Towards a durability test for washing-machines

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Abstract

Durability plays a key role in enhancing resource conservation and contributing to waste minimization. The washing-machine product group represents a relevant case study for the development of a durability test and as a potential trigger to systematically address durability in the design of products. We developed a procedure to test the durability performance of washing-machines as a main objective of this research. The research method consisted of an analysis of available durability standards and procedures to test products and components, followed by an analysis of relevant references related to frequent failures. Finally, we defined the criteria and the conditions for a repeatable, relatively fast and relevant endurance test. The durability test considered the whole product tested under conditions of stress. A series of spinning cycles with fixed imbalanced loads was run on two washing-machines to observe failures and performance changes during the test. Even though no hard failures occurred, results clearly showed that not all washing-machines can sustain such a test without abrasion or performance deterioration. However, the attempt to reproduce the stress induced on a washing-machine by carrying out a high number of pure spinning cycles with fixed loads did not allow equal testing conditions: the actions of the control procedure regarding imbalanced loads differ from machine to machine. The outcomes of this research can be used as grounds to develop standardised durability tests and to, hence, contribute to the development of future product policy measures.

Keywords:
Sustainable resources
Durability
Material efficiency
Washing-machine
Ecodesign

1. Introduction

The durability of products has the potential to play a key role in enhancing resource conservation. Product durability is among the main product design strategies used to address material efficiency (Allwood and Cullen, 2012; Ghisellini et al., 2015). Ardente and Mathieux (2014) proved through a life-cycle based approach that environmental benefits can be gained by extending the lifespan of washing-machines (WMs), even when this delays a replacement with a more energy-efficient product. Similar conclusions were also drawn for other product groups: vacuum cleaners (Bobba et al., 2016), dishwashers (Tecchio et al., 2016b), refrigerators (Bakker et al., 2014; Ricardo-AEA, 2015), ovens (Ricardo-AEA, 2015), notebooks (Bakker et al., 2014; Prakash et al., 2012) and desktop computers (Prakash et al., 2016b). Durable products also allow the reduction of the consumption of raw materials and contribute to waste minimization (European Commission, 2008; European Union, 2008).

However, the first useful service life of most electrical and electronic appliances has decreased over the last few years (from 14.1 years in 2004 to 13.0 years in 2012/13 for large household appliances), and an increasing share of appliances are replaced or disposed of before they reach their average first useful service life or an age of five years (an increase from 7 to 13% in the same period; Prakash et al., 2016a). The decline of the average service life of electric and electronic products results in detrimental environmental consequences (Bakker et al., 2014). While the Raw Materials Initiative (European Commission, 2008) calls in its third pillar for a boost of resource efficiency in the EU industry, the Strategic Implementation Plan of the European Innovation Partnership on raw materials (EIP, 2013) highlights the need for work on product life extension strategies. Such an overall objective could be tackled in several ways, for example, by considering requirements on durability under the Ecodesign Directive (European Union, 2009), and durability information in future Energy Labelling measures, as stated in the EU action plan for the Circular Economy (European Commission, 2015a). European Standardisation Organisations were requested to draft new European standards and European standardisation deliverables on material efficiency aspects for energy-related products (European Commission, 2015b) in support of implementation of the Ecodesign Directive (European Union, 2009).

Tecchio et al. (2017) have already identified two product groups, i.e. electronic displays and WMxs, with specific standardisation needs. The former product group was addressed by Vanegas et al. (2017), who...
developed a methodology to assess the ease of disassembly. In the present article, the authors focused on the WM product group, as there are opportunities to implement durability-related requirements within the framework of the Ecodesign Directive (Tecchio et al., 2017).

The article introduces a test to assess the durability performance of WM, which was applied to two case study machines. The durability test regards the whole product and not a specific component, and was based on the spinning function under specific stress conditions, since this represents the main source of mechanical stress for this product.

Experiments were run addressing three main issues: 1) to verify whether WMs currently on the market can sustain such a series of stress without any hard failure, 2) to define procedure parameters and to evaluate the degradation of a WM performance over time, and 3) to identify strengths and weaknesses of the proposed durability test to define guidelines for potentially standardised procedures.

Starting from a literature review focused on durability tests and dynamics of horizontal axis WMs (Section 2), the proposed method is introduced in chapter 3 and results are presented in Section 4, with two WM case studies. Finally, Section 5 is devoted to the discussion of the proposed durability test, with final remarks, opportunities and drawbacks.

