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APPLICATION OF RULE-BASED SYSTEM TO SUPPORT FEM SIMULATIONS IN HOT ROLLING PROCESS

TOMASZ REC[1], ANDRZEJ MACIOŁ[2], PIOTR MACIOŁ[1]*

AGH - University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków, Poland
[1] Faculty of Metals Engineering and Industrial Computer Science, Department of Applied Computer Science and Modelling
[2] Faculty of Management, Department of Applied Computer Science
**Corresponding author: pmaciol@agh.edu.pl*

Abstract

Finite element method could be effectively used in computer-aided engineering. Unfortunately, it still rarely used in industry. One of the causes is high costs of such software, as well as lack of highly qualified specialist. In this paper, the possibility of developing of rule based system for aiding of FEM simulations designing. Prototype of inference engine working with knowledge base storing engineering knowledge is used. Tests are based on simple rod rolling process. Process of optimisation of technological parameters with both FEM computations and rule-based inference is shown in this article. Temperatures and shape of rod are chosen to be optimised. Abaqus 6.7 software is used for FEM, while newly developed modelling language is used in inference. It is based on terms similar to predicates in First Order Logic and variables. It is shown, that quite simple set of rules allows finding proper solution in relatively low number of simulations. Some additional constraints and requirements are also described.

Key words: rule-based system, finite element system, computer aided manufacturing

1. INTRODUCTION

Finite Element Method (FEM) can solve many problems related to the design of technology, among others also rolled products. Despite the widely recognized efficacy of this method, its applications in industrial practice are very limited. This is partly due to the high cost of commercial applications, and inadequate qualifications of technologists, but also from the fact that the design process technology using FEM simulation is a complex process requiring specialized knowledge. The aim of our research is to develop principles for aiding of design process with rule system, equipped with the technological knowledge. In our study we use a prototype version of the inference engine with business and technology knowledge. It was developed at the Faculty of Management, AGH-University of Science and Technology. The study was conducted on the example of the selection of technological parameters of the rod rolling process (rolling temperature, and aspect ratio). Basing on FEM simulation and decision-making parameters of rolling process (temperature ranges, the aspect ratio of the finished product), parameters of the technology (bandwidth cooling conditions, size of the batch) were modified. If computed parameters of the product does not meet the technological requirements, then rolling parameters are modified independently by the inference engine. If requirements are met then set of the input parameters are considered as a basis for development of technology in production.

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2. IT TOOLS IN TECHNOLOGY MANAGEMENT

Support of technological decisions may be realized through expert systems. The current state of the art in this field may be visualised on the example of forging design, which is a complicated and time consuming process.

There are a lot of applications of expert systems into aiding of forging designing. The most frequent is supporting of designing of forged parts, basing on machined parts geometry. Caporalli et al. (2006) and Kulon et al. (1998) presented such systems. The same issue, but extended with Finite Element Method (FEM) was introduced in the paper of Kim et al. (2001). Choi et al. (1996) shown similar systems, but they presented knowledge taking into account more parameters like tolerances, forging types and tools, materials and lubricants. Ravi et al. (2003) presented system for aiding design of hot forging. The system, based on CLIPS environment, suggest such parameters as temperature, used lubricant, strain rate and die materials, basing on description of forged material. Moreover, if system predicts possibility of failures, adequate warnings are generated.

Systems based on similarity of designed technology to technologies stored in knowledge base could be also met in the literature. Katayama et al. (2004) presented system based on fuzzy rules for cold forming process designing. Glynn et al. (1995) showed system for turbine blades forging, also based on similarity detection.

Next category of expert systems is suitable for aiding of particular processes designing. Im et al. (1999) showed system for designing of ball-stud forging. The systems choose the best operations sequence, basing on starting and final shape of detail. In this case, FEM is also used for inference result verification. Choi et al. (1995) introduced an expert system for blockers designing in rib-web type forgings. Rules concern geometry and forging process characterisation.

Cakir et al. (2005) presented rule based system for machining process development. This system takes into account available tools from database and parameters of machined surfaces.

Expert systems could be also a part of computer-aided process planning (CAPP). Such a system for preliminary forging technology designing had been presented by Choi (2000).

Other interesting applications of expert systems for forming are classification of material flow in drop hammer forming (Huang, 2001) or mixed Bayesian/ruled system for defects prediction (Fujikawa, 2000).

On the other hand, Reina et al. (2004) introduced rules for forged part cost estimating, but no inference system had been proposed.

In summary, presented in literature automatic support systems of forging process design, despite different scope as well as the manner of presenting technological knowledge, are characterized by a stiff, a priori formulated structure. In consequence, user has possibility neither to develop knowledge nor introduce results of his own research without reformulating knowledge base – doubtlessly with cooperation of system designer.

