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DEVELOPING A METHODOLOGY FOR BUILDING THE KNOWLEDGE BASE AND APPLICATION PROCEDURES SUPPORTING THE PROCESS OF MATERIAL AND TECHNOLOGICAL CONVERSION

The article presents the developed IT solutions supporting the material and technological conversion process in terms of the possibility of using the casting technology of selected alloys to produce products previously manufactured with the use of other methods and materials. The solutions are based on artificial intelligence, machine learning and statistical methods. The prototype module of the information and decision-making system allows for a preliminary assessment of the feasibility of this type of procedure. Currently, the selection of the method of manufacturing a product is based on the knowledge and experience of the technologist and constructor. In the described approach, this process is supported by the proprietary module of the information and decision-making system, which, based on the accumulated knowledge, allows for an initial assessment of the feasibility of a selected element in a given technology. It allows taking into account a large number of intuitive factors, as well as recording expert knowledge with the use of formal languages. Additionally, the possibility of searching for and collecting data on innovative solutions, supplying the knowledge base, should be taken into account. The developed and applied models should allow for the effective use and representation of knowledge expressed in linguistic form. In this solution, it is important to use methods that support the selection of parameters for the production of casting. The type, number and characteristics of data have an impact on the effectiveness of solutions in terms of classification and prediction of data and the relationships detected.

Keywords: artificial intelligence; material and technological conversion; selection of parameters; prediction of mechanical properties

1. Introduction

The aim of the research was to develop methods based on artificial intelligence that would support the selection of parameters for the production of castings in the process of material and technological conversion. The prototype module, developed with the use of selected methods, allows for an initial assessment of the feasibility of this type of procedure. In the traditional approach, the selection of product manufacturing parameters is based on the knowledge and experience of the technologist and designer. In the described approach, this process is supported by a proprietary IT solution, which, based on the accumulated knowledge, allows for a preliminary assessment of the possibility of making a selected PART in the casting technology. In the solution presented above, it is important to select and develop methods allowing to support the selection of parameters for the production of castings taking into account the specific nature of the data (solutions usually used in relation to the so-called Big Data cannot be used here, the data comes from experiments and is in a limited amount, they often relate to research for new alloys or are associated with new process parameters). The sensitivity, type, quantity and characteristics of the data being the basis for the solution under development have an impact on the effectiveness of these solutions in terms of data classification and prediction and the detected dependencies. The presented research can be applied to other processes and materials used to support decision-making processes in materials science.

2. Supporting the process of material and technological conversion

The material and technological conversion is related to the change of the material used for the production of the selected

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metal element, the change of the production technology used (for example, replacement of the forging technology with the casting technology, which requires structural changes in relation to a given element (new design, new material) [1-15]. Introducing changes is related to keeping the required technological parameters (mechanical properties), economic factors (striving to reduce the production cost of the selected element), weight (reducing the weight of the element, which reduces the cost of its production, and consequently, if it is an element used in the production of cars, this will have the effect of reducing the overall weight of the car and reducing fuel consumption). Factors that influence the choice of the manufacturing method are the batch size, dimensional accuracy, size of a part, shape complexity, size of a part, weigth and cost per piece, etc. The use of a specific type of technology or its conversion in the production of metal products requires taking into account a large number of factors, also of an intuitive nature, and difficult to introduce quantitative assessments. This is often determined mainly by the experience and knowledge of the designer who designer of a given part, as well as other circumstances that are difficult to express in formal languages. The development of a methodology for constructing a domain knowledge base and inference procedures supporting the process of material and technological conversion requires the development of an algorithm for the procedure in the described case. Such an algorithm should allow the use of combination of many techniques, such as basic knowledge, simple checking rules (such as Modus Ponens) or complex (learning or machine search algorithms) to infer decisions. Complex rules are used in the chain of inference when there is no possibility of continuing classical reasoning. Based on the facts stored in the knowledge base, new knowledge is generated that can be used in the same chain of inference to make a decision. This solution uses complex formulas of knowledge and formalisms of reasoning. The indicated inference algorithm assumes that the knowledge representation and reasoning method can be formalized as a deductive system, where the knowledge is represented by formulas that may be uncertain. Experimental work was carried out to check the course of the inference process. It was checked whether the result of the inference, in terms of supporting the decision to select the technology, allows to reduce the production costs of the metal element. Also scenarios of the use of the system were developed, referring to real case studies, on the basis of which its operation was verified. Inference was made for various cases. During the tests, variable inference rules were used. As a result of the inference, system indicated the type of material that could be used to produce a specific part in the casting technology. At this stage, the correctness of the developed IT tools was verified. It has been shown that the method of constructing the knowledge base and the applied inference models and algorithms allow for the correct inference process to be carried out with the use of the developed IT system module. An example of the described algorithm is presented in Fig. 1.

