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PREDICTION OF TECHNOLOGICAL PROCESS PARAMETERS BASED ON EXPERIMENTAL DATA

PRZEWIDYWANIE PARAMETRÓW PROCESU TECHNOLOGICZNEGO W OPARCIU O DANE EKSPERYMENTALNE

A b s t r a c t

In studies of new materials or products, it is necessary to carry out a series of tests to determine the physical properties of the product as a function of the manufacturing process parameters. The technological process of making successive samples for both experimental and research purposes is a mechanism which is time-consuming and which usually requires considerable financial outlays. At the same time, scientific literature offers a large number of experimental results carried out for a similar range of problems. The idea conceived in this study is to create a model that, based on the results of experiments collected from the scientific literature, will reduce the number of necessary physical tests by replacing them with an effective mechanism estimating some of the technological process parameters. Consequently , the concept of an algorithm has been presented to estimate the parameters of the manufacturing process of ADI (Austempered Ductile Iron). It can operate as a fundamental part of a larger expert system, supporting the design and configuration of production processes in various industries. This article describes the results of tests showing the efficiency of the proposed solution and outlines plans for further development of the system to increase its effectiveness and usefulness.

Keywords: *decision support systems, information extraction, process parameter estimation*

S t r e s z c z e n i e

Podczas fazy badań nowych materiałów lub produktów zachodzi konieczność przeprowadzenia serii testów w celu określenia właściwości fizycznych wytwarzanych produktów w zależności od zastosowanych parametrów procesu produkcyjnego. Proces technologiczny wytwarzania kolejnych próbek w celach eksperymentalnych i badawczych jest mechanizmem czasochłonnym, wymagającym zwykle sporych nakładów finansowych. Jednocześnie w literaturze naukowej dostępna jest często duża liczba wyników eksperymentów, przeprowadzanych w podobnym zakresie. Ideą prezentowaną w niniejszej pracy jest utworzenie modelu, który w oparciu o wyniki eksperymentów, zebrane z dostępnej literatury naukowej, pozwoli ograniczyć liczbę niezbędnych fizycznych testów, przez zastąpienie ich skutecznym mechanizmem szacowania części parametrów procesu technologicznego. Artykuł przedstawia koncepcję algorytmu umożliwiającego szacowanie parametrów procesu wytwarzania żeliwa ADI (Austempered Ductile Iron) mogącego być bazą większego systemu ekspertowego, wspomagającego proces projektowania i konfiguracji procesów produkcji w różnych dziedzinach przemysłu. W artykule opisano rezultaty testów prezentujące skuteczność proponowanego rozwiązania oraz przedstawiono plany dalszego rozwoju systemu, w kierunku zwiększenia jego skuteczności i przydatności.

Słowa kluczowe: *systemy wspomagania decyzji, ekstrakcja informacji, szacowanie parametrów procesu*

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1. Introduction

The subject discussed in this study is a practical use of the results of experiments contained in the technical literature as a source of knowledge in expert systems to support the configuration and modelling of the manufacturing process. Regardless of the science or industry sector under consideration, the introduction of a new product invariably requires carrying out a series of tests to prove that the product has the desired properties. This type of testing, often performed with the use of specialised equipment and advanced technologies, is time-consuming and cost-intensive.

A good example of this situation is the production of ADI, which due to its properties – a favourable combination of high abrasive wear resistance with fracture toughness and fatigue strength – is an interesting alternative for materials commonly used to date in the industry, to mention the instance of selected steel grades. Continuous and dynamic development of research in this area has resulted in a significant number of experimental results describing this material. To back up the development in this particular area of studies, further research and experiments are required but, quite obviously, a substantial amount of work and financial input are needed to carry them out.

The idea conceived in this work is to use the available literature data describing the manufacturing process of ADI and, based on this data, develop the tools (methods) which will allow for the determination of the technological process parameters suitable for making products with specific properties. Another issue described in this study is testing the efficiency of such a model, especially as regards the determination of specific parameters covered by the range of its applicability.

The second chapter of the work describes the data sources used in the implementation of the presented concepts, the methods for their filtering and their final selection. The third section presents the estimation algorithm for the examined parameters, while chapter four discusses the results obtained with this algorithm. The last chapter provides a summary of the results obtained and identifies directions for further work on this concept.