The other functional capabilities that in case of expert systems are provided by the systems of structural, technological and manufacturing design (CAx). An exemplary solution with extensive tools for knowledge management is the CATIA V5 by Dassault Systemes now IBM (IBM, n. d.). This software provides wide spectra of functions and possible applications. Aside from advanced and universal tools for solid and surface modelling, the software provides a set of specialized modules which support major industrial branches such as: machine design, the automotive industry, the aerospace industry, founding, machining, plastic processing, steelworks, shipbuilding and others. Knowledge management is realized in such a manner, that it covers almost all functional models: the ones responsible for geometrical modelling of complex mechanical structures as well as those used in design of production lines or machining processes.

Advanced and flexible management of knowledge in CATIA remains understandable for the system and clear for the user, whereas at the same time it allows for the development of a formal description of design specifications, general and corporate standards or design procedures that are based on knowledge of know-how and the experience of a development team. The acquired knowledge may be used for the automation of essential tasks as well as continuous verification of works in the area of realized projects starting with the very first phases of development.

Indispensable tools for knowledge management and acquisition are implemented in Knowledgeware group of modules. They are used for acquisition and organization of model parameters that contain detailed information on the given object. Those parameters are consequently used by the user for representation of knowledge in the form of formulas, rules and verifications. The formal description is realized by means of specific editors that include a set of operators and keywords. Formulas, which in fact comprise algebraic statements, are constructed with the use of algebraic operators. The formulas and verifications are on the contrary written in the system specific Knowledgeware Language or in Visual Basic.

Diversified forms of knowledge representation that are included in the system are used in a variety of applications. Variables are defined by the formulas through the algebraic statements which utilize model parameters that in turn are automatically generated by the system as well as user-defined parameters. Those variables can be either consequently used for a straightforward definition of particular model parameters (e.g. dimensions of elements) or used in rules and verifications.

The rules allow for the development of more complex definitions of operations that are automatically executed on the model parameters. It is also possible to implement conditional instructions that can for example determine given dimensions of the object on the basis of used material or other general dimensions. Additionally, usage of loops enables iterative execution of operations, e.g. for consecutive parameters of predefined list.

Verifications are used for the control purposes of model realization in accordance with assumed conditional statements. A given condition may for example apply to the selection of a particular material, limitations concerning maximal or minimal values of dimensions etc. In the case if the verification condition is not satisfied for the actual model parameters, a special predefined warning message is displayed on the screen.

Formulas, rules and verifications are the basic knowledge carriers. They can be stored in data bases which are either embedded in individual design documents or widely available to other users for application in other projects. Such bases can be successively modified and developed.

Analysis of functionalities provided by CATIA V5 Knowledgeware highlights a particular specificity of decisions within the technology domain. In contrary to the majority of decisions supported by the rule engines in the area of management, in this case a declarative as well as procedural knowledge is considered.

3. DESCRIPTION OF PROTOTYPE APPLICATION WITH RULE-BASED INFERENCE WITH INTEGRATED FEM APPLICATION

Our experiences indicate that the most effective solution, capable of direct cooperation with majority of industrial information systems which simultaneously provides decidability, is a combination of relational model with inference system that utilizes some elements of attributive logics. Our solution, named Inference with Queries (IwQ) (Macioł, 2008), has been developed as a knowledge model and an inference engine for formulation of Business Rules Management Systems. Knowledge storage is realized near to the principles of Variable Set Attribute Logic (VSAL).

Structure of rules in developed system looks as follows:

IF premise AND premise AND … THEN conclusion

Primary elements of „vocabulary" are terms and variables. Terms are equal in certain sense to predicates in First Order Logic. Variables are represented in expressions by terms. Terms represents also expressions, functions and constants. Premises are logical expressions with following structure:

left hand term OPERATOR right hand term.

Conlusions have structure variable := term.

Below an example of rule is written:

```
IF min_rod_temperature < recrystalisa-
tion_temperature THEN
heat_transfer_coefficient:=
heat_transfer_coefficient -
delta_heat_TC.
```

Designed inference engine allows to find optimal solution of decision problems in sense of minimisation of number of queries. Innovatory feature of our system is possibility of "hanging" of inference process for time necessary to acquire knowledge about a variable. Thanks to that, longstanding and non continuous decision making processes are possible. It is also possible to acquire knowledge from external systems, working with its own data sets and different cycles, including FEM analysis.

