The Knowledge Based System for Forging Process Design based on Case-Based Reasoning and Finite Element Method

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Abstract
Forging process design is the crucial task in process planning of forging industry. It is based on the skills and accumulative expertise of the forging experts. Such knowledge of the experts is not easy to elicit directly. However, this knowledge should be managed and used to enhance the efficiency, reduce time and cost of forging process design. The forging process design is to define the process parameters, including initial raw material size, the perform shape and forming steps, the design of a die geometry, the ram velocity, and type of forging (hot or cold forging) and so on. The knowledge of forging process design can be learned and obtained from the previous design cases. This paper presents the integration of case based reasoning and finite element method for supporting forging process design. The previous forging process design cases are stored in case library and it will be retrieved by searching and matching with a new case design. The similar case is reused and revised to solve the new case problem. In addition, a finite element method (FEM) with CAE software is applied to calculate and simulate the forging process in order for making a decision and reducing the forging process and die design trial and error. The new case is tested until the case is successful before retaining in the case library to be reused in the future. The developed system is tested with forging process design of an automotive part.

***Keywords**: forging process design, knowledge based system, case-based reasoning, finite element method*

1 Introduction

Forging process is an important process of metal forming industry to deform a billet to near net or net shape of a part. The forging parts are widely used in automotive, machine, aerospace, and other parts. The advantages of forging process are to produce a complex geometry part, provide high volume production, and low production cost per unit. In addition, forging process can be obtained a production yield more than casting and machining process.

Although, now forging process has new technology such modern machine with high capacity, high quality tool materials, engineering software such CAD/CAM/CAE, however, forging process design is still needed experience and knowledge of experts, can be called Know-how, in order to solve the problem. Forging process design is to define material, suitable forge machine, forging steps, pre-form design, and forging parameters. These came from trails and error testing that may be time lost and high costing. Therefore, expertise and knowledge are required in forging process design. Knowledge of the forging experts should be captured and transferred by interpreting in to suitable format for reusing and to resolve the solution for the new problems.

Therefore, the tools for capturing and managing the knowledge are determined. Case-Based Reasoning (CBR) is one of problem solving paradigm in artificial intelligence. CBR is able to utilize the specific knowledge of previously cases. A new problem can be solved by searching similar case(s), and reusing it to be the solution of the new problem situation. This paper presents development a case-based system in order to support a forging process design. The knowledge base that is systematic managed based on a computer system. Case library is efficient stored and manipulated for supporting forging process design. In addition, FEM (Finite Element Method) is used to analyst effective stress, effective strain, temperature, and other parameters of forging process for process and tooling design. CAE (Computer Aided Engineering) is software using for simulation and analysis metal flow behavior during metal forming process.

This paper is organized into five sections. The first section reviews the case based reasoning theory and application in industrial sector, especially in engineering design methodology. The second section describes the fundamental of forging process design. The structure of the case based expert system for preform forging design is presented in the third section. The fourth shows the case study of preform forging process design. Finally, the last section is conclusions.

2 Case-Based Reasoning (CBR)

2.1 *Case-Based Reasoning method*

CBR uses the specific knowledge in the past from the ways to solve the problems, called cases. The new case problem can be executed by searching and reusing the solution from the similar previous cases in order to solve the current problem. New cases are stored in a library and it is already reused in the solution cases [1]. As mention, Case Based Reasoning is a methodology for solving a new problem based on past experiences. It is widely used in many fields such design, engineering, medical, finance, and so on. The CBR process is likely the solving problems of humans. The CBR cycle was described in [2] which consist of four processes as shown in Figure 1:

- Retrieve-retrieve similar past case matched against current problem.
- Reuse-reuse adaptation knowledge to solve current problem based on the solution of an existing case.
- Revise-revise the newly generated solution for the current problem if any contraction occurs when applied to current problem.
- Retain-retain the final solution along with the problem as a case if the case is useful in the future.

