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EVALUATION OF PHYSICAL PROPERTIES OF WAX MIXTURES OBTAINED FROM RECYCLING OF PATTERNS USED IN PRECISION CASTING

OCENA WŁAŚCIWOŚCI FIZYCZNYCH MIESZANEK WOSKOWYCH UZYSKANYCH NA DRODZE RECYKLINGU MODELI DLA ODLEWNICTWA PRECYZYJNEGO

The study investigated the properties of selected certified mixtures used to make wax patterns for the production of precision castings for the aerospace industry. In addition, an assessment of the recycled mixtures consisting of certified wax materials recovered during autoclaving was carried out. Hardness was tested via a proposed method based on penetration, creep related deformation, bending strength and linear contraction. The hardness was studied on laboratory specimens and patterns made with the use of injection molding equipment. For these patterns, linear contraction was estimated at variable pressure and for different temperature injection parameters. Deformations connected with creep and resistance were evaluated on cylindrical specimens. Differences in creep resistance in relation to the hardness were observed depending on the type of pattern mixtures. Recycled mixture has a greater resistance and smaller linear contraction than certified mixtures used for making sprue, raisers and other parts of filler system.

Keywords: Investment casting, Wax pattern, Wax blends, Pattern properties

W pracy zbadano właściwości wybranych mieszanek modelowych atestowanych stosowanych do wykonywania modeli wytapianych przy produkcji odlewów precyzyjnych dla przemysłu lotniczego. Dodatkowo badaniom poddano masę z recyklingu składająca się z odzyskanych w procesie autoklawizacji mieszanek woskowych atestowanych. Zaproponowano badania twardości metodą penetracji, odkształceń związanych z pełzaniem, wytrzymałości na zginanie oraz skurczu liniowego. Twardość badano na próbkach laboratoryjnych oraz na modelach wykonanych na wtryskarce przemysłowej. Dla tych modeli oszacowano skurcz liniowy przy zmiennych parametrach ciśnienia i temperatury wytrysku. Odkształcenia związane z pełzaniem i wytrzymałość badano na modelach walcowych. Obserwuje się różnice odporności na pełzanie w odniesieniu do twardości w zależności od rodzaju mieszanki modelowej. Masa z recyklingu ma większą odporność i mniejszy skurcz liniowy niż masa atestowana stosowana na układy wlewowe.

1. Introduction

Lost-wax casting process is very complex and consists of ten basic technological phases that shape the total errorsΔL, the major error being connected with wax pattern (ΔM) responsible for 25 up to 30% of total error ΔL [1].

Generated patterns are wax-based. Final wax materials are complex mixtures of many different chemical ingredients (which are wax-like substances) [2].

There are three basic types of wax used for making wax patterns:

a) unfilled simple – wax,
b) emulsified – modeling wax,
c) wax with filler content.

Simple wax tends to cavitate during creation of patterns in the die. Emulsified wax contains from 7 to 13% of water that partially acts as a filler. The use of waxes with fillers results in greater stability and less cavitation. A filler should be made of organic material (combustion ash-free) broken into pieces of minimum size and of density close to the density of an appropriate base wax to prevent separation of ingredients when the wax is liquid.

It is crucial that mixture of wax used in patterns is suitable for recycling, and reusable for manufacturing of sprue, runners, or even patterns.

Modern wax pattern materials are generally complex – they contain among others natural wax, synthetic wax, natural and artificial resin, filling materials, etc. These ingredients have different molecular weights and different atomic chains. As needed various formulations can be obtained to produce wax pattern with specific properties. Important parameters include melting and softening points [3, 4], hardness

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and strength, contraction and the rate of coagulation. The wax does not melt as a homogeneous material, since each ingredient has a different melting point. As its temperature rises the wax mixture passes through various intermediate stages – Fig. 1. Ingredients with short-chain melt first, when long-chain fractions are still in the solid state.