4. DESCRIPTION OF PROCEDURE SYSTEM TESTING

Numerical model of rod rolling were developed. Two variants of test were designed. In the first variant, cooling intensity influenced on decreasing temperature of rod. The rolling temperature is important technological parameter which influences on structure and mechanical properties of final product. Expected rolling temperature should ensure recrystallization and grain refinement. The heat coefficient was modified to simulate different cooling conditions with water spray.

In the second variant, the shape of mill feedstock was modified. The shape factor:

$$s = \frac{h}{b},$$

where: h – height, b – width of mill feedstock after rolling process had been optimized.

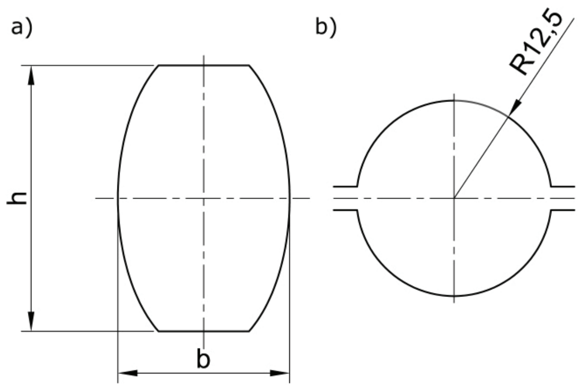

Fig. 1. Dimensions a) mill feedstock b) roll pass.

On figure 1, shapes of mill feedstock and roll pass used in test are shown. The shape factor for rod should be 1. The width and height should be equal what correspond to the expected diameter of the finished rod. If the shape factor is greater than unity then metal is not completely fill the roll gap, if $s < 1$ in the roll gap there will be overflow and the metal is flowing out between rolls.

Figure 2 shows an algorithm of technological parameters fitting. Basing on decision parameters (temperature of rolling strip and shape factor of round) computed with FEM simulation, cooling regime and dimension of mill feedstock are optimized. If calculated parameters do not meet the technological requirements for a rod, then rule-based inference engine gives updated rolling parameters. Iterative process goes on till meeting expected properties of final product.

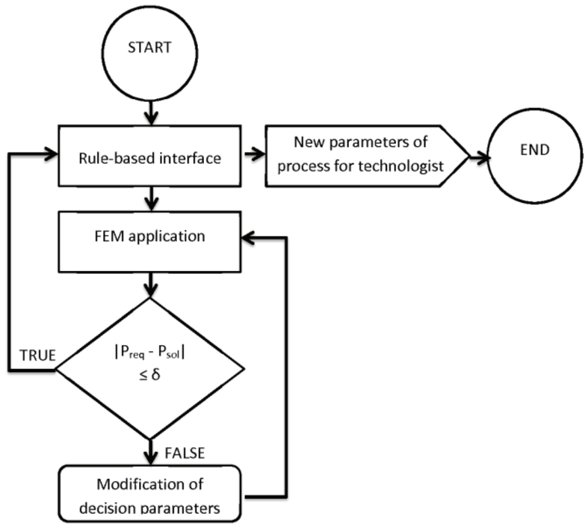

Fig. 2. Algorithm of rule-based inference engine's and FEM simulation's collaboration.

The study of rolling process were made for a rod with diameter d = 25 mm and steel grade St3S. The material's properties and technological parameters were adopted based on book Danchenko et al. (2002). Numerical simulations were carried out with Abaqus 6.7 software.

RESULTS AND DISCUSSING

Figure 3 shows the distribution of temperature on the cross-section of rod for chosen cooling conditions. The heat transfer coefficient k was an independent variable. Minimal temperature of a rod should be greater than recrystallization temperature. In this example, the recrystallization temperature was T_r = 650°C. The tolerance of the results was set to ±10°C. Starting heat transfer coefficient value was 5000 W/m^{2}K. Minimum temperature was equal to 561°C (figure 3a). The lowest temperatures values appear on the surface of the rod in the roll gap at the contact with the band rolls. In this case, the minimum temperature was lower than the recrystallization temperature T_r. Then rule-based system modifies the heat transfer coefficient to k = 3000 W/m^{2}K and simulation started again with updated k. Figure 3b shows results of this simulation. In this case, the minimum temperature of a rod increased to 639°C. However, it is still below the recrystallization temperature, hence the heat transfer coefficient was corrected by system and was finally set to 2500 W/m^{2}K.

Further numerical analysis led to the minimum temperature on the surface of the rolled rod equal to 661°C. This temperature is higher than the recrystallization temperature, and the specified tolerance is also fulfilled. It could be assumed that the proper value of k was found and iterations stop.

The results of FEM simulations of the second variant are shown on figure 4. The analysis shown that there are overflows in a roll for height h = 40 mm (figure 4a). Computed shape factor was 0.89. Based on the results of FEM simulation, the rule based system reduced height to 30 mm.

