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RULE-BASED SIMPLIFIED PROCEDURE FOR MODELING OF STRESS RELAXATION

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Abstract

A case study of rule knowledge base on developing stress relaxation in welded components is presented in the paper. The procedure of simplified decision support model formulation – including expert knowledge externalization, formalization of knowledge, the selection of variables and identifying domain of attributes is described. A decision tree was used to support creating and visualizing of the model. The result of the work is a set of rules constituting a simplified model to predict the stress relaxation parameters of stress-relief annealing applied to welded components of PZL-10W helicopter engine produced by WSK Rzeszów. Developed application can be implemented in one of the reasoning system shells.

Key words: rule-based system, knowledge base, decision support, stress-relief annealing, welding

1. CHARACTERISTICS OF THE RESEARCH WORK

The inference and the development of control models proceeds in several steps and is an iterative process where specialists perform the role of experts, not only at the stage when the model is defined, but also on the stage when

– variables of a process are selected,
– a variable domain is determined,
– inference rules are proposed,

and finally during model evaluation.

This process also requires a collaboration of experts from various areas of expertise not only from manufacturing, but also with the knowledge engineering, computer science, etc. (Rutkowski, 2005).

The aim of this research is to propose a set of control rules aiming at decreasing the stress in welded components on the basis of WSK Rzeszow specialists' technology knowledge. An inference stress relaxation model is developed in collaboration with welding experts from WSK Rzeszow. The design of the model requires the determination of a model scope, the decision criterions and appropriate selection of independent variables. Various materials, such as: Inconel 625, Inconel 718 and Steel 410 are considered in the numerical simulation of welding and heat treatment processes for manufacturing of turbine engine.

2. SOURCES OF TECHNOLOGICAL KNOWLEDGE UTILIZED IN THE MODEL DEVELOPMENT

2.1. Literature review

The knowledge base for the assessment of weldment integrity can be based on the measurement

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of residual stress and density of micro-cracks. Issues related to the relaxation of stress after welding has been discussed in numerous publications, e.g. by Tasak (2008), and Pilarczyk (1983).

Stress relief annealing leads to some stress relaxation and also can restore ductility in brittle zones. A stress-relief annealing is the most common method for removing internal stress. Thermal annealing reduces the yield strength at elevated temperatures that results in the occurrence of plastic deformation in areas, where the second invariant of internal stresses exceeds a local yield limit. Increasing the annealing temperature reduces the limits of yield and the strength of steel. That situation is usually preferred in the case of stress-relieving elements that are required to have good strength properties. The annealing temperature lowering could lead to insufficient stress relaxation. The most important parameters of stress-relief annealing are: an alloy composition, complexity of the shape and size of a product, heating rate, annealing temperature and cooling rate.

2.2. Knowledge base and experience of executive team

Authors' preliminary knowledge in the area of rule system implementation is priceless in the preparatory phase of a research project (Kluska-Nawarecka et al., 2007; Kluska-Nawarecka & Regulski, 2007; Kluska-Nawarecka et al., 2009; Mrzygłód & Regulski, 2012; Nawarecki et al., 2012; Szeliga et al., 2011, Szeliga, 2012). During the problem formulation, after literature study and discussions with engineers from WSK Rzeszów the major tasks were defined and the objectives were identified with selection of decision making criterions and appropriate variables, so called inference objects. The first step in developing a decision making support system is to determine the inference object. There are several variants of such study based on:

- The prediction model: determining the quality of the residual stress after heat treatment on the basis of welding, annealing parameters and workpiece data.
- The decision support model: determination of heat treatment parameters on the basis of the expected properties of the material after annealing process.
- The diagnostic model: determining the causes of defects in the process of heat treatment.
- The decision-making control model: determination of heat treatment parameters on the basis of the workpiece.

Finally authors followed the fourth option, i.e. decision making control model. The manufacturing knowledge base available in the WSK Rzeszow existing in non-formal documentations, industrial practice and observations recorded by technologists that can be collected together and formally coded in the form of data bases. Rules supporting a decision making process will be identified as the data base motor.