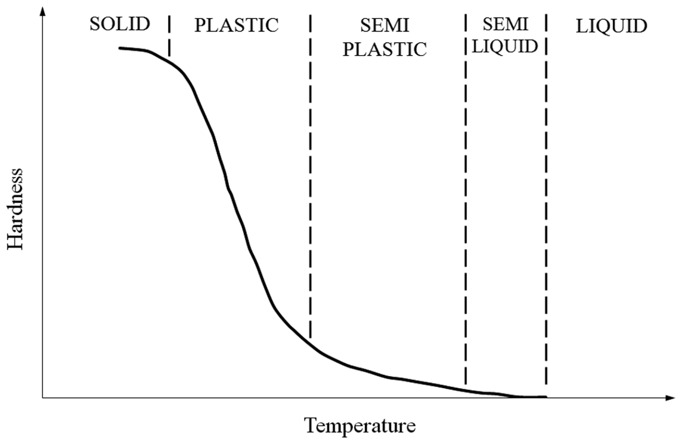

Fig. 1. Hardness of a typical wax depending on temperature

When wax pattern material has specific properties it is possible to manufacture high quality patterns and distortions associated with changes in the pattern shape are reduced during production process. At appropriate levels, hardness and resistance to creep and contraction result in stable reduction of deformations and make possible to obtain small values of dimensional inaccuracies ΔM. Thus distortions in the resulting castings are less numerous.

Obtaining minimum values of ΔM is possible through selecting of appropriate wax pattern materials and studying the bending strength of the specimens R_g. The R_g parameter may be replaced with the creep resistance parameter P_z. Creep provides with a wider range of information that can be used in technological process. Creep as a slow and constant deformation over time, depends not only on stress, but also on temperature and time.

$P_z = f(\sigma, t, T)$, where σ – stress, t – time, T – temperature [4].

Simultaneously, it is assumed that creep starts at 0.3 T_M (softening temperature) [4]. Moreover, creep occurs during the manufacturing process of patterns (indirectly associated with contraction) which affects the size of a pattern [5].

In manufacturing process, sets of patterns kept in non-air conditioned spaces are constantly exposed to creep, which may worsen the shape accuracy.

In industrial practice, wax is first obtained from melted ceramic moulds and then purified by removing water, ash, parts of ceramic mould and other physical impurities. Very often, the resulting material is enriched with new ingredients.

Although in the recycling process new materials can be obtained it is more important that the recycling is an energy-saving process [4]. Thus it can be concluded that the concept of a larger recycling and treatment of wax should be promoted as important for the development of the industry.

2. The research methodology

Properties of certified wax mixtures and of recycled wax mixtures used in the investment casting (recovered from ceramic moulds through autoclaving) were evaluated. Recycled wax mixture (referred to as ”Rec”) was achieved by combining certified wax mixtures such as: A7-FR/60, KC6052, KC4017, KC2690 and others.

Temperature range suitable for pattern formation was determined for each tested wax mixture. Several tests on hardness, resistance to creep, R_g bending strength and contraction were conducted.

Laboratory specimens for hardness testing were obtained by flooding, as specified in PN – 82/C – 04161 standard. They were flooded up to PVC rings heated up to 60°C, which resulted in the stabilization of the formation conditions of the specimens and their subsequent measurements. Several specimens from each mixture pattern type were tested, each of them in three measuring temperature zones: 15-17°C, 20-22°C, 25-27°C.

Hardness of wax pattern material mixture was tested for 10 minutes each time by penetrating of a steel needle under the load of 200 grams. The hardness of the wax pattern material is represented in the chart by the penetration rate of the needle (in units, where 1 penetration unit corresponds to the immersion of the needle for the depth of 0.1 mm (according to PN-EN 1426:2009)).

Laboratory specimens for resistance to creep testing were made by injecting the wax pattern mixture into a thick-walled steel tube at the injection pressure of 1.5 MPa. The resulting cylindrical samples were of 8 mm in diameter and of 200 mm in length. Deflection was evaluated for 10 minutes in each temperature zone by measuring specimens subjected to the load of 30 grams located on the 150 mm long arm. Subsequently changes of loaded end position specimens were measured. The results given in millimeters [mm] opened the way for the assessment of creep deformation in the process.