2. Scientific background

2.1. Life-cycle perspective and obsolescence

Testing the durability of an energy-using product, as a whole, should enhance an appropriate service life, which is essential to meet user expectations and to maximise resource efficiency. Regarding the overall life cycle of a WM, the use phase can be considered the most important contributor to environmental impacts, such as cumulative energy demand (80%), (Rüdenauer et al., 2005) and global warming potential (84%), while impact categories dependent on resource depletion (i.e. abiotic depletion of elements) are affected mainly by the production phase, which includes the impact of the extraction and refining of materials, manufacturing and packaging (Tecchio et al., 2016a). Nonetheless, the improvements of the efficiency of products during the use phase generally imply a relative shift of environmental impacts towards the production phase, due, for example, to the higher amount and complexity of electronic components (Rüdenauer et al., 2005). Tecchio et al. (2016a) demonstrated in a recent work that increased durability of WMs is beneficial for a number of environmental impact categories (such as Global Warming Potential and Abiotic Depletion Potential). The work considered a lifetime extension, thanks to durability, of up to six years, delaying the purchase of a more efficient appliance. Therefore, durability plays a key role in enhancing conservation of resources used during the production phase.

According to Prakash et al. (2016a), more than 10% of the WMs disposed of at municipal collection points or recycling centres in 2013 were just five years old or less, much lower than the expected average lifetime estimated at 12.5 years (Boyano Larriba et al., 2017). Several reasons can be adduced for this tendency, such as technology innovations, legislation changes, consumer choices, market trends and obsolescence. The fast wearing out of certain components and materials used in products is generally referred as obsolescence, and it may be due to the design of cheap products (without a focus on long-lasting performance) or a practice to limit the useful lifetime of products (European Commission, 2015a).

Several forms of obsolescence can be listed in the first group, such as the lack of quality of a component or material, psychological obsolescence induced by a desire for new trends, designs and lifestyles (Cooper, 2004 Maitre-Ekern and Dalhammar, 2016; Packard, 1960), or even economic obsolescence, when it is not an economic choice for the user to repair a product (Cooper, 2004), and are factors which cause an appliance (and other products) to be discarded and/or replaced by a new product. The functional obsolescence induced by innovations can also be a form of obsolescence: software updates may slow or limit the performance of older models, or even create incompatibilities of technological products with new models (Dalhammar et al., 2014). The work carried out by Tecchio et al. (2016a) also highlighted that the durability of products (specifically WMs and dishwashers) may be hampered by the lack of software updates and availability of software for diagnosis. Without such software, reparable of products is limited, as it becomes impossible to detect the failure mode or to test the device after repair, or simply because the failure code cannot be deleted.

In the second group, the so-called planned obsolescence, a concept already addressed by Bodenstein and Leuer (1981), we refer to the intentional shorter product lifespan, by which manufacturers may benefit directly (Bakker et al., 2014). Examples of intentional obsolescence are, for instance, the deliberate planning and design of obsolescence in products and their intentionally limited reparability. The former strategy is used to make products fail before the ‘normal’ end of life due to the use of cheaper and less durable materials. The latter strategy restricts the availability of spare parts or stops their production after the expiration of the legal guarantee; as such, this creates incompatibilities with similar parts of more recent models and prevents disassembly (Maitre-Ekern and Dalhammar, 2016).

Although there are many public discussions about planned obsolescence, there is no proof from the data available to support this hypothesis (Prakash et al., 2016a). However, different legislative approaches are currently used to provide incentives for design of durability and reparability at the EU and Member State levels. The EU started to regulate durability through the Ecodesign Directive (European Union, 2009), while Member States made use of other legal approaches, such as longer consumer warranties, the criminalization of planned obsolescence and measures to incentivize the availability of spare parts. Against the background of the technological development and innovations in electrical and electronic appliances, requirements pertaining to product lifespans and standardisation build the core of the strategies against obsolescence (Prakash et al., 2016a). On the other hand, product lifespan should be adequately linked to the technological progress and must not result in an excessive increase of energy consumption in the usage phase if newer products have significantly better energy performance (Bundgaard et al., 2015). Durability testing should, therefore, minimize the disposal of appliances because of obsolescence. As lifetime expectancy tests are often long-lasting and unfeasible, durability performance can be assessed through accelerated tests.

