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Case-Based Reasoning System for the Selection of Silumin Alloying Elements

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Abstract

This work presents the project of the application of Case-based reasoning (CBR) methodology to an advisory system. This system should give an assistance by selection of proper alloying additives in order to obtain a material with predetermined mechanical properties. The considered material is silumin EN AC-46000 (hypoeutectic Al-Si alloy) that is modified by the addition of Cr, Mo, V and W elements in the range from 0% to 0.5% in the modified alloy. The projected system should indicate to the user the content of particular additives so that the obtained material is in the chosen range of parameters: tensile strength R_m, yield strength $R_{p0.2}$, elongation A and hardness HB. The CBR methodology solves new problems basing on the solutions of similar problems resolved in the past. The advantage of the CBR application is that the advisory system increases knowledge base as the subsequent use of the system. The presented design of the advisory system also considers issues related to the ergonomics of its operation.

Keywords: Application of Information Technology to the Foundry Industry, Mechanical Properties, Silumin Alloying Elements, Case-based Reasoning

1. Introduction

From a general point of view, silumin is characterized by many desirable features, among which corrosion resistance, machinability and good castability can be mentioned. Belonging to the group of low density alloys, silumin is distinguished by electrical and thermal conductivity and also by high strength properties. Thanks to these features, silumin has many applications in electromechanics. Particular applications require specific mechanical properties, which differ from those presented by silumin EN AC-46000. The addition of Cr, Mo, V and W causes changes in silumin microstructure and may enable to achieve predetermined mechanical properties by such a way modified material [1-3].

The overall goal of presented here work is to design an advisory system that facilitates the selection of proper alloying additives and their content in order to obtain modified silumin characterized by predetermined mechanical properties. This system can be realized as a computer application, which as the input takes combination of ranges of desired parameters (tensile strength R_m, yield strength $R_{p0.2}$, elongation A and hardness HB) and as the output returns possible ways to produce such material by indicating content of Cr, Mo, V and W elements adding to silumin EN AC-46000. The base of an advice given by the system is a set of data obtained through experiments that are done in the past. The system should also be open to entering data obtained in future experiments or as a result of the production process.

2. Case-based reasoning

Case-based reasoning (CBR) is a paradigm of problem solving, which is different from other approaches in Artificial Intelligence. CBR reuses knowledge related to similar problems and their solutions that were experienced in the past instead of making and using generalized relationships between problem descriptors and conclusions. This paradigm enables also incremental, sustained learning, because the knowledge related to presently solved problems is retained and is available for reuse by a future reasoning [4].

The CBR methodology is applied to many classes of problems, among others can be mentioned automatic design (a solutions has to fulfill required constraints), planning (a solution is in the form of a schedule for achieving some state of the world), diagnosis (a solution should explain a set of given symptoms), classification, interpretation [5] and process control [6]. The overall view of CBR application to the domain of foundry industry is presented in [7].

The basic concept in CBR is a case. A case describes a specific problem and its solution that are registered in the past. In other words, a case is a pair of a problem and its solutions that both can be described as vectors of any attributes. A set of all cases used by a reasoning system is called a case base [8]. The case base is a form of the organization of the knowledge used by the reasoning.

2.1. The CBR cycle

The main algorithm of case-based reasoning is the CBR cycle [4]. Its consists of four sequential steps, called also processes or phases: (1) retrieve, (2) reuse, (3) revise, (4) retain. The CBR cycle starts when a current problem (called also a new problem) is specified and has to be solved.

In the retrieve phase the case base is searched for cases, which represent problems being most similar to the current problem. Assuming a problem is represented by a vector of real numbers, the similarity measure can be based on Euclidean distance. The cases representing most similar problems to the new problem are passed to the next phase.

In the reuse phase they are reused to solve the current problem. This process can be realized by an adaptation of the past solutions to the present problem, however in many application the past solutions are directly presented as the solutions for the current problem without any method of adaptation.

In the revise phase an assessment of the solution is made, which is returned in the previous phase. This assessment usually requires intervention of an expert or implementation of the returned solutions to the real environment. A weak assessment can lead to a correction of the solution.

The aim of the next, retain phase is to add the current case to the case base. The current case already represents the current problem (specified at the start of the CBR cycle) and the solution (returned in the reuse phase and possible corrected in the revise phase). The retention of this case allows to use knowledge related to the presently solved problem in the future reasoning of the system. After completing of the retain phase, the system is ready to solve a next problem, what involves a next run of the CBR cycle.