In order to define R_g a three point bending test (where the distance between supports was at 50 mm) was performed for selected wax pattern specimens. All tests were performed on cylindrical samples of 8 mm in diameter at the temperature of around 20±1°C.

Methodology for measuring the hardness and the creep of wax pattern specimens as well as test facilities were discussed in detail in [6].

The analysis of variability L was carried out on the patterns of 70×30 mm in size and 7 mm in thickness (Fig. 2). The analysis was performed on multiple patterns made in industrial injection molding process at various temperature levels and different injection pressure. Measurements provided data on free contraction.

One of the major issues was to determine properly the F_{WT} of cavity in injection molding die for the production of wax patterns. At this stage as patterns and the resulting ceramic mould are interconnected, some deformations of individual elements that are difficult to predict can be observed [7]. The F_{WT} of cavity is calculated analytically by estimating the deformation in all phases of the process. In terms of dimensional accuracy of patterns it is important to choose wax pattern mixture material with specific contraction [8] and mechanical properties.

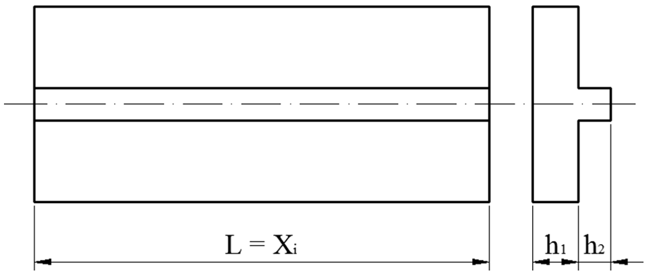

Fig. 2. The model used to evaluate the wax pattern contraction

Shaping of mixtures' properties by using additives is discussed in [9]. The study involved the analysis of the B97 and B140 pattern mixtures. It included comparison and measurement of such parameters as hardness (using the penetrometer Petrotest), tensile strength, viscosity and surface roughness.

Similar studies were carried out for dental applications where softening point and resistance to deformation were similarly considered most important parameters [10].

In the paper [11] different factors affecting the dimensional accuracy of patterns were looked at. An analysis of wax mixture composition and of manufacturing parameters of patterns was necessary to determine properly the criteria of their manufacturing process. Penetration was used again as one of the evaluation criteria for assessing wax mixture properties.

3. Results

The research was conducted to specify properties of wax mixtures approved for use in foundries and the ones achieved from recycling and it was aimed at demonstrating subsequently the possibility of their application.

In commercial practice, during preparation of the patterns and sets of patterns constant temperature should be ensured. Thus wax pattern properties can be stabilised and uncertainty of the process minimised. The recommended temperature during pattern production is 20÷22°C. The study was also conducted for other temperature ranges and included measurements of the hardness of wax mixtures and of their deformation resulting from creep.

From Fig. 3 it can be concluded that the certified mixtures (A7-FR/60, KC6052 i KC4017) are of similar hardness. Hardness of KC2690 and Rec mixtures is much smaller (higher number units of penetration). KC2690 mixture is mainly used for filling systems (sprue, runners) which explains why the Rec show greater percentage of this type of mixture.

Average deformation of the cylindrical samples of 8 mm in diameter made of a mixture of certified KC2690 is about 70% larger than the deformation values for A7-FR/60, KC6052 and KC4017 wax mixtures. The values of deformation for KC2690 and Rec mixtures are similar. Values of deformation observed for recycled mixture (Rec) were given in Figure 4. In addition it can be concluded that at higher temperatures hardness decreases while creep-related deformation increases.

