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Analysis and Validation of Database in Computer Aided Design of Jewellery Casting

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Abstract

An overview of the bibliography regarding the connection of knowledge about precious metal alloys and aspects of the use of computer aided technologies to the optimization of the jewelry casting processes is presented. An analysis of the usability of selected CAx systems was made: 1) for spatial design, called Rhinoceros 6 and 2) CAE system: NovaFlow & Solid (NF&S). The authors describe own research including data acquisition and evaluation of temperature variations during solidification of the selected Au-Ag-Cu alloy, with the identification of the phase transformations of this alloy. The intensity of heat exchange was changed (cooling of specimens under ambient temperature conditions – "normal" intensity and with the furnace – very slow cooling). The problem of completing the simulation database was pointed out and analyzed. Examples of simulations of casting selected jewelry (ring and signet) were given and compared with the result of the experiment realized in real conditions. It was confirmed that the optimization by combining experimental and simulation studies allows for the acquisition of new knowledge, and also facilitates the creation of new artistic designs of jewelry as well as performing the feasibility check, and then optimizing the chosen technology.

Keywords: Casting of jewelry, Au-Ag-Cu alloy, Thermal analysis of solidification, CAE system, NF&S, Quality prognosis

1. Introduction

Computerization and implementation of IT solutions, i.e. the introduction of information systems and computers to various areas of life and industry are ubiquitous. Enterprises decide to digitize their business domains to improve organizational and manufacturing processes, within the companies themselves as well as in their process and business environment. The enterprises seek not only the computers themselves, which serve as tools (hard), but various types of system software (soft) as well. At the turn of the 21st century, their application developed particularly well, due to the creation of programs meeting the needs in these domains. Each of these programs requires a more or less professional procedure to implement and adapt to the specificity of a particular company's operations. The foundry industry was one of the first to introduce computer programs and systems to the general practice [1-4]. This also applies to computer-aided design and casting technology in the jewelry industry, albeit more rarely [5,6].

Foundry remains one of the first technological industries in the time and content dimension, in which the optimization of production and process parameters was based on the development of computer aided systems. In this particular industry, especially in leading companies, the simulation programs/systems play an important role. They have been improved in many aspects of the application and are already indispensable in the foundry's process engineering offices as a support tool.

The development of innovative design and process solutions is where these techniques are the most frequently used, while the documentation is created using advanced programs/systems that allow the creation of 3D process geometry.

The software is developed mainly by recognized global American, Japanese and European centers. It is based on models and complex algorithms developed on the basis of physical laws of heat and mass transfer (including Navier-Stokes and Fourier-Kirchhoff and empirical formulas). Simulation systems allow modeling the behavior of liquid metal filling the mould and the process of its solidification, sometimes including the dynamics of changes in the state of stress. These programs include e.g. Flow-3D, Magma, Procast. NovaFlow & Solid, Quickcast. Thanks to this, it is possible to forecast casting defects such as shrinkages, misruns, or other defects associated with metal-mould reactions, and further eliminate their causes.

This article refers to the trends in the goldsmith industry, including computer-aided design and 3D printing of models removable by high temperature. Thanks to the opportunity to access the research workshop, it was possible to work with precious metal alloys [7].

The use of computer aid for artistic casting of gold alloys, along with completing and testing the database for process simulation, has been analyzed. The validity of using the selected simulation program for small items, such as jewelry products, will be checked. The question is whether it is worth using the above-mentioned programs, i.e. whether it will allow the specialist to identify a source of any errors that may have occurred so far while casting a precious liquid metal. The problem is not only the size of a jewelry product, but its complexity, i.e. the occurrence of finesse elements with very small dimensions. The characteristic temperatures of selected gold alloy will also be analyzed in order to identify their melting point and check how they solidify.