3. Experimental data

The projected advisory system requires data that are basis for creating the initial case base. The data originates from experiments that use silumin EN AC-46000 as the base material that is modified by addition of Cr, Mo, V and W elements. Chemical composition of silumin EN AC-46000 is included in the standard [9]. The base material is melted in a gas-heated shaft furnace and refined with an Ecosal Al 13.S solid refiner. After tapping into the ladle and deslagging, silumin is transported to a holding furnace, where the Cr, Mo, V and W alloying additives are introduced to the base alloy in the form of the AlCr15, AlMo8, AlV10 and AlW8 master alloys. The process of the alloying additives introduction is repeated several times with different quantity of the individual master alloys. The content of the Cr, Mo, V and W elements ranges from 0% to 0.5% in the modified alloy.

Castings are made on the Idra 700S die casting machine with a horizontal cold chamber. The predominant wall thickness in the castings is 2mm. Three specimens of 2x10mm rectangular cross-section are cut out from each cover in order to test the strength of the die castings. By that means prepared material is used in experimental tests that determined the following parameters: the tensile strength R_m, the yield strength $R_{p0.2}$, the relative elongation A and the hardness HB.

The data obtained during experimental tests consists of 84 records with varied content of the alloying additives. Each record includes the content of the Cr, Mo, V and W elements and also the determined mechanical properties: R_m, $R_{p0.2}$, A, HB. A cursory review of data indicates the impact of the content of the individual alloying additives on the mechanical properties of modified silumin.

4. Descriptive statistics of data and machine learning

The general problem raised in this article is how to give an advice according proper selection of process parameters regarding experimental data. This problem is usually solved by automatic acquisition of knowledge in the form of rules concerning the phenomena and relationships between process parameters. In this field methods of statistics and machine learning are used such as: induction of decision trees, fuzzy logic inference models and rough set theory applied to classification and approximation problems [3,7].

There are many dependent variables in the studied problem (the alloy properties $\{R_m, R_{p0.2}, A, HB\}$) and several explanatory variables (the content of the elements {Cr, Mo, V, W}). It is a system very difficult for analysis by the methods of regression, which allow using only one dependent variable. Studies of the relationships between variables were performed using Pearson’s linear correlation coefficient. The correlation coefficients seemed to be promising, however the relationships are well visible, but configurations of individual points indicate a strongly non-linear character of these relationships. In the situation when more independent variables enter the statistical model, we are dealing with the multivalued/multivariate model of regression. Then it should be remembered that the input variables can be mutually correlated, and that their influence may be aggravated by the influence of other variables - the situation that is commonly known as the occurrence of an interaction. In such a system, the simulation with regression models is hardly possible. Regression and even MARSplines models [3] have not been given satisfactory fitness however, they allowed to draw conclusions: with the small content of the alloying additives (0.05-0.2% on average), the values of mechanical properties are growing, but as soon as the content of the alloying additives starts increasing, the drop in the properties begins (fig1.).

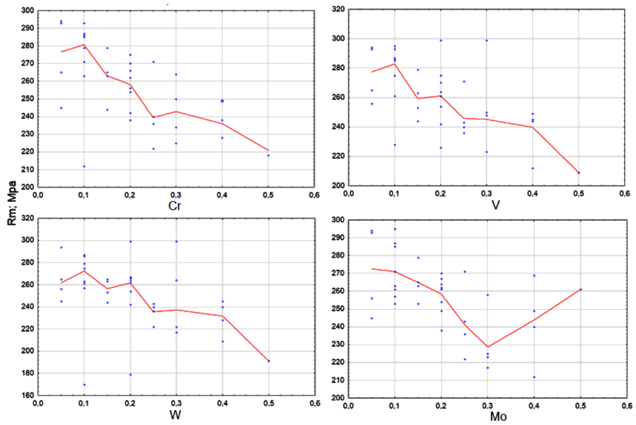

Fig. 1. Scatterplots for tensile strength R_m × alloying elements with lowess curve fitting

Such models are not able to allow for the effect of mixtures, i.e. interactions between input variables. In further part of the research, an approach to knowledge acquisition based on searching for patterns in the data will be presented. The aim of this approach is to determine qualitative relationships in the case of interaction of multiple input variables and their effect on the accompanying dependent variables in a multivariable model.

As above presented analysis shows the 84 records of the experiment data are not enough to show the rules according the impact of four parameters relating to the content of Cr, Mo, V and W elements (in the range from 0% to 0.5% in the modified alloy) on the mechanical properties of modified silumin. This conclusion justifies the application of the CBR methodology that reuses knowledge related to similar problems instead of using generalized relationships (rules) between problem descriptors and conclusions. The CBR enables also to increase knowledge base as the subsequent use of the system.