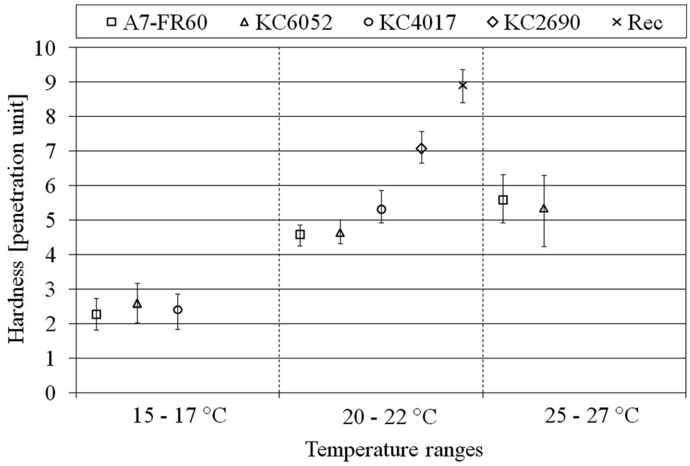

Fig. 3. Comparison of the hardness of the tested wax pattern mixtures in all temperature zones, taking into account the measurement uncertainty [12]

Recycled mixtures consisting of blends of certified wax may be used as an additive to mixtures of paraffin – stearin. From such a mixture it is possible to produce lost-wax castings with lower quality requirements.

Fresh ingredients were used to prepare PSWp mixture comprising of 70% paraffin, 25% stearin and 5% polyethylene wax. PSWp and the mixture from recycled certified blends (Rec) specimens were taken to produce several specimens as indicated below:

– Specimen 1-100% Rec
– Specimen 2-50% Rec mixture and 50% PSWp mixture
– Specimen 3-75% Rec mixture and 25% PSWp mixture
– Specimen 4-100% PSWp.

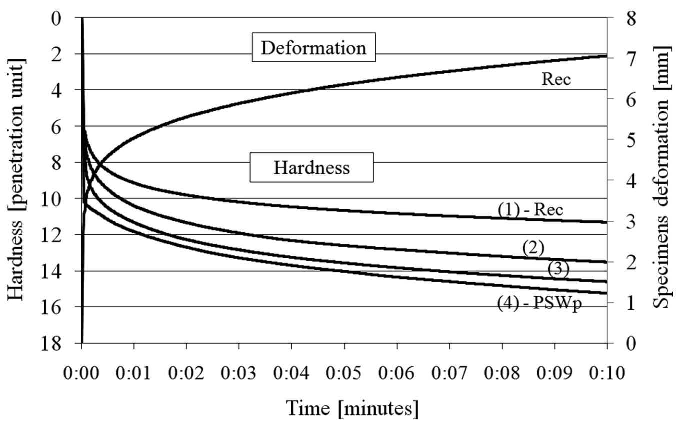

Fig. 4. Sample results of the hardness and deformation measurements during the creep process

We evaluated the hardness of the obtained wax pattern mixtures. The results of these tests are given in Figure 4. Adding 50% Rec to wax pattern mixture increased its quality and patterns made of enriched mixture were more resistant in terms of strength compared with the standard PSWp wax mixture. Increasing the Rec mixture share over 50% did not cause significant change in the hardness of the formed mixture.

Creep resistance of a pattern mixture is largely dependent on the hardness; it reflects its mechanical strength and resistance of wax pattern to deformation at elevated temperature. Deformations depend not only on the value of the forces acting on the patterns, but also on temperature and time in which they occur. The above properties determine the shape accuracy of a ceramic mould cavity.

The paper includes creep resistance study and data from measurements of wax pattern mixture R_g bending strength. The same types of patterns (specimens) were used in both analysis.

Figure 5 summarizes the results obtained for selected certified mixtures and for the recycled mixture (Rec) and paraffin – stearin mixture (PSWp).