Experimental research was carried out as part of the master's thesis made by the co-author [7] in the CAD / CAE Laboratory of Materials Technology at the Poznań University of Technology and in the private Goldsmith's Studio. Performing experiments related to the melting of gold alloys, as well as software Rhinoceros 6 and a 3D printer were made available free of charge by the above-mentioned Studio. Simulation tests for the selected jewelry products were carried out using the NovaFlow & Solid program, made available by Novacast.

2. Precious metals alloys. State of art. and chosen examples.

Precious metals generally include gold, silver and the platinum family (platinum, palladium, rhodium, iridium, osmium and ruthenium). It would be difficult to imagine today's world of advanced technology without the use of the above-mentioned metals. They are found as microcomponents in everyday objects and more widely, in modern specialist industrial processes. They are used when they cannot be replaced with "ordinary" metals. Two important limitations in their widespread use are the high price for the bullion and the supply that is not keeping up with the growing demand. The silver and gold have the longest history of precious metals, but the gold itself, known for over 6,000 years, had the greatest impact on the history of mankind and despite such a long time, the desire to obtain gold is still attractive [8].

In pure form, they are used to coat less precious metals, for example to improve aesthetics, to ensure protection, anti-corrosion. They are also used in the form of alloys in electronics, electrotechnics, for the production of artistic products, coins, medals, dishes, ending with dental prosthetics. The stability of precious metals' properties is very useful in the production of standards and as comparative material constants when measuring the physical properties of other materials [9].

Precious metals owe their popularity to their special properties, but all of the features cannot be attributed comparably and arbitrarily to each of the metals, because they constitute a diverse group. The basic property is the high corrosion resistance in the atmosphere of the ambient air, even at high humidity. Non-oxidation and resistance to all acids, with the exception of king's water (a mixture of concentrated hydrochloric and nitric acid), is another advantage. Precious metals, having high density and good plasticity, are also resistant to aggressive chemical or high temperature environments. [8].

The subject of metallurgy of precious metal alloys, including goldsmiths, and the production of jewelry, especially from a synergic viewpoint, is relatively rarely present in the literature. The cost of testing, especially regarding alloys, whose price exceeds the prices of technical alloys many times, e.g. iron (by conventionally taking the price of casting iron for 1, gold is approximately 80,000 times more expensive, platinum - 70,000 times, and silver about 1600 times). Therefore, the scenario, study methods and the research workshop are therefore specific and very few centers / laboratories conduct research on these alloys.

Historically, in the period before 1939, a series of tests of gold alloys in terms of their physical properties were carried out at the Warsaw Polytechnic (Broniewski Wesołowski, [10-12]). Later, monographs and publications referring in their entirety to the techniques and foundations of goldsmithing, including [13-16] are prevailing. There are also doctoral theses devoted to goldsmithing. The [17] describes tests of both solid gold products and the determination of the thickness of coatings of objects covered with gold using X-ray methods.

It is known that due to the content of at least two different elements in specified amounts, metal alloys have different properties, ranging from hardness or heat conductivity, and ending with obtaining a specific color. The starting point for the analysis is the well-known atlas catalog published in 1956 by Łoskiewicz and Orman, which is a valuable combination of equilibrium diagrams of combinations of double metal alloys [18]. When mentioning metals, as decorations and decorative elements, the color of the alloy has a special meaning. Different gold alloys in jewelry are used to obtain a specific color, for example of a ring or a signet. In the alloys used to create jewelry, in addition to gold, there are also admixtures of silver, copper, and possible small additions of other metals. Appropriate change of percentage composition of these three main elements (Au-Ag-Cu) makes it possible to obtain a specific shade of gold, as shown in Figure 1. The use of, for example, white or red gold, is for many of a purely aesthetic character and depends on the potential taste buyer of jewelry.

