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Influence of the polymeric materials on product's technological level - practical case of appliances industry

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Abstract

Modern products are heavily influenced by new, advanced materials in terms of enhanced existing or introduction of new product features. The technological level of new products, which is also the case for modern appliances, has to be closely correlated with their product features and applied polymeric materials. A practical case has been presented of how the main appliance features could be correlated or linked to the basic polymeric material properties as well as the way materials with or without processing technology could raise the product technological level. The main focus is placed on the practical case – a washing machine and its plastic tub, which is made of polypropylene composite. The plastic tub, namely, is a very vital component for the washing machine and during the product life-cycle exposed to complex thermo-mechanical loads. For the various commercially available PP composites with the same filler type, but different morphological structure of the basic material, benchmarking on the component's durability (creep and/or relaxation) has been conducted. Based on the experimental results, some practical comments have been given on the washing machine end-properties (e.g. vibro-acoustic damping).

KEY WORDS:
appliances
polypropylene composite
product development
product features
technological level
washing machines

KLJUČNE RIJEČI:
kućanski aparati
perilice rublja
polipropilenski kompoziti
razvoj proizvoda
svojstva proizvoda
tehnička razina

Utjecaj polimernih materijala na tehničku razinu proizvoda - praktičan primjer industrije kućanskih aparata

Sažetak

Za suvremene proizvode upotrebljavaju se materijali poboljšanih ili potpuno novih karakteristika. Tehnička razina novog proizvoda, npr. suvremenoga kućanskog aparata, mora povezati njegova proizvodna i uporabna svojstva. Opisan je praktičan primjer kako se mogu glavne karakteristike kućanskih aparata korelirati ili povezati s osnovnim svojstvima polimernih materijala. Isto tako prikazano je kako materijali promjenom proizvodnih svojstava ili bez njih mogu povisiti tehničku razinu proizvoda. Tekst je usredotočen na praktično rješenje - perilicu rublja i kućište perilice rublja koja je napravljena od polipropilenskoga kompozita. Naime, kućište je veoma vitalna komponenta perilice rublja i tijekom životnog vijeka proizvoda izloženo je kompleksnim termo-mehaničkim opterećenjima. Za različite, komercijalno raspoložive PP kompozite s istim tipom punila, ali s različitom morfološkom strukturom osnovnog materijala, uspoređeni su proizvodi na osnovi izdržljivosti komponente (puzanje i/ili relaksacija). Na osnovi eksperimentalnih rezultata predstavljeni su praktični komentari o uporabnim svojstvima perilice rublja (npr. vibroakustično prigušivanje).

Introduction

Over the last few decades product competitiveness on the market has been more severe due to the globalization and rapid technology development. The idea of wide mass production as a competitive advantage is not a guarantee for success any more - not even for economic survival. Every product could be divided into the pure technical and non-technical component – e.g. likable part as a consequence of industrial design (Figure 1a) which contributes to the product's success.[1] There are many other factors which influence market success (e.g. establishment of company's brand) and that can please even the most demanding – so-called high-end customers.[2] Considering technical products, technical functionality features prevail as foundation for quality and reliability component to gain customer's satisfaction and confidence. It is well known that desired (technical) functionality could be achieved with the material, related processing technology and geometry.[3]

Valid technical features for product benchmarking on the market are mostly agreed upon internationally acknowledged standards and guidelines, which are issued by independent (engineering) organization (e.g. *ISO*, *ASTM*, *UL*) or branch product associations. In case of household appliances these technical features are listed on the so-called energy label. This is an obligatory product declaration label on the market, with the values determined by association of household appliance producers (*CECED*). For the washing machine, besides energy and water consumption, the maximum number of revolutions of the drum in the washing machine tub is also stated. According to the law of quality of washing performance (so-called Sinner's cycle) – it is one of the most important technical issues.[4]

The vital structural part of the washing machine is the tub, which, besides thermal loading, also has to withstand very heavy mechanical loading, both static and dynamic one. As in case of any other technical product, the technical functionality of the tub in terms of revolution of washing machine drum and its loading could be achieved with applied (polymeric) material, processing technology and geometry (Figure 1b).

