in the cam (by shape). The technological working space of the carousel system is located between the synchronously rotating cam follower supports. Each cam follower is holding a vacuum-fixed hemisphere carrier from the hemisphere pick-up position to the discharge of the welded balls.

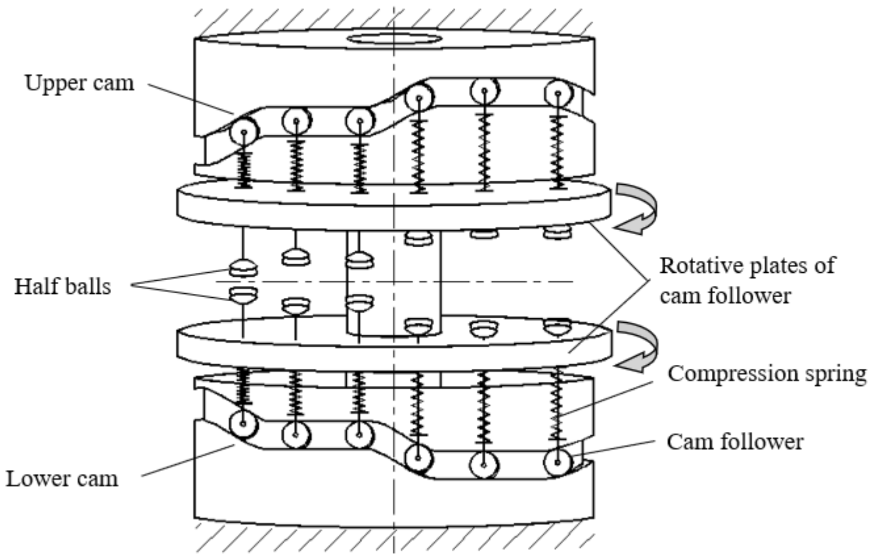


Figure 6.10. Kinematic scheme of a carousel system for assembling roll on balls.

In accordance with the technological process of welding roll on hemispheres, the general plane of motion of the upper cylindrical chamber mechanism can be defined as shown in Figure 6.11.

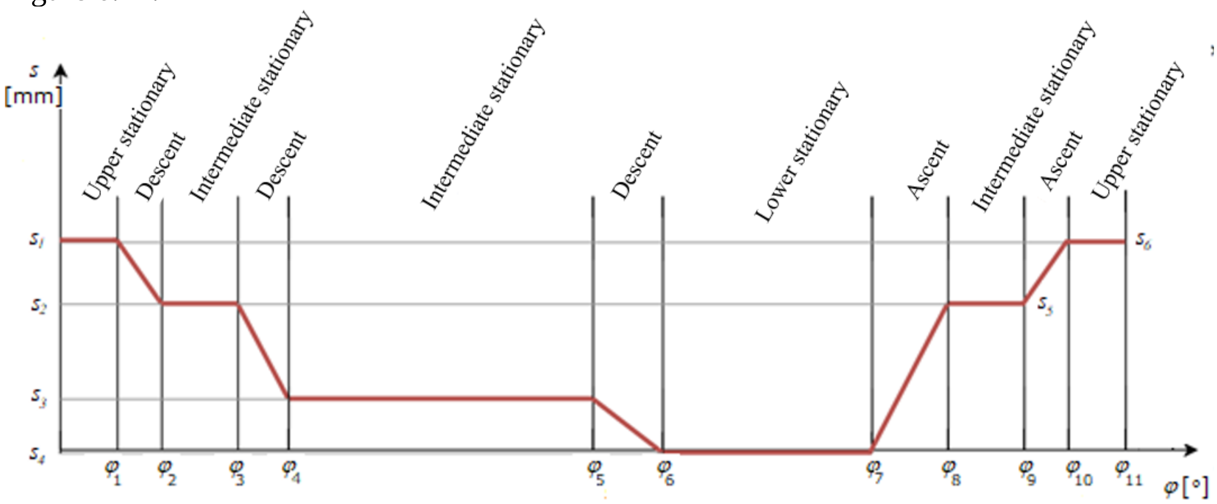


Figure 6.11. General motion plan of the cam follower for the upper cylindrical cam mechanism.

The laws of motion for the ascent and descent (see Figure 6.12) will be chosen based on adimensional characteristic values that satisfy the requirements of each technological phase [99, 100]. The laws of motion for the lower cylindrical cam mechanism will be determined analogously, these being mirrored with respect to the φ-axis.

Thus, for the avoidance of soft shocks, the sinusoidal motion law was chosen and it has the adimensional characteristic value of velocity $c_v=2$, but also the adimensional characteristic value of shock $c_j=39.5$ compared to the modified sinusoidal motion law with $c_j=69.5$ and also compared to the cosinusoidal motion law with $c_j=+\infty$, which produces soft shocks.

For the technological phase requiring high accelerations, the polynomial motion law 4-5-6-7 was chosen and it does not produce shocks and has the highest acceleration adimensional characteristic value $c_a=7.51$.