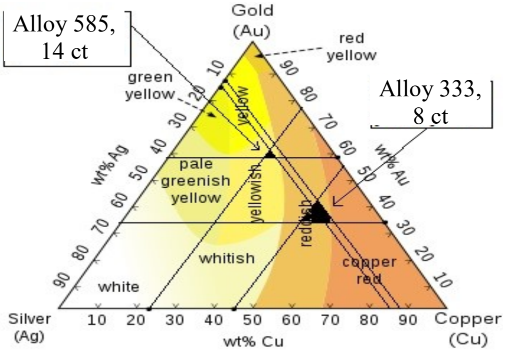

Fig. 1. Ternary plot of approximate colors of Ag–Au–Cu alloys [7,19]

3. Foundry processes used in goldsmithing and directions of use of Computer Aided Design.

Casting has been a dominant technology in jewelry for centuries, especially the investment casting method, also known as the lost wax casting, generally used in precision casting. In addition to the visual effects, in the first place, the jewelry must also have specific functional characteristics (strength, low abrasiveness [20], crack resistance [21]). Therefore, surface defects, shrinkage porosities, even minor imperfections, are unacceptable, as well as non-metallic inclusions, and oxidized alloy additions from the viewpoint of metallurgical quality. The trial and error method is less and less used in optimizing casting production processes. Traditionally for years this method, aided by simple empirical formulas, with "manual" calculations and sketches, was used for optimization of the casting concepts. Currently, this approach is gradually being replaced, due to the development of technologies. Increasingly better computers and engineering software effectively support design work and production activities at individual stages. Advanced computer simulations save time and money, which were often lost as a result of the failures of the mentioned trial and error method. Using CAD/CAE systems and the investment casting technology, various small sized products are created with a significant degree of geometry complexity. Such examples are not only in the area of automotive castings, but also, for example, parts of the bioengineering field of titanium alloys (implants, heart prostheses) [22].

CAD techniques allow to quickly make changes at any time when creating a new product concept. Such a CAD program in combination with computer aided engineering (CAE) covers a significant part of the optimization of the technology concept (dynamics of main phenomena, analysis of internal stresses and various interactions in the cast-mould system), depending on selected materials and production conditions [23,24].

When considering modern processes used in goldsmithing, the additive manufacturing methods, both those concerning models and mock-ups (purpose: visualization) as well as those enabling the obtaining of usable objects, are applied. The manufacturing process is completely computerized. The *.stl file as the virtual geometry of the model, after the appropriate processing, is sent to a 3D printer (there are several 3D printing techniques), that will allow real-time fabrication of a real object based on the virtual model. The most popular additive manufacturing methods are SLA, FDM, JM, 3DP, LOM, SLS / SLM and LENS (for details see e.g. [25]). In technologies used in jewelry, additive methods (known as 3D printing) are used to produce models removed from the mould before pouring the liquid gold alloy or with the previous melting/degassing of the model. This additive manufacturing technology is also used for the production of reusable moulds for the production of repetitive models by wax injection (for lost wax casting).

4. Methods of metallurgical quality studying of alloys in goldsmithing

In goldsmithing, quality control addresses two basic aspects. The first one is the technique of making a jewelry product, with a given degree of complexity, in connection with the precision of performance and visually-assessed features. The second aspect is related to the choice of a gold alloy, i.e. with the content of gold in the alloy itself and its appropriate metallurgical preparation.

Methods for identifying the type of alloy are rarely used in practice. An experienced goldsmith can prepare appropriate alloys without the need to check their quality by means of precise control of the chemical composition. The testing of gold alloys is more common in mass producing companies. Currently, two methods are used, spectral and cupellation method [26,27].

Precious metals can be separated from easily meltable and oxidizable additions of non-precious metals in the alloy, by melting with the lead on the cupel in an oxidizing atmosphere. This process is called the cupellation method. In the prepared alloy, under the influence of nitric or sulfuric acid, the entire amount of silver is dissolved, while the remaining gold, after weighing, gives the test of this metal in the alloy [27].