A new problem is solved by retrieving one or more similar cases from cases or knowledge base library. These cases are reused to suggest the solutions. Revising the cases will be occurred if the previous solution is not to meet for solving the problem. After modification solution of a new case, it is retained in the case library for reusing in the future. Case-based reasoning methodology is being adopted to solve problems in engineering works, especially for engineering design such product design and development, machine design, tooling design, and others, and many fields.

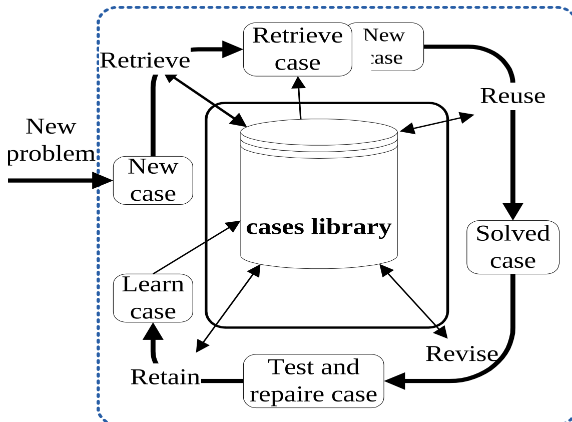

Figure 1: Case-Based Reasoning cycle

2.2 *Literature Reviews of Case-Based Reasoning in Engineering Design Research*

Butdee *et al.* developed the case based system for turning operation process planning [3]. Qin and Regli proposed the development of bearing design based on case based reasoning method by using the similar bearing design criterion (i.e. load, dimensions, etc.) for a new bearing design [4]. Kwong and Tam stated case-based reasoning to design low power transformers. The prototype system aimed to assist design engineers in formulating a configurable design of low power transformers in short time and provided the process information in the early design stage [5]. Amen and Vomacka used case based reasoning to select the materials for mechanical parts in machine design [6]. Lei *et al.* proposed case based reasoning for cold forging process design [7]. Butdee *et al.* presented the fashion trend forecasting method with case based reasoning [8]. Noomtong *et al.* developed the case based system in order to support aluminum extrusion die design by comparing a new die design problem with the previous die design cases [9]. Wang and Rong proposed a multi-level case based reasoning method for welding fixture design. This research approaches to systemize and manage myriads fixture related resources, e.g., past fixture design solutions, fixture units depository [10]. Lui and Xi presented a case-based parametric design system to realize automatic and intelligent design of turntable. CBR is used to retrieve a most similar case from the pre-built design knowledge-base and case base for a new design task. Utilizing parametric design within CAD system (Pro/ENGINEER 3.0) and knowledge base composed of parameterized 3D product model are constructed to build a new turntable design [11]. Janthong *et al*. applied case-based reasoning method to combine with AD (Axiomatic Design) in order to design mechatronics products. The design methodology was developed for adaptable design by reusing the knowledge of company to create new designs meeting customer's needs. The new components design is based on the reusing knowledge (CBR technique) to solve the new design solution [12]. As describe above, we found that a case-based reason can be successfully implemented in many fields of engineering design works.