2.2. Durability tests at the product level

An example of an EU Regulation that establishes durability requirements is represented by the Commission Regulation (EU) No 666/2013 (European Union, 2013), which sets thresholds for vacuum cleaner components, especially the durability of the hose and the minimum operational lifetime of the motor. Such a regulation for WMs does not yet exist. However, quite a few standards related to product safety are available (IEC 60335-1, 2010; IEC 60335-2-7, 2012) and address specific components, such as interlocks, braking mechanisms, doors, switches and cables. However, manufacturers use these standards to test the appliance safety under extreme conditions to ensure consumers’ safety either during the functioning of the appliance or in case of incident.

A detailed analysis of WM failure modes was carried out by some of the authors, who analysed and categorized thousands of repair services to understand possible failure modes and the relevance of tests at the product level instead of the components level (Tecchio et al., 2016a). Most recurring failure modes involved the electronics (14%, including control electronics, control panels, programme selectors, relays and line filters), shock absorbers and bearings (13.8%), doors (11.5%, including seals, handles, hinges and locks) and carbon brushes (9.7%). Tecchio et al. (2016a) reported many unrepaired bearing failures in their
statistics (44.2% of the cases), observed mainly in WMs with plastic tubs where bearings are sealed to the tub. A failure in this component may require the replacement of the part of the tub in which the bearings are contained, or even the whole washing unit (drum, tub, bearings) if the tub consists of one single plastic part. These repair actions usually cost 60–100% of the WM’s original price, influencing the choice of the user when it comes to repairing or replacing the appliance. Another analysis, conducted through different sources of information (consumer reports, consumer organisation test reports on life tests, service reports, manufacturer feedback) revealed that the spinning operation is a main source of stress for the whole machine and many failures are associated with the tub/drum system (Prakash et al., 2016a).

On the one hand, these statistics highlighted that even though some failure modes occur with higher frequency, drawing durability requirements from specific components can be ineffective for two main reasons; firstly, because a component outside the context of the machine is not subject to the same type of stress and, secondly, because a significant percentage of failures (25%) include more than one failing component (Tecchio et al., 2016a). A specific investigation of the lifetime of residential WMs, limited to the German area, has also shown a clear correlation of the actual lifetime achieved with the frequency of use, supporting the assumption that the actual operation of the appliance is the major factor which limits its useful life (Hennies and Stamminger, 2016).

### 2.3. Dynamic behaviour of a horizontal axis WM

We provide a dedicated section on the general construction and dynamic behaviour of a horizontal axis WM to understand the reasons for the high mechanical stress to which a WM is subject. Horizontal axis WMs can be seen physically as a vibrating system where the tub (including the drum) is fixed with two (or three, in some cases) springs on the top of the housing. As such, the system may be described in a simplified way by the physical formulas of a free oscillation. This oscillator is energized by the movement of the drum, which rotates with an angular velocity ω. Considering r as the radius of the drum and g as the gravitation acceleration, any kind of laundry will stick to the inner wall of the drum when the condition of Eq. (1) is verified.

\[
\omega > \sqrt{g \over r}
\]

(1)

This will be the case for ω of about 60–70 rpm, for the usual dimensions of household WMs. Some unbalancing may occur because the laundry may not be distributed evenly on the wall of the drum. For simplification purposes, it is assumed that the imbalance can be simulated by only one single mass element \( m_0 \) (as in Boyraz and Gündüz, 2013). The force of the movement of the oscillator now depends on the mass \( m_0 \) of the imbalance which is rotating and will cause the total drum to displace. Such kind of forced oscillation is well-known due to its resonance behaviour. At the resonance frequency \( \omega_R \), defined in Eq. (2), where \( K \) is the spring constant and \( m \) is the total mass of tub and drum, this would lead to an infinite amplitude.

\[
\omega_R = \sqrt{K \over m}
\]

(2)

This frequency is typically between 150 and 600 rpm for horizontal axis WM designs, thus, between the frequency for washing (about 50 rpm) and spinning (1000 rpm and more). Additional dampers are installed to introduce a damping of the movement of the tub to limit the amplitude to that which can be afforded by the space between the tub and housing of the machine.

This kind of system is well-known in physics as forced oscillation with damping, and can be described in the one-dimensional case by a simple differential Eq. (3), where \( F_0 \) is the oscillating force and \( c \) the damping factor.

\[
m {d^2x \over dt^2} = F_0 \sin \omega t - c {dx \over dt} - Kx
\]

(3)

Isolation techniques are applied to reduce the undesirable effects of vibration. The vibration isolation system can be active or passive depending on whether the external power is required for the isolator to perform its function or not. A passive isolator consists of a resilient member (stiffener or spring) and an energy dissipater (dampener). Examples of passive isolators include metal springs, cork, felt, pneumatic springs and elastomer (rubber) springs. An active isolator is composed of a servomechanism with a sensor, signal processor and an actuator.