5. Material databases in simulation systems, their specifics and methods of obtaining

The problem of databases in the area of modeling and simulation has been described in [2,24]. Data on, for example, the melting point or the density of popular metals, less often alloys, are generally available. Entering them into the simulation system database is easy. The problem grows in the case of limited access to the whole dataset needed to carry out the simulation. In this case, users must conduct literature exploration or/and perform / commission laboratory experimental research. The purchase of a database is a much faster, but more expensive solution. There are companies / systems with very extensive databases that are updated periodically. A special module, for example in the NovaFlow & Solid system, called the Database, allows to access the database purchased with the program or enter user's own parameters and update the database of the program with such parameters as solidus and liquidus temperature of an alloy and variation curves of thermal conductivity, specific heat and density with temperature [24].

These preliminary databases of materials for alloys and moulds, as well as their proper analysis, help the user to make an assessment and the correct choice. This requires a decision on the readiness to introduce the values of thermophysical coefficients into the calculations. To identify the material, the name, type (cast material or mould), location, composition and physical properties as well as thermophysical properties are needed. Having such a knowledge will be sufficient to properly parametrize the program.

With the development of technology and software, simulation systems have facilitated access to an increasingly valuable database. Therefore, the results of a simulation calculation incompatible with reality due to erroneous parameterization of materials are presently less frequent, when it comes to the most popular alloys and mould materials. Casting alloys in goldsmithing does not correspond to this observation in a similar way.

NovaFlow & Solid, Magmasoft simulation systems or others have their own databases of basic cast-mould systems. If the user has a need to simulate a cast of popular metals / alloys, the information they need will be: the material of the mould and cast metal / alloy, the way of filling the mould cavity, initial temperatures (moulds, mould cavities, metal) and the fixed point of alloy introduction. However, the lack of availability of the necessary materials is not a problem. The programs have the option of updating the database, but then there is a need for detailed information and knowledge of how the values of thermophysical factors affect the results. The so-called sensitivity of simulation results to arbitrarily introduced interchangeability of individual material parameters can be tested to indicate those that affect result deviations to a high degree [24].

Data describing materials and phenomena that properly refer to reality are a guarantee of the quality of results in the simulations. When introducing a new material into the system, an important issue should be taken into account, i.e. the source of data for the material being introduced. Based on generally available information, they should be properly verified against the results of other tests. The best solution, however, is making own experiments [24].

6. Computer aided systems. Way of use of CAD/CAE (on example of Rhinoceros and NovaFlow&Solid)

The most important stage in the design of a jewelry product is the idea and translating it into a geometrical model. The ideas are translated into 3D models of varying complexity, which could be, extremely, composed of hundreds or even thousands of elementary geometries. The wide range of tools available in Rhinoceros [28,29] allows to create virtually any shape. The program's functions allow modifying basic shapes and obtaining different shapes by transforming geometry and the freedom of creative shaping. Supporting SPLOP function and UDT (Universal Deformation Technology) technologies allows superposition of 3D models, with appropriate proportions and dimensions. As stated above, it allows for any artistic modifications.

The main type of geometry used during modeling is NURBS (Non-Uniform Rational B-Spline), meaning fully editable curves and surfaces that can be combined to form complex objects. NURBS is characterized by ease of creation and high precision, which is why it is often used in technology and industry [28]).

Among the simulation systems dedicated to the foundry, two subgroups of simulation programs are distinguished, depending on the numerical solution method used, using (based on [30]).:

- orthogonal finite differences - OFDM (Orthogonal Finite Difference Method),
- finite elements - FEM (Finite Element Method)

The NovaFlow & Solid program [31,32] belongs to the first group.

There are three NovaFlow & Solid (NF&S) system modules: Pre-processing, Main processing, Post-processing. The first of them - the correct preparation of the simulation conditions - remains the most important stage (the database of alloy and material of the mould, boundary and initial conditions, geometry of the cast-mould system and its discretization).

7. Simulation studies and a validation experiment. Methodology and course of research

The conditions necessary to authenticate the results of simulation of casting processes result from the preceding description, based on own experience and literature [24,33].