5. Design of the advisory system

By the design of the advisory system case-based reasoning (CBR) is used, which is presented in the 2-nd section. The application of CBR enables the system to solve problems with the reuse of earlier registered data (including the data obtained during the performed experimental tests) and also enables learning on the base of results of tests that will be done in the future.

5.1. Construction of a case

A case describes a specific problem and its solution. The default user of the system is a technologist. He needs an advise in the selection of the proper alloying additives (and their content) in order to obtain the material with the predetermined mechanical properties. The problem is therefore to obtain the modified silumin that is characterized by the determined mechanical properties: R_m, $R_{p0.2}$, A, HB. The solution describes the content of the Cr, Mo, V and W elements, which have to be introduced to the base alloy in order to solve the specific problem, what means to obtain the material characterized by the specific mechanical properties.

Taking into account the ergonomics of the system, we propose that the problem is represented by classes for each mechanical property. It means that the user enters the specific class of the individual mechanical property instead of specifying the precise value of the mechanical properties. Such a method of data input should be easier than entering of specific values of the individual mechanical properties. The proposed classes are presented in Table 1.

Table 1.
The classes of the mechanical properties

The name of the class	The numeric representation of the class	R_m; MPa	$R_{p0.2}$; MPa	A; %	HB
very low	1	[0, 195.80)	[0, 102.20)	[0, 2.74)	[0, 103.60)
low	2	[195.80, 221.60)	[102.20, 114.40)	[2.74, 3.68)	[103.60, 108.20)
medium	3	[221.60, 247.40)	[114.40, 126.60)	[3.68, 4.62)	[108.20, 112.80)
high	4	[247.40, 273.20)	[126.60, 138.80)	[4.62, 5.56)	[112.80, 117.40)
very high	5	[273.20, ∞)	[138.80, ∞)	[5.56, ∞)	[117.40, ∞)

Due to the number of data, a larger number of classes should not be created, so that the numbers in particular intervals do not drop below 5. In turn, a smaller number of classes would not allow to reflect the natural distribution of these features (Fig.2.).

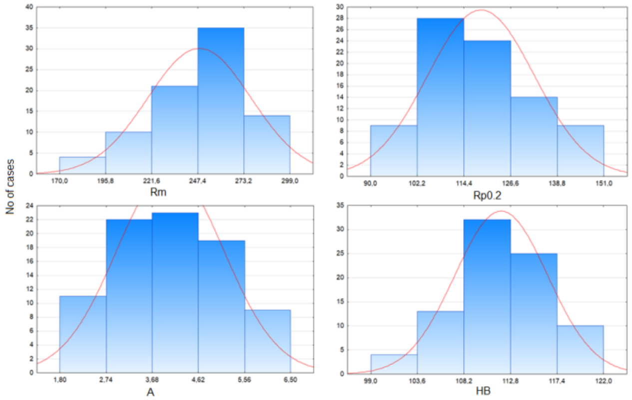

Fig. 2. Empirical distribution of properties

The ranges of the classes are selected according to the overall range of data obtained during the performed experimental tests. Having regard to this idea the problem p_i (as a part of a case) is defined as the vector:

$$p_i = \left(cl_i^{rm}, cl_i^{rp}, cl_i^{a}, cl_i^{hb}\right) \tag{1}$$

where cl_i^{rm} is the numeric representation of the class of the tensile strength R_m, cl_i^{rp} is the numeric representation of the class of the yield strength $R_{p0.2}$, cl_i^{a} is the numeric representation of the class of the relative elongation A, cl_i^{hb} is the numeric representation of the class of the hardness HB (each for the problem p_i).

The solution s_i of the problem p_i is represented as the vector:

$$s_i = \left(co_i^{cr}, co_i^{mo}, co_i^{v}, co_i^{w}\right) \tag{2}$$

where co_i^{cr} represents the content of Cr, co_i^{mo} represents the content of Mo, co_i^{v} represents the content of V, co_i^{w} represents the content of W (introduced to the base alloy in order to solve the problem p_i, what means introduced to the base alloy in order to obtain the material characterized by the classes: $cl_i^{rm}, cl_i^{rp}, cl_i^{a}, cl_i^{hb}$).