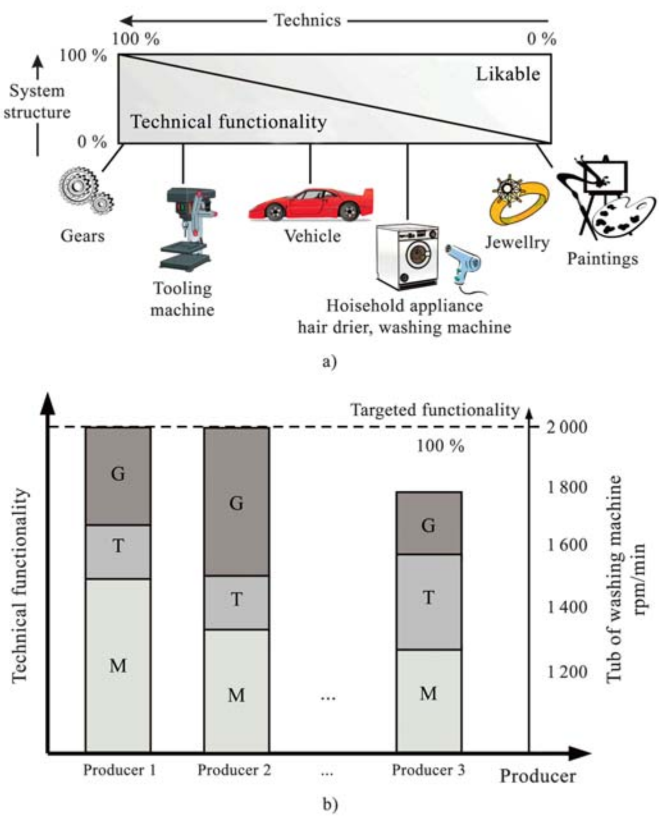

FIGURE 1 – Products and relevant technical features - Material (M), Technology (T), Geometry (G); a – product and issue of market success;[1] b – tub of washing machine and influence on functionality

Nowadays, most tubs are made of polymeric material with commercial declaration (PP + 40% of $CaCO_3$). But despite the same laundry loading, these washing machines have different technical capabilities - revolutions of the drum.

A product designer encounters many open issues. The most important among them are:

– what is the share of contribution to the final technical feature by (polymeric) material, processing technology and geometry,
– could polymer structural properties be correlated with the end product features,
– how and to what extent could contribution of polymeric material properties to the final technical feature be maximized,
– how could quality assurance of polymer product properties within the product service life be evaluated.

Appliance industry and polymer product design

Polymeric product design follows many existing standards and guidelines for product design procedures. The substantial difference and particularity in comparison to other materials is due to the time-dependency of polymeric material properties. Another issue is also great influence of structural morphology properties on polymer material properties and consequently on polymer product features.[5,6] Very important correlation of material morphology and mechanical properties was already proven[7,8] and even integrated as possible quality control tool in industrial environment[9.10] This correlation could be presented in a flow-chart diagram, modified for polymer tub and washing machine functionalities (Figure 2)[9].

It is very obvious that final polymer product properties are therefore largely dependant on the *temperature-pressure* processing conditions. It is possible to write down these relations in a mathematical form using the Knauss-Emri algorithm. With other analytical tools it is also possible to directly and qualitatively relate mechanical spectra (retardation/relaxation) to the molecular mass distribution, which define the *starting kinetics molecular organization*. Based on these facts, for the needs of daily engineering work a procedure of interconversion is enabled, which calculates the material functions and mechanical spectrum, obtained experimentally.[6,7]