In the area of simulation system applications for designing, process optimization and quality forecasting of cast jewelry products, as described in [5,6,34], the methodological approaches are practically identical to that in the case of industrial castings made of technical alloys.

In [34] the study results (equipment by NETZSCH company used) of the selected Database parameters for the 14ct gold alloy and the mould material called Silk were given. The disclosure of parameters necessary to carry out simulations for gold alloys practically does not happen. In [5,6], the importance of research on the parameters and completeness of the Database is emphasized, with the use of experimental research also on real jewelry objects.

Our simulation tests use the NF&S 6.0r5 system. Mould filling and solidification of 2 jewelry products were simulated: a ring and a signet (Figure 2). Figure 3 presents two geometries of complete layouts in the form of so-called "trees" containing cast elements (in the form of professional, multi-element and in a simplified form, containing only 2 elements from Figure1, in order to save the time of simulation realization).

For implementation of the first realized series of simulation calculations, the parameters suggested in NF&S Database for Jewelry alloys (Ag-Cu) were used.

Unfortunately, the data given there only applies to pure gold.

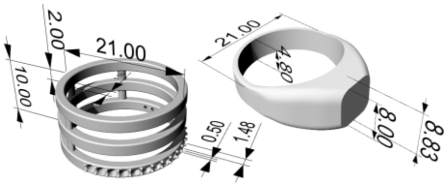

Fig. 2. Elements designed in Rhinoceros 6: ring and signet ring (geometries used in final simulations)

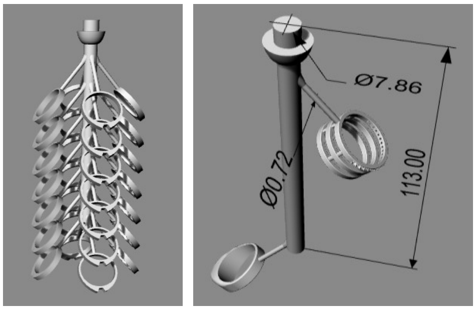

Fig. 3. Complete sets ("trees") of cast elements, (left: typical layout for serial production, right: simplified layout containing 2 elements, see Figure 1)

The data for the plaster mould material came from the same base (material called Mould - Plaster). This data is presented in Table 1. The size of the 3D discretization grid was assumed as a cube with side dimension of 0.7 mm .

Table 1.
Parameters of "Jewelry casting" proposed to simulation by NF & S system (during the first stage of our simulations)

Parameters	Poured alloy	Mould	Mould cavity:
	Pure gold	Plaster	Air in mould
Initial temperature	1160°C	600°C	600°C
Liquidus	1062.992°C	-	-
Solidus	1062.985°C	-	-
Thermal conductivity W/m/°C	318 (20°C) 257 (≥°1025°C)	2 (100°C) 0.50 (≥1000°C)	
Specific heat J/kg/°C	128 (20°C) 170 (≥1070°C)	840 (20°C) 1200 (≥1000°C)	
Density, kg/m^3	19300 (20°C) 18320 (1060°C) 18270 (≥1080°C)	1500 (20°C} 1250 (≥1000°C)	
Latent heat, kJ/kg	65	-	

Results of simulation of the layout (sequence of loss of liquid phase) with use of the simplified geometry is shown in Figure 4.

The conclusion that follows from this first step of the calculation shows that the pre-processing parameters should still be modified on the basis of intuition, to facilitate the complete filling of the mould cavity (Table 2).

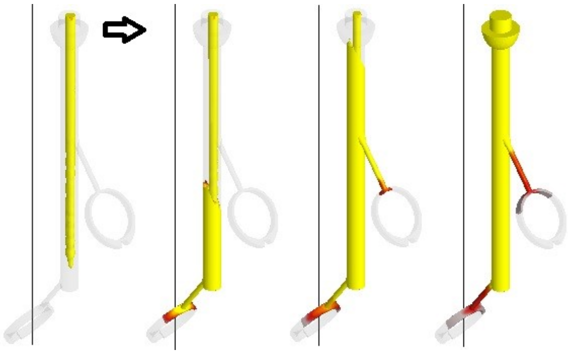

Fig. 4. Visualization of 4 stages of the process simulation, indicating the unexpectedly rapid course of solidification at the end of filling and the formation of misruns in both elements (the metal has solidified before filling the mould cavity)

Table 2.
Modified parameters of "Jewellery casting" proposed to simulation by NF&S system (during the second stage of simulations). The simulation results (Figure 5) are not satisfied.