The choice of a metal product manufacturing technology is also associated with access to innovation data, which may indicate new solutions resulting from the implementation of research projects, patents and information posted on websites. For this purpose, a document search model can be used, with the use of a meta-knowledge base. An exemplary solution concerns obtaining information in the field of innovative foundry technologies. The developed methodology for creating the knowledge base and the procedures for its use are universal and can be related to any problem area. The solution is related to searching for documents and is carried out with the use of a meta-knowledge base constructed with the use of an intuitive formalism and gives the possibility to assess the degree of certainty of the obtained results. It is important here to propose the application of the approach to technological knowledge. The effectiveness of a given solution relates to functionality covering both the creation of meta-knowledge as well as a problem-oriented technological knowledge base and decision-making procedures.

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Input: φ – hypothesis formula, KB – finite set of labeled formulas, d – max
       depth, STRATEGY – strategy of the proof tree search
Output: Proofs of φ : l from KB
T := tree with one node (root) s = [φ];
OPEN := [s];
PROOFS := ∅;
while OPEN ≠ ∅ do
    n := the first element from OPEN;
    Remove n from OPEN;
    if n is empty then
        Add to PROOFS the path from s to n;
        if STRATEGY is not exhaustive then
            Return PROOFS;
        end
    end
    if the first formula of n represents action act then
        Execute act; if act was successful then
            add results of act to KB;
            E := node generated from n by removing act;
        end
    else
        K := knowledge transmutations, which consequence can be unified with
        the first formula of n;
        E := nodes generated by replacing the first formula of n by premises
        and actions of transmutations from K;
        if the first formula from n can be unified with element of KB then
            Add to E node obtained from n by removing the first formula;
        end
    end
    Remove from E nodes generating loops;
    Remove from E nodes with proofs longer than d;
    Append E to T connecting nodes to n;
    Add nodes from E to OPEN;
    Order OPEN using STRATEGY;
end
Return PROOFS;
```

Fig. 1. Developed algorithm

Data mining methods supported by rule induction algorithms based on the theory of rough sets or decision trees allow for the construction of a knowledge base in the form of a set of rules enabling inference regarding heat treatment scenarios for the alloy of a given chemical composition. Based on the rules obtained by this method, the correct classification of the variants of the selected treatment can be made. The classification problem, although known in industrial applications, is not always effectively solved due to the sensitivity, type, number and characteristics of the available training data. In this case, testing was conducted on the basis of the collected experimental data.

The constructed algorithms have the advantage that they are well scalable and provide the ability to automatically generate rules. The model of representation and the use of knowledge expressed in linguistic form differs significantly from the situation when data and knowledge are obtained through a physical experiment or have a numerical form. An important stage in building the model is the selection and implementation of an appropriate formalism of knowledge representation that allows for its effective use. This is especially the case with incomplete and / or uncertain knowledge.

As part of the work, a model of knowledge collected in the form of an attribute table was created used in relation to hybrid combination, fuzzy logic formalism and rough sets. The solution has been tested on data from the visual monitoring result, specifying the value of the attributes representing the features of the tested casting. In the long run, such monitoring can be carried out in an automated manner, through the use of image recognition methods. The key stage of the considered process is the use of the attribute table to identify the defect. The form of this table results from the essence of the information system model. The model was verified with the use of a developed, dedicated IT module.

An important aspect supporting the material conversion process is the development of a domain knowledge base regarding casting defects. This action focused in detail on the problem of casting defects, and in particular on the methodology of recording the knowledge about the causes of casting defects, and the development of a solution that will support the method of preventing defects. Knowledge that allows to avoid a defect in the production process is very important when developing a new technology and / or using a new material to produce a given structural element. The scope of knowledge covers the entire technological process. Introducing knowledge in this area into the system requires activities that include:

a) recognition of the type (name) of the defect;
b) identification of the cause of the defect, using methods of representation of knowledge that take into account its incomplete and uncertain nature;
c) indication of defect prevention methods, using the knowledge obtained from dispersed and heterogeneous sources.

When looking for a new technology, it should be remembered that the new type of material must provide at least the same mechanical and functional parameters as the original material. The choice of the production method used is influenced by the batch size, dimensional accuracy, size and complexity of shape, type of necessary machinig and thermal treatment, etc. These factors also create the final cost of the product. In this situation, the decision problem faced by the designer of a specific product (machine part) consists in the selection of material and its production technology, which ensure the fulfillment of specific technical requirements, while allowing the minimalization of production costs. In the work [6], the data allowing to compare the group of group of castings made of ausferritic ductile iron (ADI) with other technologies and materials used for their production were summarized. These data were taken as the basis for the creation of a knowledge base expressed in terms of Reliable Reasoning Logic (LPR), taking into account the knowledge obtained from experts. The presented solution takes into account the fact that its basis is the possibility of collecting and sharing incomplete and / or uncertain knowledge, because many premises in the field of foundry technologies are intuitive. The use of LPR in these conditions is an innovative approach, making it possible to map human reasoning. The production process of metal products is associated with many aspects that affect the final product. Among others, aspects related to the acquisition and integration of knowledge from different available sources, may support the improvement of production processes. The second aspect is the choice of production variants, especially in the context of creating new products or improving the properties of those already implemented in production. In the above-mentioned thematic areas, an important form of support for technologists are IT systems with the functionality of knowledge processing based on artificial intelligence methods. The new type of material must provide at least the same mechanical properties and reliability as the original. The choice of the production method is influenced by: batch size, dimensional accuracy, dimensions of a part, complexity of shape, type of machinig and heat treatment processes. All of these factors are also included in the cost of production. In this situation, the problem that the designer and technologist of a given product (machine parts) must face is the choice of material and the method of its production, which will ensure that certain technical to be met, and will allow for the maximum reduction of production costs at the same time. When using the proprietary LIIS (LPR Intelligent Information System) system considered here, it is very important to indicate the appropriate material that could replace traditional materials (forged steel, cast steel). This material can also be heat treated ductile iron (ADI), which has a favorable relationship between tensile strength (Rm) and elongation (A5), while offering significantly lower production costs (savings of about 20%). The decision to use ADI cast iron, however, must be based on a more detailed analysis of the requirements imposed on the product and its properties, including, for example, damping capacity, corrosion resistance, dimensions, batch size or weight of a single casting? The basis of the knowledge base are hierarchies that were defined during consultations with experts. In order to show the course of the process of selecting the appropriate technology and material, scenarios have been developed, showing how, for example, a dialogue can be established between the system supporting such a process and the person responsible for the selection of the material. It is worth noting that the entire process is based on information from an expert (usually a designer). The important thing here is that it is a verbal message. There is no formula, method or algorithm that will allow for the conversion.

For the entire process, you can only define its framework. The scenarios are intended to show an example of a simplified scheme of proceeding in the case of searching for the appropriate material and / or technology that should be used in the conversion process. The scenarios show examples of events where there is a small amount of external information (premises) that will allow to indicate an appropriate solution. They are obtained as a result of human or system reasoning, on the basis of accumulated knowledge. This knowledge does not come from a single source, but from many heterogeneous sources. The inference process requires the ability to associate even seemingly unrelated facts, and to take into account the uncertainty of the context, similarity and hierarchy. This possibility is provided by the construction of a applied system with the use of LPR.