Applicability is even more acknowledged if we are aware that for full characterization of polymeric material and reliable determination of stress-strain properties it takes as many as 21 material functions from 12 independent material tests. Limited only to the field of linear viscoelasticity and linear stress-strain relations, we would need only 4 independent measurements or, with respect to constitutive equations, we would theoretically need only 2 measurements.[11,12] In order to eliminate thermo-mechanical history of polymeric material (processing influence, crystallinity and curing, service temperature) and to get only material characteristics, we have to conduct annealing of polymer material above the melting temperature of the chosen polymer and then controlled cooling is performed to the equilibrium phase. The annealing phenomenon is a well known procedure from thermal plastic identification tests [e.g. Differential Scanning Calorimetry (DSC), Dynamic Mechanical Analysis (DMA)].[13]

In case of the polymer tub in the washing machine, due to constant load by the upper and lower counterweights the polymer tub is exposed to the creep phenomena (Figure 3a).[14] This structural polymer element is permanently exposed to the influence of the upper counterweight, which

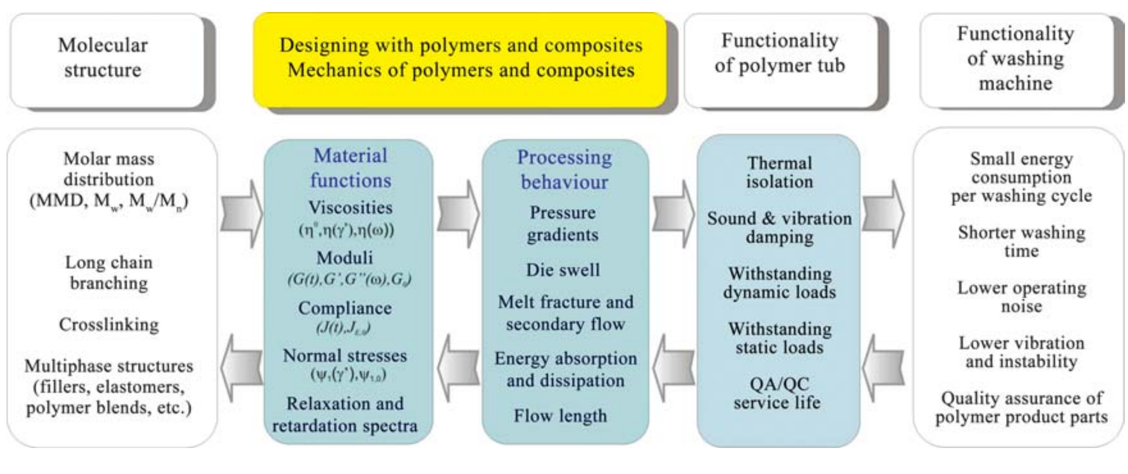

FIGURE 2 – Correlation of polymer morphology with relevant product technical features[9]

is fastened to upper pins (Figure 3b) and to the weight of the metal drum, which is fixed in the bearing of the polymer tub (Figure 3c).

Occasional thermo-mechanical dynamic loading during the washing cycle contributes to the structural creep phenomenon, which produces certain eccentricity – e (Figure 3c), which then produces excessive vibrations even resulting in the system break-down.[15,16]

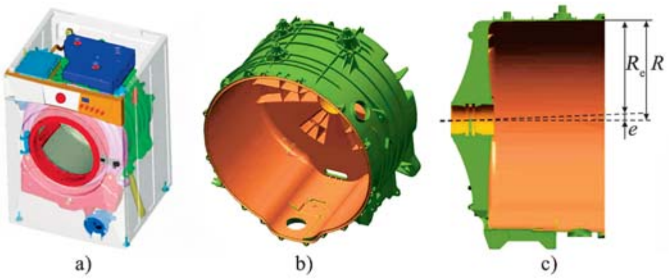

FIGURE 3 – Washing machine with polymer tub and eccentricity due to the creep:[14] a – washing machine; b – polymer tub; c – eccentricity of polymer tub

Therefore, there is a need to evaluate the change of the product dimension due to permanent and occasional thermo-mechanical loading during the service life. The durability of such product is influenced by basic polymeric material and processing conditions, which could be easily determined and evaluated.[13,17]

Before the corrections and enhancement take place, the product reference values should be available. Every product has two main groups of features – primary (e.g. washing machine – washing clothes) and secondary (e.g. washing machine noise), which have to be technically properly evaluated. With respect to the customer protection and principles of sustainable development, for most of the (white goods) products and even houses or cars energy label has been introduced in the EU.[18,19]