Parameters	Poured alloy	Mould	Mould cavity:
	Pure gold	*PlasterZI150418*	Air in mould
Initial temperature	1300°C	700°C	700°C
Liquidus	1062.992°C	-	-
Solidus	1062.985°C	-	-
Therm. conduct. W/m/°C	318 (20°C) 257 (≥°1025°C)	0.4 (constant value)	
Specific heat J/kg/°C	128 (20°C) 170 (≥1070°C)	840 (constant value)	
Density, kg/m^3	19300 (20°C) 18320 (1060°C) 18270 (≥1080°C)	1250 (constant value)	
Latent heat, kJ/kg	65	-	

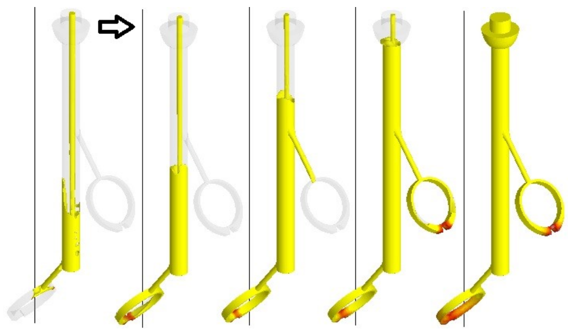

Fig. 5. Visualization of 4 stages of simulation after changing parameters according to Table 2 (almost complete filling of mould cavities was achieved).

The initial series of simulations allowed to state that compatibility of database in NF&S with the real conditions requires performing basic tests in the form of thermal analysis of

Au-Ag-Cu alloy solidification (with Zn addition) – the chemical composition is presented in Table 3.

Table 3.
Chemical constitution of Au-Ag-Cu (+Zn) alloy for the studies

Composition of Au-Ag-Cu alloy	14 carat (585)	
	Weight %	g
Au	59.00	16.31
Ag	14.00	3.87
Cu	23.00	6.36
Zn	1.40	0.39
Total	97.40	26.92
Impurities	2.6	0.72

The tests were carried out by melting the alloy in ceramic crucibles heated by a gas burner or in a laboratory furnace, using borax as a flux (Figure 6).

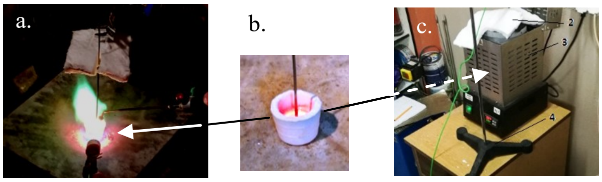

Fig. 6. Elements of workplaces for thermal analysis: a - propane-butane burners, b - 15 cm^3 ceramic crucible and K-type thermocouple, c - laboratory furnace with capacity of 1200W, T_{max} = 1150°C

The results of the heating and cooling curves are shown in diagrams in Figures 7 and 8.