The system kinematics of WMs has been studied by scientists (Bae et al., 2002; Chen et al., 2015; Conrad and Soedel, 1995; Nygård and Berbyuk, 2012; Türkay et al., 1995) and even more by industry to find the ideal compromise between the imbalance occurring during the spinning of the load, spring dimensioning, damper characteristics and the gravimetric weight of the whole oscillating system. The lower the maximum imbalanced mass expected, the less the gravity mass of the whole ‘swinging’ system needs to be or the lower the space between tub and housing must be.

The lifetime of relevant parts of a WM are also affected heavily by the imbalanced mass, as this is induced as vibration to all parts, especially to those in the oscillation group. This explains why it is so important to know and restrict the imbalanced mass strictly in relation to the design of the structure and components used to avoid lifetime failures.

### 2.4. Measurement imbalance and strategies to influence the imbalance

A load imbalance may represent the easiest way to introduce a mechanically stressed condition during the test. However, the drum imbalance is normally regulated by the electronic control unit (or control procedure) during the actual use, which stops the washing cycles if it exceeds a threshold value decided by the manufacturer. Typically, a control procedure for imbalanced conditions influences the distribution of the textile load before the beginning of the spinning function. When an equal distribution is achieved, the imbalanced load stress is lower and, therefore, higher spin speeds may be achieved. If the load cannot be equally distributed, as it was with the fixed imbalanced load adopted in these tests, the control procedure may either limit the mechanical stress to the structure by reducing the spinning profile (especially by reducing the highest spin speed and its duration) or decide to try to redistribute the textile load.

Measuring the actual imbalanced mass occurring during a spinning cycle is a prerequisite for being able to control or reduce the associated mechanical stress. The most straightforward way of measuring the imbalanced mass is to measure the displacement of the tub during low spinning (but above the critical speed needed to fix all textile articles to the drum surface). However, this requires an accurate sensor and, thus, additional costs. Therefore, the way used most is to utilise information that is already available, namely the speed of the motor driving the drum, as it is used to control the speed of the drum. The spin speed measured will vary depending on the total size of the imbalance, being lower when the imbalanced mass is lifted and accelerating when the imbalanced mass is going down. The variation of the motor speed, compared to the intentional speed, provides a good measure of the size of the imbalanced mass. This is, however, not an absolute measure of the mass, but a relative measure that needs to be calibrated to the motor control characteristics. Additionally, it depends on the total mass of the drum including the textile load, as this gives the inertia of which the imbalance is just part.

Special speed profiles are used which intend to distribute the textile load on the inner drum surface as equally as possible. These profiles ramp up the speed of rotation slowly between about 50 rpm, where the textiles are still falling, up to about 130 rpm, where all textiles stick to
the inner drum surface by the centrifugal forces (Fig. 1).

At this point, the measurement of the imbalance may already indicate that it is too high to continue the spinning to spin speeds above the resonance frequency without the amplitudes being too high for the tub. Consequently, the spinning would be stopped and, subsequently, a next ramp-up would try to achieve a better distribution of the textiles on the inner drum surface and measure the imbalance achieved again. This process may continue several times. If the acceptance limit of imbalance is not exceeded, a second phase of spinning may occur at a lower spin speed, and another measurement of the imbalance may be carried out. This second measurement will give a more precise value of the imbalance as some of the water bound in the textiles will have already been extracted. Whether the spinning to a high spin speed is continued, will be decided at the end of this phase. Such kind of ramp-up profiles are implemented in almost all horizontal axis WMs.

When the decision to go to a high spin speed is taken, the attempt to pass the region of the resonance frequency is made as quickly as possible (Fig. 2).

However, if the acceleration is too fast, too much water will be extracted in too short a time to pump it away. Water extraction occurs at about 800 rpm in a first phase and, thus, the inertial mass of the drum is reduced. A third imbalance measurement occurs again at a low spin speed and can be made with higher accuracy. Following this measurement, a decision will be taken on the final spin speed profile used to get the best possible water extraction of the textiles, also considering the mechanical stress, especially regarding the bearings of the drum.