In our case, the energy label for the washing machine (Figure 4a) is presented with primary features – e.g. washing performance and secondary features – e.g. energy efficiency (Figure 4b).[3]

The features are rated either by efficiency classes - from G (the worst) to A (the best) or by exact values (e.g. noise, water consumption). In the case of the washing machine, a polymer product designer has to be aware of the following polymeric material features – attributes (Figure 4c):

– mechanical – tensile modulus, Izod impact strength;
– physical – density, mould flow index, shrinkage;
– thermal – Deflection Temperature Under Load (DTUL), specific heat capacity.

An average contemporary washing machine, namely, consumes about 50% less energy and 65% less water than the average machine of 1985, improvements being largely driven by new materials as well as labelling.[4]

The most cost-effective solution for polymeric product enhancement is with geometry (shape) unchanged, due to high mould costs. Enhancement of material features closely related to polymer material processing features is consequently desired.

Polymeric materials and product enhancements

The main focus will be on polypropylene (PP), which was first produced commercially in 1958 and is very similar to polyethylene (PE), and now produced in very large quantities (41 million tonnes in 2009).[19] In white goods industry, it has gained popularity as a low-cost material with very good chemical resistance (fresh and salt water and most aqueous solutions).

Some of the existing polymer properties (e.g. calcium carbonates improves toughness, stiffness, extrusion behaviour) could be enhanced with various additives and functional fillers, or even added (e.g. metallic look). Polymer materials are therefore very often labelled as multifunctional, with different properties which can be custom adjusted or tailored according to the (design) demand.[21] In the past 15 years, the washing tub has been produced with PP composites with various fillers and additives instead of the metal (stainless steel).

Qualifying a new plastic material as a recognized component has to comply with various international standards (tests) defined by the *UL* or other associations (e.g. *ASTM*, *ISO*) - *UL 94 - Flammability* (HB and V rating), *UL 746A - Short Term Properties*, *UL 746B - Long Term Heat Ageing* ,*UL 746C - Use in Electrical Equipment Evaluations*. Besides, there are also standards for a specific case of application – e.g. washing machines.[10,21,22]

The heat insulation of the washing machine polymer tub is very important, since 50% of energy in the regular washing machine is consumed by the water heater. The comparison of heat insulation for metals and polymers shows that polymer materials have around 50 times higher value than