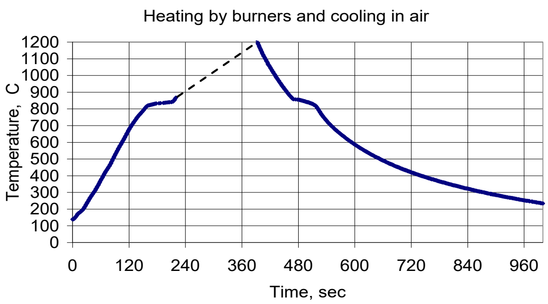

Fig. 7. Heating and cooling curve for study no.1 (specimen 1)

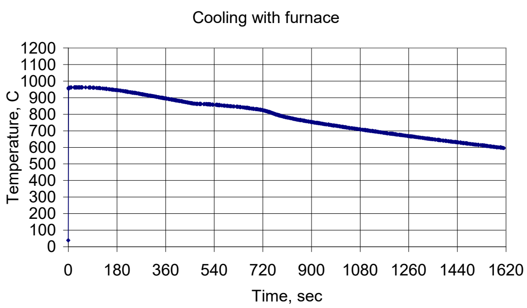

Fig. 8. Cooling for study no. 2 (specimen 2)

Specimen 1 (heating with a burner) was cooled down under ambient temperature conditions. Specimen 2, after melting in the oven, was cooled along with the furnace to identify the effect of very slow cooling.

On the basis of the presented graphs, both characteristic alloy temperatures were estimated: T_{liq} = 868°C, T_{sol} = 832°C. A new set of parameters for final simulations is shown in Table 4.

Table 4.
Final modification of Au-Ag-Cu (+Zn) parameters used to simulate the elements shown in Figure 2b in NF&S system

Parameters	Poured alloy	Mould	Mould cavity:
	Pure gold	Plaster	Air in mould
Initial temperature	1100°C	600°C	600°C
Liquidus	868°C	-	-
Solidus	832°C	-	-
Therm.conduct. W/m/°C	318 (20°C) 257 (≥°1025°C)	0.25 (100°C) 0.43 (≥1000°C)	
Specific heat J/kg/°C	128 (20°C) 170 (≥1070°C)	900 (20°C) 1130 (≥1000°C)	
Density, kg/m^3	19300 (20°C) 18320 (1060°C) 18270 (≥1080°C)	1100 (20°C} 1040 (≥1000°C)	
Latent heat, kJ/kg	65	-	

The Figure (Figure 10) presents the results of the prognosis for the location of the shrinkage porosity defect, which occurred only on the signet (the region of the final solidification, see Figure 9) as a defect called the surface sunk. In the same Figure, a view of the discretization 3D mesh is shown, of cube size 0.5 mm.

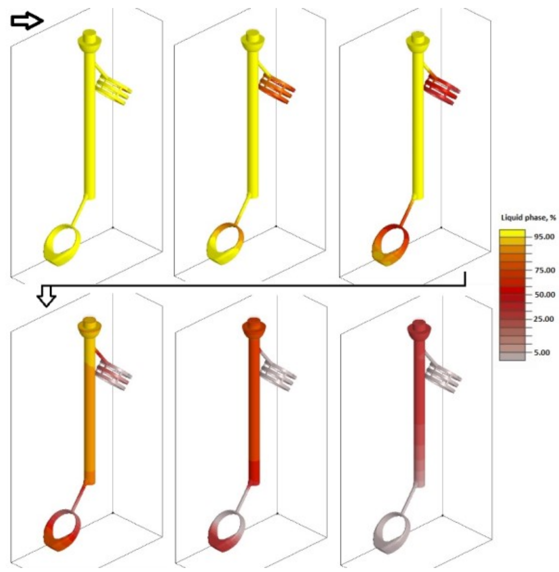

Fig. 9. Selected stages of simulation of solidification of ring and signet out of Au-Ag-Cu alloy (+Zn), discretization grid Δx = 0.5 mm

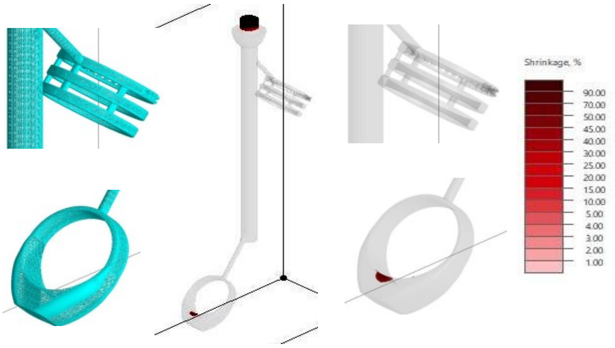

Fig. 10. Forecast of shrinkage defects in the raw cast of the ring and the signet and fragments of the 3D mesh model ($\Delta x = 0.5$ mm)