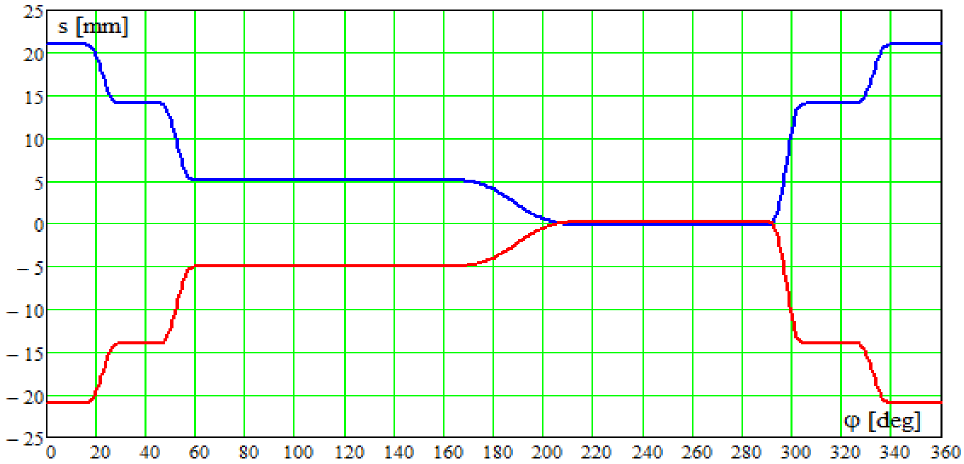


Figure 6.12. The law of motion of the cam follower for the upper and lower cylindrical cam mechanism.

Figure 6.13 shows the profiles of the cylindrical cams arranged in the appropriate positions required by the technological and constructional conditions. Between the theoretical profiles of the two cams, a technological distance of $l = 200$ mm and the radius of the cam rollers $r_R=15$ mm was imposed.

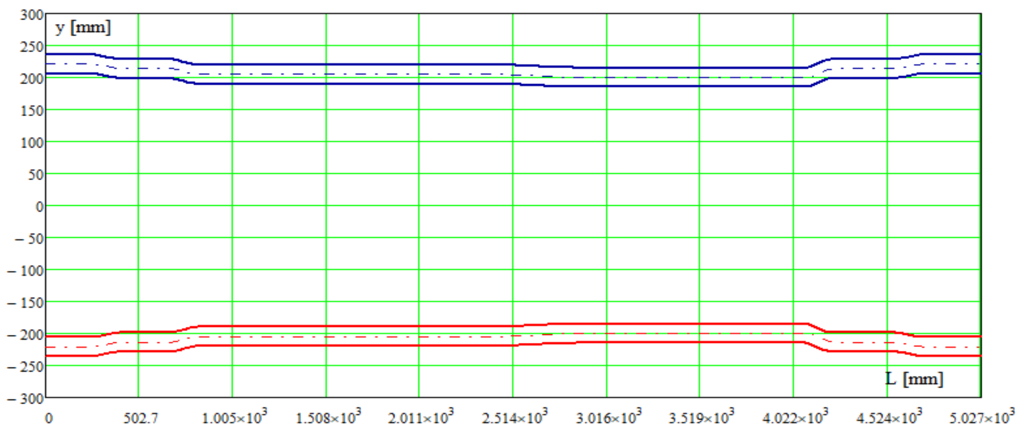


Figure 6.13. Theoretical and actual profiles of upper and lower cylindrical cams.

7. Final conclusions and future research directions

Final conclusions

The accelerated rise in raw material and energy prices, increasingly frequent climate change, the demands for transition to a Circular Economy and the competition in the consumer goods market require fast adaptation of manufacturing technologies. The cosmetics industry also subscribes to the same trend and the research in this thesis aims to respond to these challenges.

The research has identified alternative methods and technologies to reduce raw material and energy consumption in the production of components in the cosmetics industry, generically referred to as roll on balls.

The choice of polymeric materials was made taking into account the recyclability aspects of both the roll on balls and the other components that make up the end consumer product.

Comparative researches of the welding technologies of the components made of polymeric materials were carried out, with experiments and multiple qualitative measurements of dimensions, mechanical resistance and visual appearance being carried out. From the research carried out, several technologies were selected that can ensure significant increases in productivity in the case of the manufacture of roll on balls (Table 7.1).

Table 7.1. Final quantification of roll on ball welding technologies.

Indicator	**Clasic technology**	**Alternative Technology**				
		US	**F**	**EI**	**IR**	**L**
Performance indicator (%)	100	85	36	107	93	36
Estimated probability of using the technological process in a manufacturing line	**in use**	low	low	**high**	**medium**	low

The alternative technologies that can be the basis of some roll on ball manufacturing lines are welding with a hot plate and welding with infrared radiation.

The exploitation of the results of this research can provide the basis for the design of a flexible high-productivity manufacturing line for roll on balls.

The research results can also be used in the production of thin-walled spherical objects in various industries (automotive, toys, leasure articles, medical implants, environmental protection, etc.). When it comes to producing hollow polimeric balls that do not require the polishing phase, the viability of these alternative technologies becomes even greater, including ultrasonic welding.

Future research directions

The exploitation of the research results presented in the PhD thesis provides a solid platform for defining future research directions:

- Optimisation of ultrasonic welding technology;
- Optimisation of the roll on ball polishing/calibration technological process;
- Standardisation of technical specifications, testing and acceptance procedures of roll on balls;
- Design and implementation of a high productivity roll on ball manufacturing line;
- Identification of similar spherical, thin-walled products that can be manufactured by the alternative methods studied;
- Testing alternative materials used in the production of roll on balls that meet the requirements of Sustainability and the transition to the Circular Economy.

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