3 Forging process design

3.1 *Principle of forging process design*

Process design in metal forming generally involves the selection of the initial raw material size, the perform shape and forming steps, the design of a die geometry, the ram velocity, etc. [13]. Forging is a deformation process in which the part is compressed in two dies, using either impact or gradual pressure to form shape of the part. Forging is an important metal forming process, because the parts from forging process have good mechanical properties more than other processes. In addition, these forging parts are used in widely applications. In general, forging process can be classified by forging temperature (hot/warm, cold), forging machines (hammer, press), and forging dies (open die, impression die, and flashless die). Forging process is very complicated with large plastic deformation, and the forging technical experts are essential and valuable for effective process and die design. The integration of knowledge base and experience is required to support forging process design [14]. Forging process design involves the selection of machine, material, die, type of forging, and forging parameters. This information must be defined by the forging experts based on their skills and experiences. The forging parameters have to seriously control during metal deformation. There are die materials, work piece material, press type, velocity of ram, friction type, coefficient of friction, die temperature, and work piece temperatures. Therefore, in metal forming process the knowledge of the experts are significant to affect operation efficiency, quality, and reliability. Although, today computer software has been developed for helping a forger to simulate metal forming process but it is not cover entire phases, especially, to make decision in process design. The computer software such CAD/CAM which has been widely used in forging and other metal forming tools design and manufacturing, but most are limited to improve engineering numerical calculation efficiency. Therefore CAE (Computer Aided Engineering) is applied in order to analyze metal deformation feasibility based on numerical method and simulate metal flow in die cavity. Additionally, AI (Artificial Intelligence) has played an important role in metal forming process for solving the problems by obtaining the knowledge from the metal forming experts to be transformed in computer system. The system can suggest the solutions by deriving from the knowledge base.

3.2 *Forging process design based on artificial intelligence tools*

Ravi *et al*. developed the expert system for design hot forging process based on material workability. The knowledge form materials' experts is acquired and formulated in term the rule based expert system. The expert system is developed using C Language Integrated Production System (CLIPS). It can address three types of functions, namely, forging process design, material information system, and forging defect analysis [15]. Ho and Mathew presented the development a case-based reasoning system (CBRS) to assist engineers for aiding the forging process and die design built on the ontology tool, called Protégé. CAE tools as DEFORM 3D can be simulated for design a forging die [16]. Masel *et al*. proposed a rule-based system to quickly estimate the geometry and volume of the forging die. The developed system was tested with an axisymmetric part as aircraft engine component [17].

3.3 *Finite element method in forging process simulation*

Knowledge base not only elicited from experts, but it can be captured from finite element method as shown in these researches. Kim proposed the application of the three layers artificial neural networks based on a black propagation algorithm with finite element method to design the initial billet and die geometry for forging process. The neural networks can reduce the number of finite simulation [18]. Kim and Park developed the expert system to automate axisymmetric hot forging process by using finite element analysis to determine the appropriate values of the factors. The rule-based system written in Fortran and AutoLISP and operates on AutoCAD environment [19]. Hsiang and Ho applied the neural networks integrated with finite element method for design a die of radial forging process [20]. Yin *et al*. stated a framework for knowledge discovery from finite element analysis data. The knowledge is formulated in term of fuzzy set [21]. In addition, finite element method has played an important role in study of metal forming parameters for obtaining process efficiency. Liu *et al*. presented the combination of a perform design method with FEM based forward simulation and the UBET (Upper Bound Elemental Technique) reverse simulation technique for forging preform design. The billet designed by this technique can achieve a final forging with minimum flash [22]. Tomov *et al*. used FEM to simulate and analysis of closed die forging with respect to flash formation at the end of the final impression filling [23]. Thiyagarajan and Grandhi proposed using finite element analysis to optimize of both 2D and 3D preform shape design. A multi-level design process was developed to find suitable basis shapes or trial shapes at each level in metal forming process [24]. Choi *et al*. used a three-dimensional rigid plastic finite element method analysis to optimize an open die forging process in production of circular shape (i.e. round bars, spindles, rotors, etc.). The study focused on the effect of feed rate and rotation angle for optimum forging process design [25]. Abdullah *et al*. presented the finite element analysis for study the effect of process parameters to assist cold forging die design for making decision in die and process design phases. The study investigated the stress distribution, load displacement curve, and effect of die geometry by using ABAQUS software [26]. Lee *et al*. simulated forging process by finite element analysis by the triangular and tetrahedral mini elements. The complex rotor pole cold forging process was simulated to investigate the forging shape in each forming process [27].