2.3. Internal procedures and standards

Each of the engine elements has the exact specification in the manufacturing process output. The specifications are established according to materials treatment standards. Two of the standards: American (AMS) and international (ISO) are generally available, but inner specifications are confidential. Those confidential specifications are available for the study but the knowledge base and decision making models derived from that specification are still the property of the WSK Rzeszów. Following that, decision tables, decision trees and the rules are presented here without confidential details.

Heat treatment of turbine engine case is carried out after welding. It may also be used during engine overhaul when a case is repaired by welding. When the control procedure shows that weld cracks exceed security limits, a repaired element must be rewelded.

Typical heat treatment of a case consists of a vacuum annealing conducted following the procedure:

1. Securing of required level of a vacuum. Some depreciation of this vacuum state is permissible during the process.
2. Heating of a furnace to a required temperature.
3. Continuous heating of a chamber to the annealing temperature and maintenance of this temperature for a specified period.
4. Cooling a furnace with a specific rate up to the minimum temperature and further cooling a case up to the ambient temperature.

Annealing the single parts of a case and components is carried out in a furnace with a fixture for maintaining shape and dimensions of elements in the risk of deformation due to thermal dilatation. The same device is use in a case maintenance procedure.

2.4. WSK base of knowledge

The information available from production engineers appointed by WSK Rzeszów is valuable source of knowledge for the development of process control model. Non-formalized knowledge based on industrial experience is called by managers „tacit knowledge" and the know-how. Without the knowledge of the practical aspects of decision-making in an industrial environment, without familiarity with the most common dilemmas emerging technology, it is impossible to develop a control model and propose rules of inference. In the later stages of the work, other sources of the knowledge play only auxiliary functions. The major task of the engineer of knowledge is the externalization of the experience of experts.

To develop the control model of stress relaxation, the knowledge of production engineers were codified following a cycle of interviews and the model assessment. The cycle was repeated several times that helps in avoiding modeling errors and identification of decision rules.

3. KNOWLEDGE CODING FOR RULE-BASED EXPERT SYSTEMS

The knowledge coding is the next step in the design process of the control model for welding. The objective of coding is to represent a production engineering knowledge in such a way that it can be implemented into the inference process. Moreover, the introduced formalism should be clearly understood by a production engineer who can evaluate and verify the knowledge. Several methods were used to perform that process by developing the following objects: decision trees, decision tables, and rules of inference.

3.1. Selection of inference parameters

The first step in the design of the decision making system is the identification of parameters i.e. variables in rules for concluding. The number of variables can be proposed, regardless of whether they will be used or not in the final model. Variables can be selected according to the future application, determining which of them will be used in relations and which will be evaluated in the inference process. A domain of each parameter/variable is determined as a field attribute. In this model some of variables could appear both as a result of conclusion or a rationale. For example: a variable specification can be a result of conclusion of the inference in the first phase and later may appear as a variable in further rules.

Production engineering experts may selected the following variables in the decision making process:

– specification of materials,
– necessity of fixture usage during stress-relief annealing,
– heating rate,
– number of stops during the heating period for a supply of argon.

3.2. Decision making tables

One of steps of complete decision-making model is to answer the question related to maintenance of a work piece shape, i.e. whether the fixture usage is necessary during a heat treatment? This decision is important from economical point of view, because mass of a fixture, which ranges to several kilograms, absorbs heat and therefore, the oven to reach the same annealing temperature must be heated longer than for the case of heat treatment without such device.

The base surface is often the outer cylindrical surface and a cylinder base. Some parts could be supported simultaneously on various surfaces. A fixture strengthening a workpiece should be used for flexible parts. A production engineer is making a decision on which surfaces a fixture should applied. Usually, those are outer surfaces of a workpiece.

Diameters of a workpiece are considered together with dimensional tolerances and shape requirements such as flatness and roundness. Dimensional tolerances and geometrical tolerances are controlled after heat treatment. An attachment and detachment in a strengthening should be easy and unambiguous.

To eliminate thermal deflection after a heat treatment various repair operations are used, such as straightening operation for bars and tubes or spinning for the cylindrical parts.

The final heat treatment process is marked by the acronym, HT. When such operations are final, and there is high risk of deflection then to secure the shape within strictly prescribed tolerances a strengthening fixation must be used.