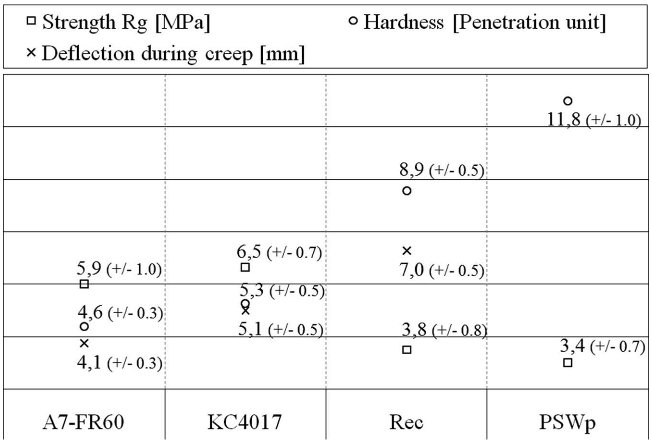

Fig. 5. Summary of bending strength, hardness and deflection for the tested specimens

Bending strength of specimens including Rec mixture was about 60% of the strength of A7-FR60 and KC4017 mixture (Fig. 5). With lower bending strength of Rec mixture, a greater creep-related deformation could be observed.

Given all the results, in particular the values obtained for the PSWp mixture, it can be concluded that measurement of hardness of wax pattern mixtures may contribute to the evaluation of their strength properties. It was found that the specimens with greater R_g strength were also more resistant to creep. The strength parameters of certified wax pattern mixtures comprising A7-FR/60 and KC4017 are significantly higher compared to the recycled mixtures and paraffin – stearin mixtures.

Evaluation of technological parameters of pattern mixture, such as hardness and creep resistance can provide with valuable information to assist to pattern mixtures selection in the production phase of lost-wax casting process. An analysis may also be used to evaluate the possibility of using a recycled mixture (Rec) in industrial practice. A recycled mixture includes certified wax blends in amounts dependent on the type of the product portfolio and the construction of a pattern set. It is therefore important to compare the properties of the Rec mixtures and the properties of certified mixtures as presented in Figure 6.

The authors of this paper proposed to define the $R_{D/H}$ coefficient. It is the ratio of the value of deflection measured during a creep test to a needle indentation during a hardness test. The properties were determined using the same linear displacement transducer and expressed in millimeters. The resulting (unit less) $R_{D/H}$ values were normalized such that the lowest value is equal to [0,1]. The results were summarized in Figure 6. The graph makes possible a qualitative evaluation and comparison of the patterns mixture characteristics. The most significant deformation in relation to a hardness (ratio $R_{D/H}$) was observed in KC2690 mixture. Although the hardness of Rec mixture is similarly low, its creep resistance is greater than this of KC2690 mixture. This is due to the presence of hard pattern materials in Rec mixture. A7-FR/60 mixture is the most resistant to creep even though the hardness of the KC6052 and KC4017 mixtures is comparatively high.

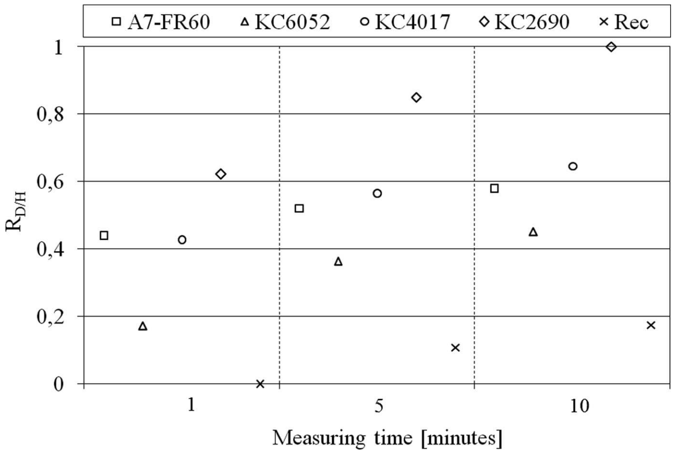

Fig. 6. The ratio of sample deformation in the creep process to pattern mixture hardness

The problem of wax pattern contraction is studied by multiple authors. For example, in [13] the author measured dimensions of the patterns to determine the effect of injection parameters and of the type of injected mold material on dimensional and shape accuracy of wax patters.