A case describes an individual problem and its solution, so the case $case_i$ is defined as the vector:

$$case_i = (p_i, s_i) = \\ \left(\left(cl_i^{rm}, cl_i^{rp}, cl_i^{a}, cl_i^{hb}\right), \left(co_i^{cr}, co_i^{mo}, co_i^{v}, co_i^{w}\right)\right) \tag{3}$$

The case base Δ, as the representation of the knowledge of the reasoning system, contains all cases used by the reasoning system:

$$\Delta = \{case_1, case_2, \ldots, case_N\} \tag{4}$$

where N is the number of cases.

Before the first use of the projected advisory system the initial case base has to be prepared [10]. The initial case base contains 84 cases ($N = 84$) created according to 84 records of the experimental data (as presented in the 3-rd section of the article).

Example 1.

One exemplary record of experimental data is as follows: content of Cr = 0.15%, content of Mo = 0.15%, content of V = 0.15%, content of W = 0.00%, R_m = 279 MPa, $R_{p0.2}$ = 138 MPa, A = 5.3 %, HB = 110. Taking into consideration the proposed classes of the mechanical properties (as presented in Table 1.), this record concerns the material of the 5-th R_m class (very high tensile strength), the 4-th $R_{p0.2}$ class (high yield strength), the 4-th A class (high elongation) and the 3-rd HB class (medium hardness). This record is transformed into a case, which:

- represents a problem: how to obtain a material of the 5-th R_m class, the 4-th $R_{p0.2}$ class, the 4-th A class and the 3-rd HB class?
- represents a solution: modify silumin by the addition of Cr = 0.15%, Mo = 0.15%, V = 0.15% and W = 0.00%.

This case is numerically represented as $case_x = (p_x, s_x) = \big((5,4,4,3), (0.15\%, 0.15\%, 0.15\%, 0.00\%)\big)$. This case is one of the case base Δ. The case base initially contains 84 cases according to available experimental data.

5.2. Specification of a current problem

The current problem relates to the new problem that has to be solved by the projected advisory system. The problem is to obtain the modified silumin that is characterized by the determined mechanical properties. As it is presented in Table 1., we propose to use the specific classes (very low, low, medium, high, very high) for each of the mechanical properties (R_m, $R_{p0.2}$, A, HB). So, the current problem may be specified by entering a specific class for each of the mechanical properties. However, it should be taken into account that the technologist can be interested in obtaining advices, which concern only a part of the properties. It is even possible that the user wants to obtain a help according a modification of silumin, which enables to achieve a predetermined class of only one specific mechanical property, e.g. the hardness HB. It is therefore assumed that some mechanical properties can be irrelevant by the specification of the problem that has to be currently solved. So, the current problem p_{cur} is defined as:

$$p_{cur} = \left(\left(r_{cur}^{rm}, cl_{cur}^{rm}\right), \left(r_{cur}^{rp}, cl_{cur}^{rp}\right), \left(r_{cur}^{a}, cl_{cur}^{a}\right), \left(r_{cur}^{hb}, cl_{cur}^{hb}\right)\right) \tag{5}$$

where r_{cur}^{rm} is the relevance of the tensile strength R_m in the current problem (0 – irrelevant, 1 – relevant), cl_{cur}^{rm} is the numeric representation of the class of the tensile strength R_m, and similarly for all other properties $R_{p0.2}$, A, HB.

Thanks to such definition of the current case we give the technologist an opportunity to specify only selected mechanical properties. This is very important in terms of ergonomics of the system use.

Example 2.

Assuming that the technologist is looking for material of very high tensile strength without any other constraints according mechanical properties, the current problem should indicate the 5-th R_m class and irrelevantness of all other classes of the mechanical properties. This current problem is numerically represented as $p_{cur} = \big((1,5), (0,0), (0,0), (0,0)\big)$.

5.3. The retrieve phase

As it is presented in the 2-nd section, the reasoning of a CBR system starts immediately after the current problem is specified. The first phase of the reasoning is the retrieve phase. During this phase the aim of the projected advisory system is to select in the case base Δ the most similar cases to the current problem p_{cur}. The case base Δ is defined by the equation (4) and the current problem p_{cur} is defined by the equation (5). The selection process requires the use of a similarity notion that is a function, which usually gives a similarity assessment as a real value from [0, 1], as presented in [8]. We propose the similarity measure that is based on the Euclidean distance and that takes into account the relevance of the individual mechanical properties:

$$sim(p_{cur}, case_i) = \frac{1}{1 + \sqrt{r_{cur}^{rm} * \left(cl_{cur}^{rm} - cl_i^{rm}\right)^2 + \cdots + r_{cur}^{hb} * \left(cl_{cur}^{hb} - cl_i^{hb}\right)^2}} \tag{6}$$

The algorithm of the retrieve phase computes the similarity for each one case in the data base Δ.The result of the algorithm is the set Rel that contains the most similar cases to the current problem that is specified earlier by the user.