2. The model of the process and characteristics of source data

The industrial process, which is the subject of the present study, is related with the production of ADI. ADI is the casting material formed by appropriate heat treatment (OC) conducted on ductile iron, which is the starting product for the ADI production. The heat treatment consists of two stages, i.e. austenitising and austempering. The parameters of the heat treatment, including the temperature – T_a and time – t_a, of austenitising, and the temperature – T_{it} and time – t_{it} of austempering, are selected in accordance with the attributes the manufactured product is expected to have, e.g. high ductility and moderate strength and hardness, or vice-versa, low ductility but high hardness and strength. The combination of the desired properties must be optimal for subsequent operating conditions of the cast item.

To obtain data on the ADI manufacturing process, a number of reference literature items describing the subject and incorporating the results of experiments have been reviewed

[1–9]. Based on the data collected, a general model of the manufacturing process was proposed using the following base process parameters:

– chemical composition of cast iron – the percent content of the following elements: C, Si, Mn, Mg, Cu, Ni, Mo, S, P, B, V, Cr, Ti, Sn, Nb, Al;
– the size of the samples;
– the time and temperature parameters of the manufacturing process:
  ○ T_a – temperature of austenitising [‘C],
  ○ t_a – time of austenitising [s],
  ○ T_{it} – temperature of austempering [‘C],
  ○ t_{it} – time of austempering [s].

The outcome of the manufacturing process described by the above mentioned parameters is a material tested after the manufacturing for its mechanical properties. The basic characteristics that are available in most of the literature reference data include:

– tensile strength (Rm),
– elongation (A5),
– hardness (HRC).

Based on the literature review, 192 variants of the ADI manufacturing process were selected and characterised with the aforementioned parameters of the manufacturing process, including the mechanical properties of the products obtained by the described processes of manufacturing. To eliminate the discrepancies that might occur due to large differences in the chemical composition of the base cast iron, the source data was filtered.Subsequently, a group of 70 products with similar chemical composition and temperature (T_a) and time (t_a) of the austenitising process was selected.

The difference between the manufacturing process parameters occurred only in the data on the temperature (T_{it}) and time (t_{it}) of austempering. Examples of the experimental data (17 out of 70) are provided in Table 1.

Table 1

Fragment of the experimental results (17 out of 70) on which the tests were based

LP	C	Si	Mn	Mg	Cu	Ni	Mo	S	P	Cr	T aus['C]	t aus[s]	T wyg['C]	t wyg[s]	Rm	A5	HRC
1	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	230	1800	896	0,8	54
2	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	230	3600	1120	1	51
3	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	230	4500	1320	1,8	48
4	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	230	5400	1560	2,9	47
5	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	230	7200	1450	1,9	46
6	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	230	14400	1600	2,4	47
7	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	230	21600	1590	2,6	46
8	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	230	28800	1580	2,8	46
9	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	1800	1160	1,4	48
10	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	3600	1490	3,8	44
11	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	4500	1420	2,6	43
12	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	5400	1450	4	43
13	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	7200	1480	3	44
14	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	10800	1500	3,6	44
15	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	14400	1520	4	44
16	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	21600	1500	4,2	43
17	3,59	2,52	0,31	0,03	0,03	1,53	0,32	0,01	0,02	0,04	900	7200	260	28800	1470	4,8	43

A model of the manufacturing process based on the data selected for testing and the elements for final estimation are presented in Figure 1. In the adopted version of the model, the input data was product properties (Rm, A5, HRC) and the parameters that the model was expected to determine were the temperature (T_{it}) and time (t_{it}) of austempering. The selected model of parameter estimation allows subsequent determination of the efficiency of the proposed solution, mainly by comparing the obtained results with those set in the literature.

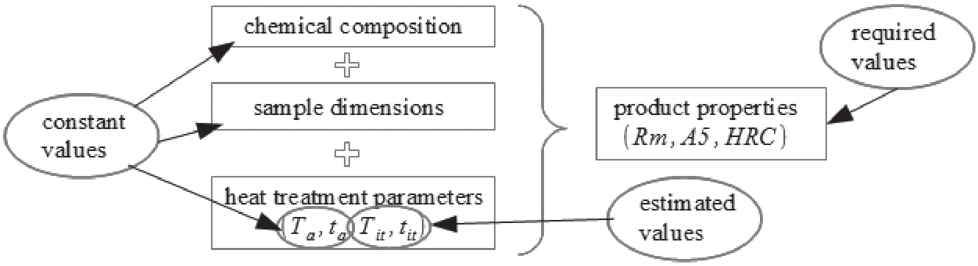

Fig. 1. Model and parameters of the manufacturing process

3. The concept of a model for parameter prediction

The concept of a model to predict the technological process parameters is based on an idea of the approximation of process parameters using the data on other technological processes but with input parameters similar to the process to be estimated. This model is a relatively simple solution, but it has to show the validity of the presented approach and pre-determine which process parameters can be measured in that way.