The operation of the described solution was checked on the basis of the developed scenarios presented in the Figs. 1 and 2. In a given Iron Plant of the Foundry Institute in Krakow, currently the Casting Technology Center in Łukasiewicz Research

Fig. 2. Scenario 1

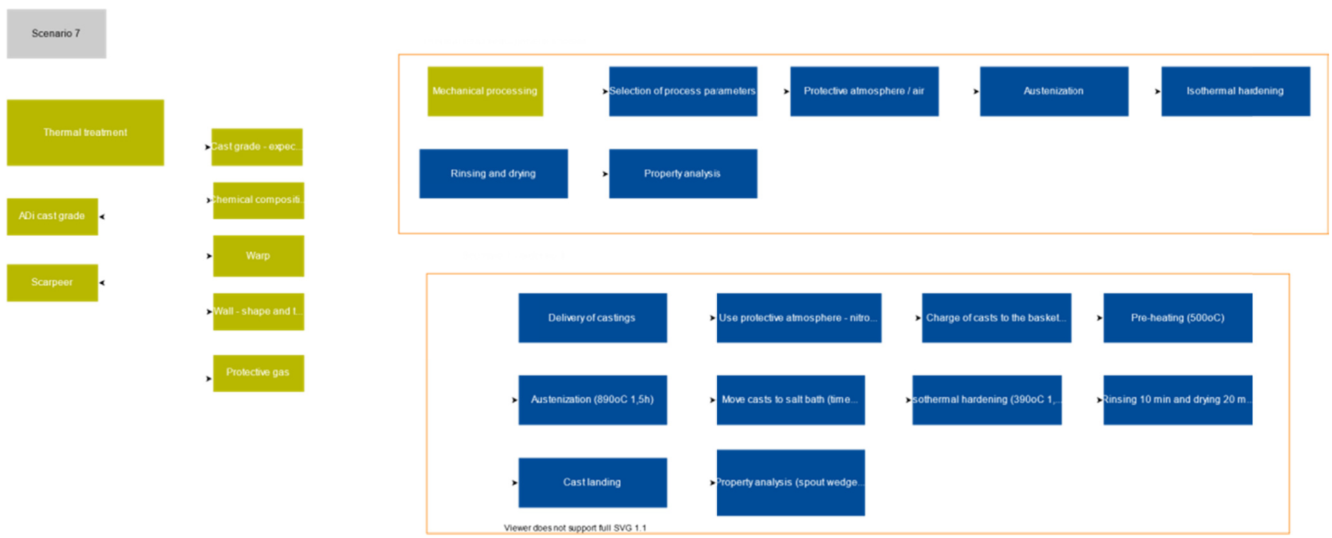

Fig. 3. Scenario 7

Network – Krakow Institute of Technology, trial series of castings were made. The material and technology used to make these tools confirm the operation of the scenarios used to verify the developed knowledge base and inference system.

The analysis of the impact of isothermal transformation parameters on the impact toughness of unalloyed cast iron with spheroidal graphite may be a simple solution to build a model. In the described case, cast iron from three different heats with chemical compositions (W1, W2, W3) presented in TABLE 1 was used for the tests.

TABLE 1

Chemical composition of cast iron,% wt

Mark of the melt	C	Si	Mn	P	S	Mg	Cu	Ni
W1	3,65	2,59	0,18	0,052	0,014	0,060	—	—
W2	3,41	2,62	0,30	0,046	0,016	0,056	0,48	—
W3	3,39	2,62	0,29	0,042	0,010	0,036	0,51	0,72

1644 / 5000

The critical temperatures during continuous heating and cooling at a constant speed (0.019 K/s) were determined using a dilatometer. The microstructure of cast iron melts was investigated. Mechanical properties of the tested castings were determined. An impact test was carried out on a PSW 300 Charpy hammer with a maximum impact energy of 300 J. The experimental data concerned the production of ADI cast iron in two variants of heat treatment and three melts with different chemical compositions. Additionally, three separate samples were tested for each case. The obtained results were analyzed. The first stage consisted in determining the qualitative and quantitative variables. The correlations were then checked using the linear Pearson correlation coefficient. On the basis of the analysis, it can be concluded that the determined correlation coefficients clearly indicate a strong dependence of the impact toughness on the ausferritization temperature. The austenitizing temperature as well as the austenitizing temperature after subcooling have a much smaller effect on the impact toughness. The conducted analysis showed that the ausferritization time did not affect the obtained values of the measured impact toughness. With regard to the qualitative variables, it can be concluded that the variable of the heat treatment variant has an impact on the impact toughness, as does the variable of the melt (chemical composition). The performed analysis confirmed that the determination of the sample variable had no influence on the impact toughness. Based on the analysis, it can also be concluded that the influence of the chemical composition is smaller than that of the heat treatment parameters. The next step was to apply the regression equation as presented below:

$$KV = 0{,}065815 * T_{AF} + 0{,}004086 * T_{A2} - 0{,}014061 * T_A$$

where:

- T_A (t_g) – nominal austenitizing temperature; range: <830,950> [ºC],
- T_{A2} ($t_{g'}$) – austenitizing temperature after subcooling, domain: {830; 860; 900; null} [ºC] (no value for processes without cooling – variant V1) — the variable can also be considered a qualitative variable depending on the calculation method used,
- T_{AF} (t_{pi}) – ausferritization temperature, range: {300; 400} [ºC] – this variable takes only two possible values; it can also be treated as a qualitative variable depending on the calculation method used,
- KV – breaking energy value KV, J; range: <5,4; 19,9> [J].

The conducted analyzes showed that linear regression does not allow taking into account the influence of categorical predictors. However, it is possible to define how the categorical variables influence the *KV*. Moreover, it was found that variant II of heat treatment (with sub-cooling) increased the average values of impact toughness. It can also be noticed that heats 2 and 3 have higher *KV* values, which means that the addition of Cu and Ni increases the impact toughness, as does the pre-cooling. In the next stages of the work, the data were analyzed using approximation methods that allowed the use of both quantitative and qualitative variables. Each of these methods offers a different way to obtain forecasts that provide different functions. In the developed approach, the methods using decision trees obtained the most precise and accurate results, especially with the use of CART (Classification and Regression Tree) induction. Such an assessment is caused not only by the high-quality obtained approximation, but also by the easy interpretation of the obtained results by a human. The last feature in the presented approach is important in the context of adapting the developed solutions in systems supporting the process of material and technological conversion. The experience gained during the system building process shows that the use of data analysis methods, allowing for their easy interpretation, ensures functionality in the eyes of technologists. All the results obtained in the data analysis process have been experimentally verified under laboratory conditions.

3. Summary