2.5. Accelerated life tests

Even though different sources estimated lower user rates (Kruschwitz et al., 2014; VHK, 2014), the number of standard washing cycles used for the WM product fiche is 220 per year, as set by the Commission Delegated Regulation (EU) 1061/2010 (European Union, 2010). Consequently, if we want to test the durability of WMs through a conventional life test, considering an average lifespan of 12.5 years (Boyano Larriba et al., 2017) resulting in 2750 washing cycles, this would require more than a year of testing, due to the complexity of adopting automated procedures. Conventional tests, therefore, seem to be no longer efficient enough and solutions are needed to accelerate them, while not losing significance and correspondence with user experience (Tucci et al., 2014). Differently, an automated endurance test for a specific component can be significantly faster. Exemplarily, a one-way clutch with built-in ball bearing was tested on actual WMs for 2600 h of continuous cycle operation (equivalent to 5200 washing cycles), in only 108 days (Ishiyama and Iga, 2000). This evidence highlights the need for an accelerated procedure able to reduce the time required to obtain reliable results, and to reduce the costs and burdens to manufacturers and market surveillance authorities which run the test.

Engineers in the manufacturing industries have used accelerated life test (ALTs) experiments for many years (Escobar and Meeker, 2007). Accelerated testing consists of a variety of methods for shortening the life of products or hastening the degradation of their performance (Nelson, 2009). The ALTs with overstressed conditions try to simulate
the actual user behaviour and can be an effective method of acceleration for WM. Statistical methodology has been improving rapidly in recent years, and statisticians have developed a lot of statistical methodologies for accelerated testing applications (a detailed introduction of statistical methods is provided by Nelson, 2009, 2015). The relationship between accelerating variables and the actual failure mechanism is usually extremely complicated. Thus, other environmental factors should be controlled to reproduce actual use environments (Escobar and Meeker, 2007).

Tucci et al. (2014) used ALTs as an integrated method for WM design. They used 500 cycles with a total of 24 WM of the same brand and type, each equipped with a load imbalance placed inside the drum, representing the only over-stressing parameter. Each test cycle consisted of two phases, with 90 min of low speed cycles and 20 min of spin cycle. An actual washing cycle was performed for each test every 50 cycles to control how the washing performance evolved during the test. De Carlo et al. (2013) used the same strategy to estimate the reliability of WM parts through accelerated degradation tests. Accelerated degradation tests focus on the so-called soft failures, damage caused by the degradation process that will eventually lead to failure and malfunction. Twenty-four machines of the same brand and model were tested with 500 spinning cycles of 30 min each (also reducing the duration of each washing cycle from 1.5 h to 30 min). In this case, the spinning cycle is relevant, since the target of the study is again to observe the drum deformation. The imbalances permitted in the drum were rubber plates with a load of 400, 650, 800 and 950 g, bypassing the control unit of the machine with external controls.

The ALTs showed their potential, but also highlighted some critical issues and limitations. It is essential, for example, to have a dedicated laboratory for the experimental measurements and investigate all of the possible failure modes (Tucci et al., 2014). Moreover, De Carlo et al. (2013) stated that a finite element method analysis was necessary to prepare suitable overstressed conditions when studying a specific machine. These findings must be considered in the case of new endurance tests or durability procedure development for WM.

3. Method

The research approach consisted of different steps. We initially conducted an analysis of the available durability standards and procedures (both conventional and accelerated) to test products and components. We then narrowed the analysis to WM, already identified as a product group with opportunities to implement durability-related requirements within the framework of the Ecodesign Directive. The goal was to understand frequent failure modes and dynamics that can induce higher stress to the appliance and, therefore, potentially hamper durability. Spinning at a high speed appeared to be the most stressful part of a washing programme for a horizontal axis WM, therefore, weak points in the mechanical design of such machines may be identified through a series of spinning cycles. We, therefore, developed a durability test based on spinning cycles to prove that such a concept can deliver useful information to assess the durability of WM. We then defined the conditions and the performance parameters to be measured during such a durability test, to provide a procedure as close as possible to a standardised test. Finally, the procedure was tested on exemplary WM to observe the feasibility, repeatability, relevance and constraints of such a test.