Wax patterns deform over time (before ceramic slurry is applied). This is confirmed by the research of [14], where wax pattern contraction in one hour after injection was X_c = 0.3÷0.5%, and after 24 h the contraction reached the value X_c = 0.5÷0.7%. X_c deformations in a set time interval were dependent on the position of the pattern surface in the injection mold. It was connected with the phenomenon of restricted or free contraction immediately following the injection (X_c'). In practice free contraction is a rarely observed phenomenon because a mixed type of contraction is registered more often for elements of complex geometries.

Figure 7 shows the impact of injection pressure and temperature on the contraction of A7-FR/60 certified mixture. The contraction of pattern mixtures was evaluated on the basis of changes in the patterns linear dimension under selected parameters and at temperature of injection. Patterns with solidification module of approximately 0.25 cm were selected for this purpose.

An average contraction decreased on increasing the injection pressure, and the nature of change was observed at 65±5°C. For all of the studied wax mixtures the injection pressure decisively influenced the rate of contraction.

Contraction was also evaluated on patterns made from other mixtures used in the research. For recycled (Rec) mixtures registered values of an average contraction were in the range of $S_K = 0.88^{\pm 0.08}$%. KC2690 mixture showed the highest values of contraction compared to other mixtures. As a consequence, it was not possible to produce patterns with appropriate dimensional stability.

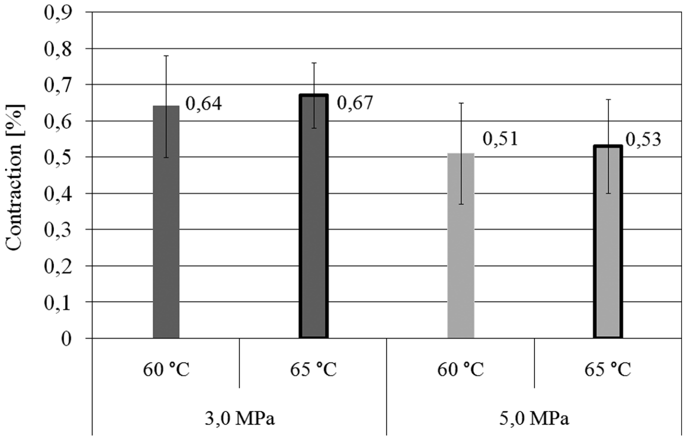

Fig. 7. Patterns contraction (change of L_{nom}) made from A7FR60 mixture, comparison of the results obtained with the injection molding equipment

Similar conclusions are found in [15] where the authors analysed patterns with complex structures made from KC4017B mixture in terms of mold temperature, melt temperature, injection velocity, holding time and packing pressure. It was found that the stability of the pattern dimensions is influenced by time and injection pressure but not by temperature.

4. Conclusions

1. It is acceptable to test hardness of the actual patterns but then pattern thickness should be at least 12 mm. The sample size has little effect on the value of hardness, measured in units of penetration.

2. The influence of temperature on the hardness of pattern mixtures was observed.

3. It was noticed that the time interval of measurements had little impact on the hardness evaluation of hard pattern mixtures.

4. The use of hardness and creep tests at different temperatures makes possible a rapid evaluation of the quality of patterns mixtures, which is crucial in terms of the properties comparison of patterns made from different materials.

5. Differences in creep deformation of patterns according to the type of the pattern mixture were observed. Thus it becomes possible to draw a distinction between mixtures with greater hardness and more resistant to creep and mixtures with lower hardness and creep resistance.

6. Pattern mixture obtained from the recycling of hard waxes can be used to perform accurate castings for general engineering industries.

7. Use of mixtures from approved recycled wax mixtures instead of the PSWp mixtures will result in the reduction of energy consumption in manufacturing and in high quality of the investment patterns.

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