Variables consisting so called decision table does not distinguish between types of support surfaces, e.g. cylindrical or flat. Such information is already included among others in the variable named: "deformations". The decision table, shown as the table 1, assigns a number of decision rules to the heat process scenarios. It can be read as follows:

– scenario 1 – when a heat treatment is in interoperation stage and tolerances of the supporting surface are loose, and a deflection may could exceed a tolerance, then a strengthening fixation must be applied.

Table 1. *The decision table showing a requirement for a strengthening fixation during stress-relief annealing.*

Possible scenarios:	1	2	3	4	5	6
TREATING STAGE	internal			final		
TOLERANCES OF SUPPORTING SURFACES	loose		tight	loose		tight
ANTICIPATED DEFORMATIONS	YES	NO	YES	YES	NO	YES
Use of stress-relief annealing apparatus	NO	NO	YES	YES	NO	YES

source: own study

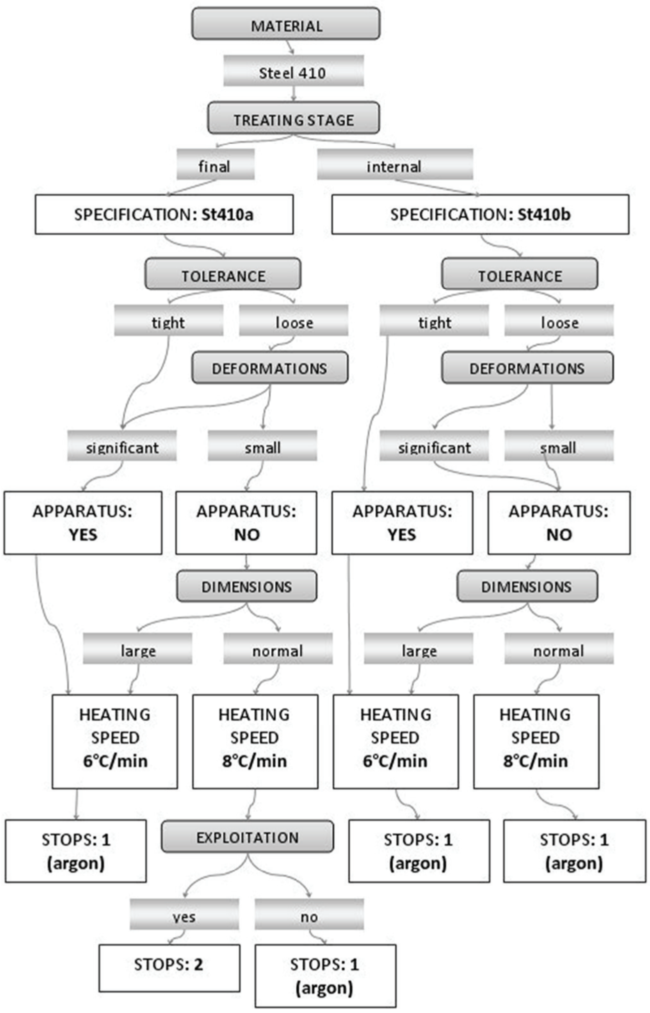

Fig. 1. *A part of the decision tree to determine the heat treatment parameters on the basis of a workpiece-decision-making control model.*

This rule can be avoided, as in this particular scenario the information on thermal deflections is redundant. Therefore, this parameter could be omitted, because a decision is made on the based on the information about the heat treatment stage and appropriate tolerances. The rationales for each decision making should be described for each manufacturing process scenario. This redundancy will be eliminated following the future process analysis.

3.3. Construction of decision trees

The process of knowledge acquisition from experts is much more laborious than it would appear following this study. However, results of such acquisition are gathered collectively in the decision-making table. For the sake of simplicity, the authors decide to omit a number of steps leading to the refinement of relations and inference rules. The entire decision tree makes depicts rules in a comprehensive manner. Since the whole tree exceeds one page and the information is confidential, the value of the parameter 'specifications' is presented only by the appropriate acronym or symbol (see figure 1). To describe the idea of the decision tree only a small portion of a full model is presented here only for Steel 410.