3.1. Method development

The work conducted by Tucci et al. (2014) and De Carlo et al. (2013), and private communications with a WM manufacturer were used as the foundation of our durability test. The proposed test is based mainly on the spinning programme, as almost all WM offer programmes that allow either a spinning or a rinsing cycle combined with a final spinning cycle. The “rinse & spin” programme which was used by the consumer organisation Altroconsumo (2015) for an assessment of WM durability and reparability could be adopted for future developments of the method.Aligned with relevant literature, the durability test includes the execution of 500 spinning cycles, run in series on the same machine. An imbalanced load of a maximum 500 g is fixed on the drum of the machine during each spinning cycle to simulate a stressed condition, and the machine is programmed to reach the highest spin speed. After each spinning cycle, the WM is allowed to rest and cool down for at least 10 min. Spinning duration is defined as the duration of spinning at maximum spin speed with a tolerance of 30 rpm. Duration and spin speed are measured during each spinning cycle.

The maximum imbalanced load considered in this procedure was initially fixed at 500 g. In contrast to De Carlo et al. (2013), who adopted heavier imbalanced loads, the present test does not bypass the machine control procedure for imbalance with external controls. The standard IEC 60335-2-7 (2012) requires slightly higher loads (0.2 kg or 10% of the rated capacity, whichever is greater), but for only four cycles; furthermore, the endurance test is run for safety purposes.

Initial, intermediate and final inspections of the machines were included. These are conducted through visual inspection of the accessible components (especially for initial and final inspections), and by performing washing programmes according to EN 60456 standardised procedures (IEC 60456, 2010). Modifications of the EN 60456 procedure have been included for practical reasons: no soiled test strips and no detergent for washing performance measurements are used, as the only parameters monitored are water consumption, electricity consumption, time and spin speed profile. The weight of the spun load is recorded and the remaining moisture content (RMC) is calculated using the conditioned weight of the load at the end of such a washing programme (see EN 60456, 2010, for details). These washing programmes are carried out every 100 spinning cycles, for a total of five washing cycles during the spinning test, plus another washing programme conducted after the initial inspection (see Fig. 3).

The imbalanced load is removed from the machine during the washing programmes. Spin speed, energy consumption and water consumption are measured by appropriate sensors and recorded continuously. Any failure or deterioration of the WM is monitored during the test.

3.2. Method testing phase

Two WM from different manufacturers were selected for the test, called WM A and WM B. Both machines are currently on the market, declared in Energy Efficiency class A++ (EU Regulation), declared a highest spin speed at 1600 rpm and spinning performance class A (RMC < 45%). Both are declared to have a maximum washing capacity of 8 kg of cotton load.

Rubber plates have been used during the spinning cycles to mimic a constant imbalance. These plates were placed onto the inner drum surface with a spring rod fixed to the opposite side of the drum.

Both machines were operated initially with different fixed imbalanced weights to see how the control procedure for imbalance works.

WM A delivered the same spinning profile for all imbalanced weights up to 500 g (Fig. 4).

WM B only showed an expected profile (up to 1600 rpm) for the lowest imbalanced weight of 200 g (Fig. 5). Regarding higher imbalanced weights, the machine repeatedly tried to distribute the load more equally on the drum surface and, when this failed, decided to spin at lower spin speeds.

Observing both results, we decided to start the spinning tests with an equal imbalanced load of 300 g for each machine. The initial imbalanced load was defined considering that both WM showed a straightforward spinning without redistribution phase during the initial tests. We also opted for increasing the mass of the imbalanced load during the test, depending on the trends observed regarding the parameters measured (maximum spin speed and duration of maximum spin speed).
4. Results and discussion

4.1. WM A: spinning cycles

Fig. 6 shows the maximum spin speed and spinning duration for WM A from spinning cycle 1–500.

Regular gaps between the data indicate the execution of one washing cycle every 100 spinning cycles. An initial imbalanced load of 300 g was chosen, as both machines showed a straightforward spinning without redistribution phase for this mass in the initial test (see Section 3.2, and Figs. 4 and 5). WM A performed at these conditions without any problems. Therefore, we decided after 159 spinning cycles to increase the weight of the imbalanced mass to 500 g, the maximum imbalanced load considered for this test, for the remaining spinning cycles. WM A showed a constant spinning rate at a spin speed of 1605 to 1610 rpm for about 145 s most times. The increase of the imbalanced load at the 160th cycle caused a reduction of the spinning time to about 107 s for about 50% of the cycles, then returned to the usual average duration of 145 s.

WM A moved about 10 cm away from its original standing position in 20 cycles, although it was positioned well at the beginning of the test series. This movement always occurred in the first spinning tests of the day after the imbalanced weight was increased to 500 g. The machine was always placed back to the original position for the next cycle.

4.2. WM B: spinning cycles

WM B (Fig. 7) showed a more variable behaviour.