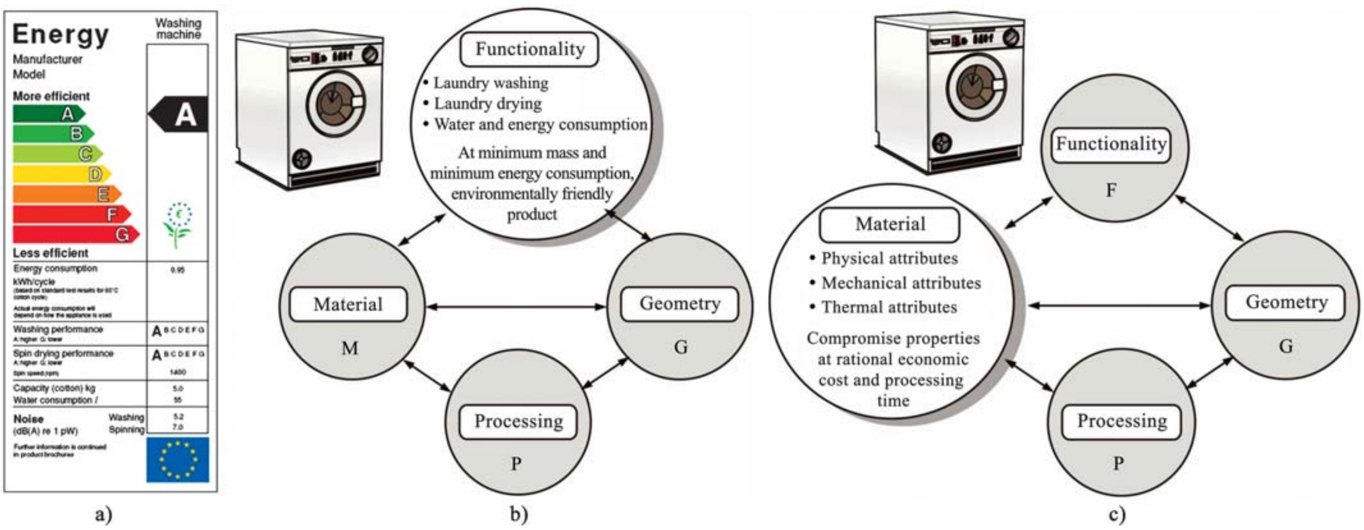

FIGURE 4 – Product functionality and polymer material properties – the case of a washing machine:[3] a – energy label; b – primary functionality (features); c – material and product functionality

metals. Higher heat insulation means less heat energy for the washing cycle and therefore shorter washing time.

There is an evident enhancement of overall material and processing properties with micro and nanofillers, which are no more exception in commodity products. Besides cost reduction (e.g. less material, lighter products), the processing time is cut almost in half by using the same mould as for *traditional* composites.[21,24]

In industrial environment, it is well known that polymeric materials are time-dependent, which has even been included in recent industrial guidelines for polymer products design. This includes time-temperature relations and description of the creep/relaxation phenomenon as well as polymer damping properties, which are dependent on the frequency and temperature.[25,26]

Because polymeric materials are time-dependent, the durability issue is very important. Practical case of durability as safety issue is the polymer tub, which is exposed to the cyclic and complex thermo-mechanical stress during the life cycle. In the most extreme case, this could lead to polymer product geometry deformation and the breakdown (Figure 3c and Figure 5).[10,23]

Polymer washing tub for the vertical axis washing machine (top loader) is presented in Figure 5, but this issue has the same effect and importance for the horizontal axis washing machines (front loader)

After long-term service under regular thermo-mechanical loading the rear part of the polypropylene composite tub could be so deformed (Figure 5b) that the metal drum would (rub or scrub) at the front tub walls. Such deformation is a time-dependent process and the limit is the initial gap between the metal drum and the polymer tub (Figure 5a).

Time-dependence of polymeric materials is evaluated with the already standardized material testing (*ISO 899* (2003)) and various polymeric materials could be compared to each other under specified conditions (e.g. pre-treatment, temperature and humidity).

Enhancement of the polymer washing tub properties with given geometry, as in any other polymeric product, can be achieved by improved material properties and additionally after the processing. It is known that thermo-mechanical history (e.g. processing) could be completely eliminated from the material by annealing.[13]

In this case, we are evaluating time-dependent properties (creep) of polymer composite (PP + 40% $CaCO_3$) – enhanced with the processing technology (Figure 6a) and without enhancement with the processing technology (Figure 5b).

The difference for non-annealed samples (*material+processing technology*) and an annealed sample (*only polymer material(composite)*) are presented in graphs (Figure 6)[27] as master compliance (creep) curves (J - creep) in logarithmic values.