The last stage of the validation was manufacturing of a real casting, going through a 3D printing using available Form 2 printer from Formlabs company (SLA method, [25]). A photopolymer resin suitable for burning in the furnace was used for the experiment. After hardening (exposure to the UV lamp for 30 minutes), the prints prepared in this way were placed on the sprue of "tree" core. According to the rules of the goldsmith's art, a gypsum mould was made and subjected to heat treatment, finalized with its annealing (Table 5, Figure11).

Visual assessment of the castings did not show the presence of the surface sunk defects, also in places that were indicated by the NF&S system as sensitive. Internal porosity tests by non-destructive testing have not been conducted.

Table 5.
Scheme of burning a plaster mould

Operation	Temperature	Time
Evaporation of free water	177°C	1h
Removal of constitutional water	370°C	1h
Phase shift (anhydrite)	800°C	2h
Cooling to the pouring temperature	600°C	1h

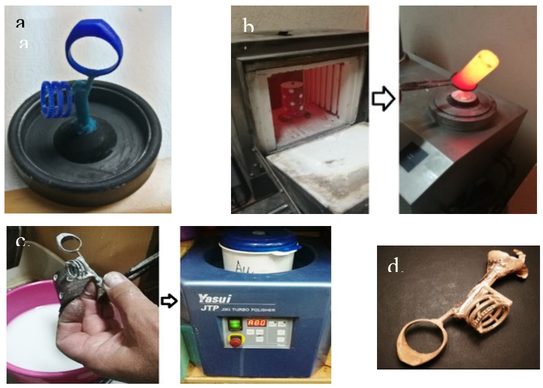

Fig. 11. View of the stages of raw casting production: a - resin model, b - burning and mould pouring, c - cleaning and polishing of the cast, d - raw casting after cleaning

It can be hypothesized that the volume shrinkage of the Au-Ag-Cu (+Zn) alloy used was less than that resulting from the variability of the density curve (Database) in terms of feeding temperature (from superheating temperature to final solidification). Nevertheless, it is certain that in the final solidification zone of the signet, the structure (more specifically, its local compactness) may contain little, insignificant discontinuities.

The dimensions of the filling system (especially thin runners) proposed in the project have been confirmed as effective, allowing a complete filling of the both mould cavities (ring and signet).

8. Summary

The genesis of the presented research resulted first of all from literature reports on simulations of jewelry shaping processes [5,6,34]. A strong emphasis was placed on the need to develop studies on databases of both precious metal alloys, mainly gold, and materials used to make moulds in jewelry (most often they are made of specially thermally treated gypsum-plaster material).

It turns out, that the main purpose of the simulation is to predict the re-creation of finesse thin-walled shapes of cast jewelry [34] (using the correct value of alloy parameters, including viscosity variability and thermophysical parameters of the plaster mould). However, the defects of shrinkage porosity, as long as they do not affect the surface quality and/or the strength and resistance to cracking, are considered acceptable.

The topics of the goldsmith and jewelry industry were first undertaken in the research of the CAD/CAE Laboratory of Materials Technology at the Poznan University of Technology. The specificity of this industry requires meeting a number of conditions, which are particularly expensive in the field of experimental research.

It was confirmed that the optimization by combining experimental and simulation studies allows for the acquisition of new knowledge, and also facilitates the creation of new artistic designs of jewelry as well as performing the feasibility check, and then optimizing the chosen technology. This will reduce the manufacturing costs of these products in the goldsmith's workshops, accelerating the stage of casting tests in real conditions and the success of the project.

Acknowledgements

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