At the beginning, the maximum spin speed reached with an imbalanced load of 300 g was between 1400 and 1500 rpm. However, this speed increased cycle by cycle and reached 1540 rpm after about 20 cycles. The spinning time at the maximum spin speed was about 150–175 s. The imbalance of WM B was increased to 350 g (at the 108th cycle) at the same time in the testing as when the imbalance in WM A was increased to 500 g, to also induce a maximum stress on the structure of this machine. Subsequently, the maximum spin speed dropped to below 1500 rpm and the duration varied between 120 and 180 s. The maximum spin speed dropped further to 1468 rpm from the 222th cycle onwards, and kept constant for most of the cycles up to the end of the test. Spinning time varied between 140 and 230 s. The total time of the spinning programmes extended by more than 10 min, due to continuous attempts of the control procedure to redistribute the load, as described in Section 2.3. This redistribution was, however, not possible due to the fixed imbalanced mass.

Overall, the spinning tests performed on the two WMs showed variations in maximum spin speeds and respective durations. Results,
especially for WM B, clearly showed the behaviour of the control procedure when detecting an imbalanced situation and its effectiveness in mitigating the stress induced by this imbalanced load to the structure and components of the WM. This ensures a reduced stress on the WM structure as the control procedure tried to avoid the excessive wearing of key components and prevent early failures. However, the consumer may have to wait longer for the execution of the washing programme, as the repeated attempts to distribute the load equally takes time and, if the maximum spin speed and duration is limited, it also reduces the spinning efficiency, meaning that the load is wetter than it could or should be.

4.3. Washing cycles

Complete washing programmes (Standard cotton 60 °C) were executed following the standard EN 60456, modified according to Section 3.1. Diagrams of all six washing cycles for water intake, energy consumption and spin speed over time are shown for WM A (Fig. 8) and WM B (Fig. 9).

Water consumption for WM B was not correctly recorded in the first two cycles, therefore, it is only reported for cycles 3–6 (Fig. 9).

Results for WM A showed comparable behaviour regarding spinning in all six washing cycles, without any problems due to imbalance. Looking at WM B, instead, relevant differences are visible in the spinning profile, especially regarding the final spinning. Indeed, the declared highest spin speed is reached in just one of the six washing cycles (run #1 in Fig. 9).

The highest spin speed in the other trials is not reached or is only reached for a very short time. It seems that the spinning in runs 2–6 is somehow truncated due to problems of imbalance. If these results were to be confirmed in a test carried out fully according to EN 60456, the declared spin speed (1600 rpm) and spinning performance (class A) of this machine may be challenged. The instability of the spinning process also shows up in the RMC of the spun load (Table 1).

While WM A shows almost constant RMC values for all washing programmes, RMC results for WM B were affected by a higher variation. Only the RMC value of the first washing cycle for WM B is aligned with the declared class A of the spinning performance.

4.4. Visual inspection

We performed a visual inspection before and after the testing. The back cover sheet and the top plate were removed to do this. Pictures were taken of parts that may be subject to deterioration or damage during the testing. None of those parts exhibited any sign of abrasion, stress or leakage. Rubber debris was found in WM B during the spinning cycles and at the final inspection, due to the contact of the door gasket to the rotating drum. Indeed, the stainless steel front side of the drum in WM B came in contact with the rubber door gasket under the stress test conditions causing abrasion of the rubber.

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Fig. 5. Spin speed profiles of WM B, recorded during the extra spinning programme for various fixed imbalanced weights.

Fig. 6. Spinning profile parameters: maximum spin speed and spinning duration for WM A from cycle 1–500. Regular gaps between the data indicate the execution of the washing cycle every 100 spinning cycles.
Some pieces of debris were also found on WM A, but were much smaller in size and of a dark colour. However, it was not possible to identify the origin of the debris. There is normally a gap of about 1–3 mm between the (rotating) drum and the door gasket under conditions of no stress. Under stress conditions, however, the drum is deformed during spinning and the gap may be reduced to 0 mm and, consequently, abrasion starts. In the long run, leakages in the rubber door gasket may result. Regarding WM A, an unexpected movement of the machine occurred in the first spinning tests of the day in the first spinning cycles right after the increase of the imbalanced load to 500 g. A higher friction of cold dampers might explain this. Dampers are typically already warm when starting the spinning function during conventional washing cycles.