A dedicated inference algorithm, which is a part of the information and decision-making module with a knowledge base, as well as the introduced modification of the formalism, enabling the recording of domain knowledge, were presented. A solution for obtaining information on innovative foundry technologies, in the field of creating meta-knowledge, problem-oriented technological knowledge base, as well as decision-making methods in information systems were presented. The methodology of building the knowledge base with the use of rough sets and the development of a knowledge model in the form of an attribute table, which is a hybrid combination of the fuzzy logic formalism and rough sets, as well as the developed solution for the selection of knowledge representation methods using formalisms, supporting the process of diagnosis of casting defects were presented. The aforementioned works help to support the process of material and technological conversion. These relationships have been confirmed experimentally. In the process of creating this class of solutions, decision-making systems require large amounts of data. The problem is getting enough data through a physical experiment. Methods for assisting the casting production parameters selection were described. For example, methods that allow the knowledge base to be supplemented with data on the selection of heat treatment parameter values to obtain ausferritic ductile iron with appropriate impact strength using machine learning methods, supporting vet machines, decision trees, and neural networks. The obtained results of the works have been confirmed experimentally.

The results presented in the publication were obtained in the projects "Innovative production process of cast iron castings using an intelligent information and decision-making system." Task 2. "Industrial network infrastructure" under the Intelligent Development Operational Program for 2014-2020, INNOMOTO sector program, POIR.01.02.00-00-0248 / 1, implemented in the period 01/09/2017-31/03/2018, financed by the National Centrum Badan i Rozwoju, and in the project LIDER / 028/593 / L-4/12 / NCBR / 2013, Information and decision-making system supporting the production of ADI cast iron, implemented in the period 01/12/2013 – 30/09/2017, financed by the National Center for Research and Development.

The use of IT tools in the process of material and technological conversion enables a preliminary assessment of the feasibility of a given process. The presented proprietary solutions in the field of inference algorithms, formalisms for recording domain knowledge and the construction of knowledge bases, as well as supporting the selection of the chemical composition and parameters of the technological process allow for limiting the number of physical experiments in laboratory or industrial conditions, and in the case of their implementation, for more precise planning of work. The presented solution is a tool supporting the technology of manufacturing specific products. This solution has been tested in the context of the production process of forestry machinery components under the TECHMATSTRATEG 1 project as part of the project with the acronym INNOBIOLAS entitled "Development of innovative working elements for forestry machines and biomass processing based on high-energy surface modification technologies of the surface layer of cast elements"; agreement no. TECHMATSTRATEG1 / 348072/2 / NCBR / 2017. The developed methods open the possibility of increasing the efficiency of supporting foundry processes by introducing solutions based on artificial intelligence and data analysis, the use of which to construct systems allows the subject area to cover a much larger range of data, so far omitted due to their incompleteness, uncertainty, heterogeneity and the fact that many of the premises in the field of foundry technologies are intuitive. The developed predictive algorithms and machine learning methods were the basis for the continuation of work under the project POIR.04.01.04-00-0027 / 18-00. Development of innovative technical and material solutions was used in the construction of an autonomous agrorobot under Measure 4.1 of the Intelligent Development Operational Program 2014-2020 co-financed by the European Regional Development Fund

In particular, the following should be indicated as significant components of the presented achievements:

1. Supporting innovative production technologies on the basis of experimental data with the use of artificial intelligence methods;
2. Formalization and processing of domain knowledge in order to adapt it to the implemented decision-making procedures;
3. Document search model, with the use of a meta-knowledge base.
4. Development of a methodology for constructing heuristic models that enable finding (estimating) relationships between important process parameters;
5. Searching for domain knowledge with the use of dedicated programming tools;
6. Supporting technological conversion with the use of artificial intelligence formalisms
7. Development of the concept and implementation of proprietary prototype solutions supporting the production processes of castings.

Prototype solutions were tested using the available experimental data.

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