3.4. Rules of inference

Inference control rules can be generated on the basis of a decision tree. These rules are shortened to include only the necessary conditions for achieving an inference. For example, selected few rules are the following:

```
IF material = "Inconel 718"  AND treat-
    ing_stage = "final"
    THEN specification = "Inc718a"
IF treating_stage = "final" AND tolerance =
    "tight"
AND deformation = "significant"
    THEN apparatus = "yes"
IF specification = "Inc718a" AND heat-
    ing_speed = "6°C/min"
    THEN number_of_stops = 0
IF specification = "625" AND heating_speed
    = "8°C/min"
AND exploitation_treatement = TRUE
    THEN number_of_stops = 2
```

Using this type of rules production engineer can decide about indicated variables such as: specification of materials; utilization of strengthening fixture during annealing, heating rate, and number of breaks application of an argon dose. Those rules are also ready to be implemented in one of expert system shells.

3.5. Example of use case

Reading a decision tree or applying some rules of inference in a daily routine can be presented in a form of dialogue with a user. The dialogue can be advanced as follows:

```
MODEL: What kind of a material are the
       parts made of?
USER: Steel 410
MODEL: Treating stage is final or internal?
USER: Final
MODEL-CONCLUSION: You should use Specifica-
       tion of parameters sign Spec410a
MODEL: Is tolerance of dimensions tight or
       loose?
USER: Loose
MODEL: Is the risk of deformation signifi-
       cant?
USER: Yes
MODEL-CONCLUSION: You should use elements
       geometry sustaining apparatus during
       stress-relief annealing
MODEL-CONCLUSION: You should apply heat
       rate at 6 celsius degrees per minute
MODEL-CONCLUSION: You should plan 1 stop
       for argon application
```

4. APPLICATION OF KNOWLEDGE MODEL

Presented in the paper rules was implemented in the system ReBIT (Banet et al, 2011). ReBIT is the Business Rules Management Systems which combines the capabilities of the rule-based decision support system with the expressiveness available in algorithmic programming languages. System acts as expert system shell. It implements an engine of inference and give an opportunity of developing a knowledge base. The system was developed in the Department of Applied Computer Science of the Faculty of Management AGH in Krakow.

Research team decided to apply forward inference. Knowledge base consists on several dozens of variables and tens of rules. Decision variables are constructed from: specification (which is a set of 16 parameters of stress-relief annealing), a requirement for a strengthening fixation, heating speed and number of stops.

The whole system with developed knowledge base was successfully implemented in WSK Rzeszów.

5. SUMMARY

The task was performed with the following works:
- acquisition of the knowledge from the best practice of production engineering in WSK regarding e.g. stress relaxation after welding of engine case and its components,
- codification of the expert knowledge on the present-day process experience and ways for decisions of heat treatment parameters for selected materials and components;
- codification and implementation of manufacturing know-how in a decision table, decision tree, and control rules of inference.

The final step of an “expert” system development consists of the derivation of rules for the control of a stress relaxation process. Set of such rules would be used in future by process engineers for supporting decisions for the design of stress-relief annealing. Developed knowledge base is a functional model of stress relaxation control. The model was sent to the WSK Rzeszow for evaluation. The mayor result of this paper is an attempt to codification of previously informal expert knowledge and a proposition of inference rules. For further application, the presented scheme should be implemented in one of inference systems.

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UPROSZCZONA PROCEDURA MODELOWANIA RELAKSACJI NAPRĘŻEŃ OPARTA O SYSTEM REGUŁOWY

Streszczenie

Artykuł ma na celu przedstawienie studium przypadku tworzenia regułowej bazy wiedzy w zakresie relaksacji naprężeń powstających w elementach spawanych. Opisana jest procedura powstawania uproszczonego modelu wspomagającego podejmowanie decyzji – obejmująca eksternalizację wiedzy ekspertów, formalizację wiedzy, dobór zmiennych i określanie dziedzin atrybutów. Jako narzędzie wspomagające proces tworzenia i wizualizacji modelu wykorzystano także drzewo decyzyjne. Wynikiem prac jest zestaw reguł stanowiący uproszczony model, który na podstawie wartości kilku zmiennych zdefiniowanych przez użytkownika określa parametry procesu wyżarzania odprężającego stosowanego w WSK Rzeszów do produkcji części składowych silników śmigłowcowych PZL-10W. Model taki może być w przyszłości implementowany w systemach wnioskujących.

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