4.5. Final remarks

Looking specifically at the performance of the two WMs, the overall durability test showed that the execution of washing and spinning programmes is not carried out uniformly throughout the five hundred spinning and the six washing cycles. Looking specifically at the problems due to deterioration of the machine, the presence of rubber debris at the end of the spinning cycles in WM B was mentioned.

The approach adopted in this durability test lies between the strategies used by Altroconsumo (2015) and De Carlo et al. (2013). Altroconsumo observed hard failures in four of the twenty-four WMs analysed, but through a conventional test of 2500 rinse & spin cycles, with partial load (60% of the rated capacity, of which 85% was cotton textile and 15% was sponge material), which can be very lengthy. De Carlo et al. used 500 spinning cycles with different imbalanced loads, but the control procedure in their experiments was by-passed through external controls, rendering the test no longer relevant for a WM on the market. Our approach, on the other hand, aimed to be relatively fast (500 spinning cycles and 6 washing cycles) and applicable to different WMs, without deactivating the control procedure for the detection of imbalance. The idea of having a common procedure which could be used to guarantee durability performances of WMs is still an interesting task, but the definition of realistic loads (and, therefore, mechanical stress) remains the most challenging issue.

5. Conclusions

The objectives of this research were to develop a (potentially standardisable) procedure to test the durability performance of WMs and to verify whether WMs currently on the market can sustain a series of stress conditions without any hard failure. The application of the durability test based on spinning cycles with fixed loads did not show any
significant failure of any part of the two exemplary WMIs used in this first experiment. However, the attempt to mimic the stress induced on a WM did not allow equal testing conditions. The actions of the control procedure regarding imbalanced loads differ from machine to machine: actions regarding the procedures and precision in detecting the imbalanced load, the procedures to distribute the textile load uniformly at the start of spinning cycle and the reactions in adapting the spinning profile to a certain level of stress.

With these conditions, it appears that the attempt to induce certain stress on a WM by carrying out a high number of pure spinning cycles with a fixed imbalanced load does not allow having equal testing conditions. Such kind of testing protocol could even be counter-productive if used to assess and compare the durability performance of WMIs, as it pretends to replicate durability, while real performance (e.g. RMC, washing time) has already deteriorated after some cycles. This exercise shows very clearly how important it is to link durability tests to real life stress conditions and to the performance of the product. Stress tests on individual components may be useful for certain aspects, such as safety requirements, but need to be considered in the context of the product and the way they are used in this specific product.

This exercise has also shown what parameters of a WM (imbalance treatment procedure, actual spinning profile, RMC and maximum spin speed) are relevant to assess its durability. Future developments could then replace spinning cycles (with fixed imbalanced loads) with a series of washing cycles, with real load and various programmes. The selection of washing programmes should include all temperature levels and could consist mainly of short programmes. The number of washing cycles, for instance, should represent two or more years of washing practice in an average European household (500 cycles seems to be the minimum number of cycles for reliable tests). In this way, the overall duration of such a test would not be much longer than the stress test applied in this work. Moreover, it would have the advantage of mimicking actual stress conditions, as the stress is coming from real scenarios. A related durability test could hence require that when three machines of the same model are tested in parallel, at least two withstand the test (‘double 3’ method, according to IEC 60410) without any failure and without deterioration of the values declared on the energy label. This can be verified by performing a full test following EN 60456, where all parameters as required by Energy Labelling and Ecodesign are measured at the beginning and after all cycles. Ecodesign and Energy Labelling regulations could then be amended to include the requirement that the declared and required values are also to be maintained for a certain time frame (e.g. two years of operation, as simulated by a preset sequence of washing cycles).

As previously recommended (Tecchio et al., 2017), this work also aimed at further stimulating the discussions between industries, academia and policymakers about industrial practices that will enhance resource efficiency in products, focusing especially on improving durability performance. Durability requirements at the whole product level (i.e. considering the product as a whole system where all different components interact together) proved to be needed and could be enforced via product policies coupled with appropriate vertical (product-specific) standards. However, they will be only successful if they are verified by responsible market surveillance authorities based on affordable and reproducible test procedures and, hence, further standardisation work is needed for this product group. The present research on WMIs will serve as input into the ongoing activity of the working group ‘durability’ of the Joint Technical Committee 10, set-up by CEN and CENELEC to address the standardisation mandate M/543 (European Commission, 2015b) aiming at developing generic standards which cover Ecodesign requirements related to material efficiency aspects. This work also has the potential to trigger activities to develop vertical standards on specific product groups, which could, hence, be used in the next reviews of Ecodesign regulations for the WM product group.

**Disclaimer**

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