Detailed prediction algorithm for the model used in this study is shown in Figure 2. The idea of the algorithm operation is to select an N number of samples (experimental results) with properties most similar to the expected input parameters. Since 3 types of properties (Rm, A5, HRC) were considered, a total of 30 samples were selected. The estimation of the parameters T_{it} and t_{it} consisted in the calculation of these values based on the values of the same parameters used for similar products, taking into account the degree of similarity with respect to input parameters.

4. The results of a model operation for parameter prediction

To verify the model's efficiency, a series of tests based on 70 samples were carried out. Partial results of those tests are shown in Table 1. To eliminate the effect of the parameter type and value, before the estimation process, standardisation of all the data was done. The results determined by the algorithm were also returned in a standardised form, easy for back conversion.

The results of algorithm operation for the estimation of the standardised values of parameters Tit and tit are presented in Table 2.

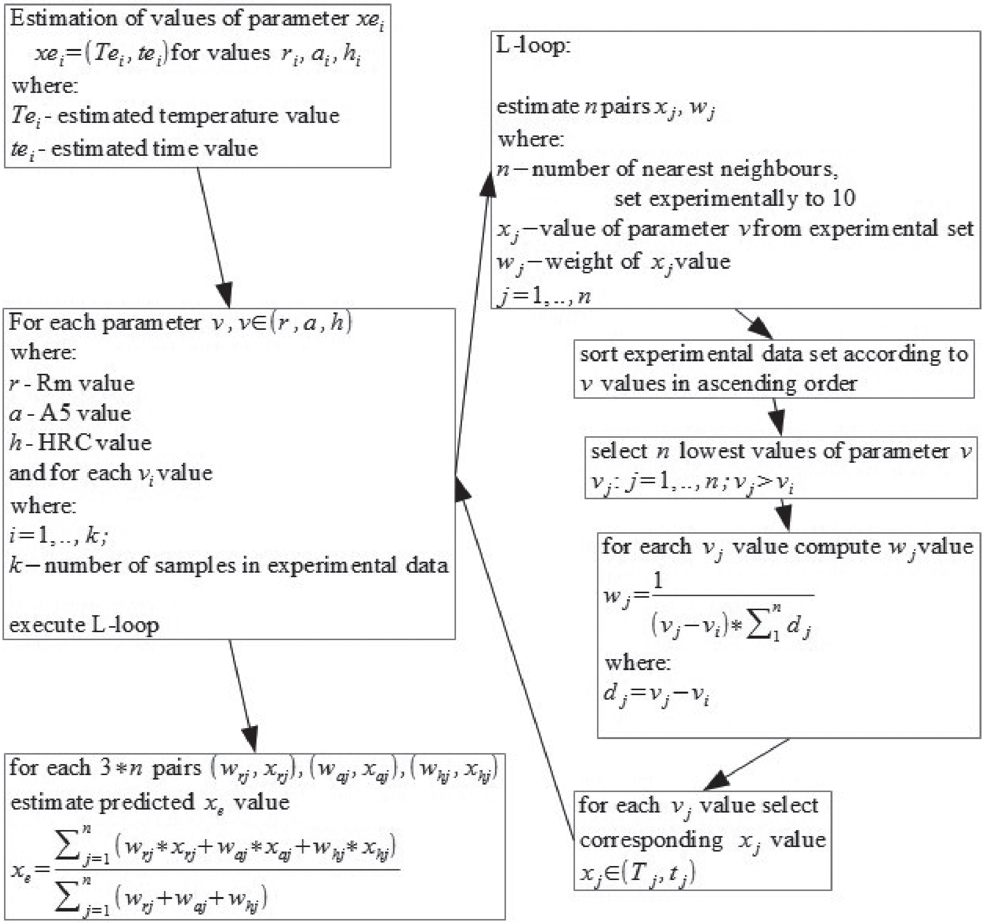

Fig. 2. An algorithm of a model for parameter prediction

For each of the samples, a mean square error was calculated based on the value estimated and value given in the literature. The estimation efficiency was based on the dependence of the mean square error and standardised range of parameter values according to Equation 1:

$$Eff = \frac{range(x) - \sqrt{mse}}{range(x)}$$
$$range(x) = \max(x) - \min(x) \qquad (1)$$

The values of the estimation efficiency for time (t_{it}) and temperature (T_{it}) are shown in the graph in Fig. 3.