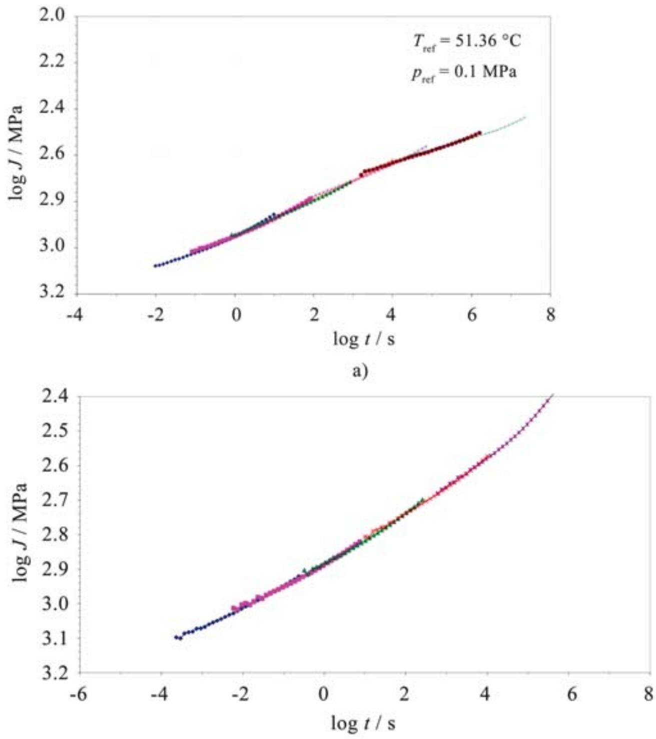

FIGURE 6 – Creep (compliance) master curves – non-annealed and annealed polymer material: a – compliance master curve – non-annealed; b - compliance master curve – annealed

When master curves are designed, the comparison (benchmarking) criteria are:

– level of initial (glassy) creep compliance or even (equilibrium) creep compliance;
– creep time stability ("slope of creep curve") at given time interval;
– temperature stability of creep properties at given time and given temperatures.

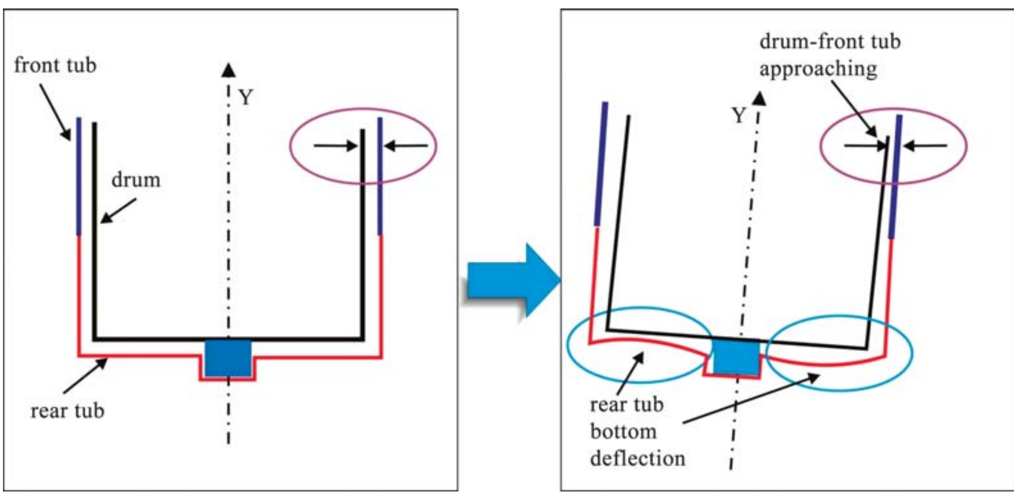

FIGURE 5 – Polymer washing tub and durability issue in its lifetime[10,22]

Other evaluation criteria could be obtained with the interconversion (e.g. relaxation, damping properties), but this could be done only in the linear viscoelasticity range. In the industrial environment, polymer product testing measurement system also has to be made in order to simulate the real conditions. Such testing or measurement systems are unfortunately rare and very unreliable, because it is very difficult to get reliable data from approximate (simulated) testing conditions.[6,28]

Conclusion

Proper polymer product design procedure undoubtedly requires time-dependent properties characterization, which implies direct or indirect determination of basic material properties and modification of these material properties by processing technology. These data are fundamental for further polymer product features (e.g. dimensional stability, static and dynamic mechanical properties) as well as for the accelerated, physical ageing procedure. All these data have to be correlated with the technical features valid for product benchmarking in order to achieve market competitive advantage.

The proposed procedure also offers the possibility of evaluating the rate of contribution for all three major factors - basic polymer material properties, processing technology and product geometry to the final product feature.

The theoretical background has been proven in the practical example of polymer tub in the washing machine. Basic polymer material and samples from the product (polymer tub) as results of processing technology have been tested with the creep test, whereas other properties were calculated with the mathematical tool – interconversion.

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