Example 3.
Assuming the current problem presented in the Example 2, the CBR system computes the similarity between the current problem $p_{cur} = \big((1,5), (0,0), (0,0), (0,0)\big)$ and each one case in the data base Δ. It is clear that the most similar are cases, which represent problem strictly related to the 5-th R_m class (without any relevance to other mechanical properties). The set Rel contains all cases from the data base Δ, which strictly relate to the 5-th R_m class.

5.4. The reuse phase

We propose that the projected advisory system displays the set Rel during the reuse phase. This set is the output of the previous phase of the overall reasoning. We do not propose to use any adaptation method, because individual solutions contained in the set Rel can be different, as different ways to achieve the same goal. As an example to this remark, a situation can be given that the current problem relates to obtaining the modified silumin, which is characterized by the very low class of the hardness HB. The initial case base contains 4 cases that represent different solutions in order to obtain silumin characterized by the very low class of the hardness HB. These 4 solutions are different – concern different alloying additives that are introduced to the base alloy. The technologist can choose a particular solution from the set Rel according to his knowledge or technical possibilities.

Example 4.
Continuing the Example 3, the CBR system displays the computed set Rel that contains the most similar cases to the current problem presented in the Example 2:

- $\big((5,5,3,3), (0.10\%, 0.00\%, 0.10\%, 0.00\%)\big)$,
- $\big((5,4,3,1), (0.20\%, 0.00\%, 0.20\%, 0.00\%)\big)$,
- $\big((5,5,3,4), (0.10\%, 0.00\%, 0.00\%, 0.10\%)\big)$,
- …,
- $\big((5,4,4,3), (0.15\%, 0.15\%, 0.15\%, 0.00\%)\big)$.

Above are shown only 4 cases. The whole set Rel contains 12 cases. The last shown case is the case presented in the Example 1.

5.5. The revise phase

The base of the revise phase is the preparation of silumin according to the chosen solution at the previous phase. This material has to be used in experimental tests that determine the mechanical properties: the tensile strength R_m, the yield strength $R_{p0.2}$, the relative elongation A and the hardness HB. If the mechanical properties differ from the classes specified by the current problem, the technologist is expected to choose another solution from the set Rel. This solution has also to be assessed by the preparation of silumin and the determination of its properties.

Example 5.
Continuing the previous Example, the technologist chooses one case from the whole set Rel e.g. $\big((5,4,4,3), (0.15\%, 0.15\%, 0.15\%, 0.00\%)\big)$. The chosen case represents a solution: modify silumin by the addition of Cr = 0.15%, Mo = 0.15%, V = 0.15% and W = 0.00%. The technologist is expected to revise this solution by preparation of such modified silumin and determination of its mechanical properties. Assuming the experimental test revels R_m = 282 MPa, $R_{p0.2}$ = 140 MPa, A = 4.9 %, HB = 109, the solution proposed by the CBR system can be accepted without any other modifications and tests.

5.6. The retain phase

The data obtained as a result of the revised phase should be add to the knowledge of the projected advisory system. The knowledge is represented by the case base Δ. We propose to add to the case base new cases that represent all individual materials, which are produced and tested in order to confirm the correctness of the solutions proposed by the advisory system. Thus, the retain phase consists of the creation of cases representing the produced materials and their mechanical properties. These cases are next added to the case base Δ in order to be used at subsequently reasoning of the projected advisory system according a problem that will be probably solved in the future.

Example 6.
Continuing the Example 5, the performed experiments revels data that should be transformed into a case and added to the case base Δ. The retained record of data specifies content of Cr = 0.15%, Mo = 0.15%, V = 0.15%, W = 0.00%, R_m = 282 MPa, $R_{p0.2}$ = 140 MPa, A = 4.9 %, HB = 109. The record is transformed into a case that is numerically represented as $case_{N+1} = \big((5,5,4,3), (0.15\%, 0.15\%, 0.15\%, 0.00\%)\big)$. This case is added to the case base Δ, what enables to use the retained record of data by the next usage of the CBR system.

6. Conclusions

The design of the advisory system is specified. This system helps the technologist in the selection of proper alloying additives and their content in order to obtain modified silumin characterized by predetermined mechanical properties. Application of case-based reasoning has simplified the system design and has given the pattern for operations related with this initiative. Another benefit of the CBR application is the increase of the knowledge base as the advisory system is used and the advices are revised. The designed system is characterized by increasingly greater effectiveness as its increasing use.

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