Based on the data compared in Table 2 and using the graph in Fig. 3 representing all the tests conducted, the following conclusions have been drawn:

Table 2

Fragment of a set of standardised experimental data (17 out of 70) with predicted values

LP	Real		Estimated		Rm	A5	HRC
	Temp	Time	Temp.	Time			
1	-1,892	-0,875	-1,418	0,254	896	0,8	54
2	-1,892	-0,769	-1,276	-0,043	1120	1	51
3	-1,892	-0,663	-1,252	0,158	1320	1,8	48
4	-1,892	-0,452	-1,222	-0,010	1560	2,9	47
5	-1,892	0,395	-1,428	0,155	1450	1,9	46
6	-1,892	1,241	-1,358	0,046	1600	2,4	47
7	-1,279	-0,875	-1,023	0,058	1590	2,6	46
8	-1,279	-0,769	-0,849	-0,107	1580	2,8	46
9	-1,279	-0,663	-0,797	-0,076	1160	1,4	48
10	-1,279	-0,452	-0,866	0,081	1490	3,8	44
11	-1,279	-0,028	-1,049	0,087	1420	2,6	43
12	-1,279	0,395	-0,987	0,091	1450	4	43
13	-1,279	1,241	-0,883	-0,091	1480	3	44
14	-1,279	2,088	-0,556	-0,107	1500	3,6	44
15	-0,666	-1,087	-0,703	-0,242	1520	4	44
16	-0,666	-0,875	-0,682	-0,090	1500	4,2	43
17	-0,666	-0,769	-0,668	0,004	1470	4,8	43

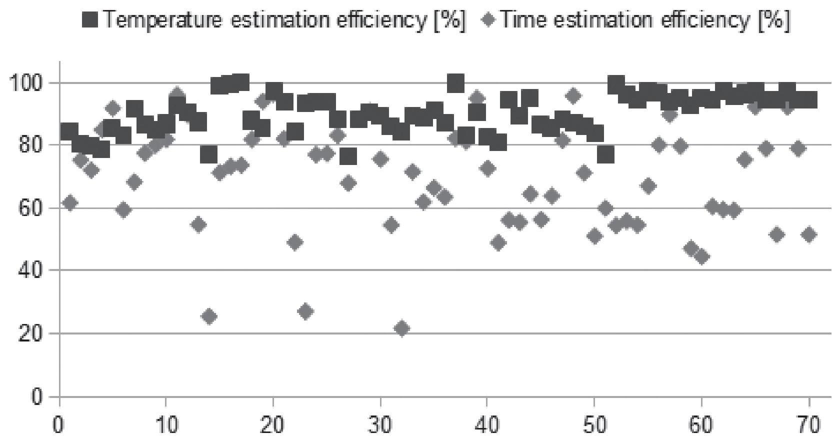

Fig. 3. Efficiency of estimation of the process time and temperature

– the presented model for the process parameter estimation is very efficient in the estimation of the austempering temperature (T_{it}). The average estimation efficiency obtained on 70 samples was 90.06%,
– the efficiency of estimation of the austempering time (t_{it}) at an average level of 69.74% allows only to indicate the order of magnitude of this parameter,

– after a more detailed analysis of the austempering time – product properties relationship and calculation of the values of this correlation it can be concluded that the effect of the austempering time on product properties is much less pronounced than that of the austempering temperature (T_{it}) – thus confirming once again the lower efficiency of estimation done with the help of the developed model.

5. Conclusions and further work

The results of the study indicate that the approach using the literature data jointly with the developed algorithm for the process parameter estimation is applicable in the estimation of selected process parameters. The results show high efficiency of estimation obtained for austempering temperature (T_{it}) and average efficiency for austempering time (t_{it}). However, the mere fact that these results could be derived from a relatively small number of data and using a simple estimation algorithm proves the validity of the conducted research. It seems advisable to continue studies on the development of models estimating the parameters of the production process based on the data in the literature. The next stage in the development of the presented approach will relate to the extension of the range of data on which the applicant model is based, and to the use of a more advanced applicant models and algorithms. Examples of solutions that can be used as estimation models are neural networks and fuzzy logic elements.

Summing up, it can be stated that the results presented in this paper confirm the validity of the adopted concept of studies and the implemented system is a promising solution for further development and research work in this field.

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