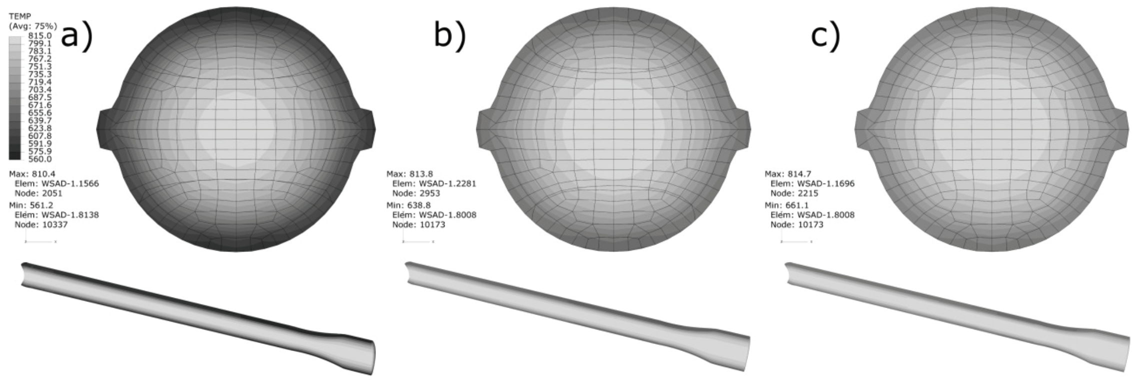

Fig. 3. Distribution of temperature in rolled rod.

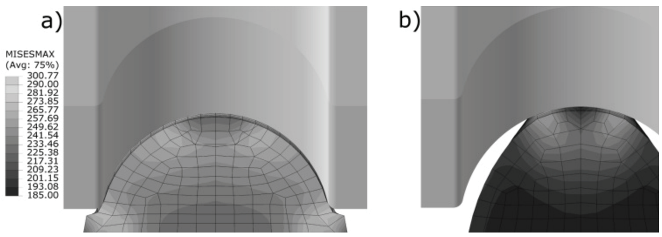

Fig. 4. Distribution of stress intensity in cross section of rolled bar and way of filling the roll gap.

For the new height of mill feedstock the shape factor was 1.12 and again final product's properties do not filled expectations (figure 4b). In the next simulation, height was set to 34 mm. In this case, rod is filling the roll gap and there is no overflow (figure 4c). The shape factor for a given height was 1.04. Then, it could be assumed that the chosen parameters are proper.

6. SUMMARY AND CONCLUSIONS

Obtained results shown that relatively simple set of rules allows to resolve technological problems with few numerical simulations. It confirms possibility of combination of rule based inference system and FEM analysis into one technology design aiding tool. During investigations, ale some additional requirements, necessary for practical implementation, was nominated. At first, it has to be possible to hang inference process and restart it in the same point. Secondly, automated communication between inference engine and FEM software has to be established, it should include not only numerical, but also not numerical parameters' exchanging.

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ZASTOSOWANIE REGUŁOWEGO SYSTEMU WNIOSKOWANIA DO WSPOMAGANIA ANALIZY WALCOWANIA NA GORĄCO METODĄ ELEMENTÓW SKOŃCZONYCH

Streszczenie

Metoda elementów skończonych mogłyby być skutecznym narzędzie komputerowym wspomaganiu projektowania technologii. Niestety wciąż jest ona rzadko używanych w przemyśle. Jedną z przyczyn są wysokie koszty takiego oprogramowania, a także brak specjalistów o odpowiednich kwalifikacjach. W niniejszym artykule przedstawiono możliwości zastosowania systemu regułowego do wsparcia projektowania symulacji MES. Wykorzystanie prototyp silnika wnioskowania współpracujący z bazą wiedzy o charakterze technologicznym. Testy oparte zostały o modelowanie procesu walcowania prętów. W artykule przedstawiono proces optymalizacji parametrów technologicznych w oparciu o model MES oraz omówiono sposób doboru parametrów symulacji w oparciu o wyniki wnioskowania. Optymalizowanymi parametrami są temperatura i kształt pręta. Jako oprogramowania MES użyto systemu Abaqus 6.7, natomiast do wnioskowania zastosowano prototyp systemu regułowego opracowanego z udziałem Autorów. Jest on oparty na termach, zbliżonych do predykatów w rozumieniu First Order Logic oraz zmiennych. Wykazano, że dość prosty zestaw zasad umożliwia znalezienie właściwego rozwiązania w przy wykonaniu niewielkiej liczbę symulacji. Opisano również dodatkowe ograniczenia i założenia.

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