Form research reviews and the cases study in the automotive parts forging industry, we found that the information from the previous forging process design cases are reused and revised in forging process design engineers to make a decision to define the forging process parameters during process design phase. Therefore, the knowledge of a forging process design can be extracted from these cases. Then the case based reasoning is determined in this paper to be used for supporting and managing the knowledge base of forging process design.

4 The framework of case-based system for forging process design

4.1 *Case-based system for forging process design*

The framework of case based system for forging process design is illustrated in Figure 2. The system initiates by user input a new forging process design case via the user interface. A new case consists of case content such case number, forging part category, application, standard references and material of a part. A forging part model has to create in solid part format with CAD system as SolidWorks, because it can be directly extracted features. Part features, attributes and values are obtained by Application Programming Interface (API). API is coded on Visual Basic programming language. Part features are shape, geometry, mass, surface area, dimensions, center of gravity, and so on. And part attribute values are also captured in details of each feature dimensions. The assumption of this research is a similar forging part and forging process type (hot/cold forging) that has likewise forging parameters. The developed system will search by matching a new case with previous cases in case library by comparing features and calculating similarity percentage. The similar case is retrieved from case library. The case will be revised based on the developed knowledge base system before it is tested in forging process to confirm the case. In addition, the case can be evaluated by simulation with finite element method as

MSC.SuperForge software. The case is unaccepted after testing it will backward to revise case again. The steps are iterated until a new case is accepted. Finally, the acceptable case is retained in the case library. This framework is not only used the case base system for managing the knowledge of forging process design, but finite element method and simulation software are employed to help the forging die and process design to evaluate and estimate the appropriate forging process parameters.

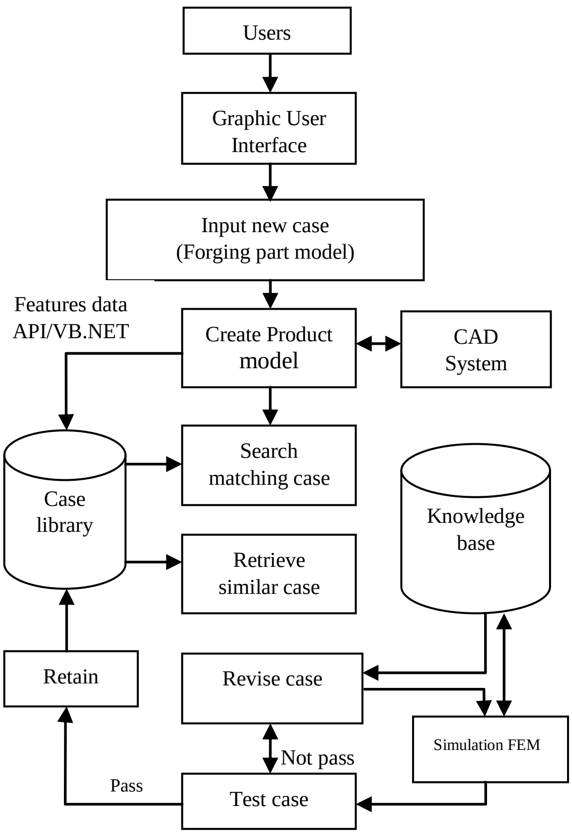

Figure 2: The framework of case-based system for forging process design

4.2 *Mathematic model in CBR for searching cases in case library*

The case-base in case library generally consists of two main parts: problem description and solution. Therefore, a set of case-base can be defined as illustrated in equation 1.

$$Case_i = X_{forging} = \{P, F, M\} \tag{1}$$

Where *P* is part features set, which include:

- Part category (i.e. connecting rods, axial shaft, crankshaft, wrench, …)
- Part dimensions (i.e., height, width, length)
- Web and rib dimensions (i.e., web height, web width, rib height, rib width, …)
- Corner radius (i.e., maximum corner radius, minimum corner radius)

Where *F* is forging parameter, which include:

- Type of forging (i.e., hot, warm, or cold forging)
- Lubricant (i.e., graphite based alcohol, graphite based water, …)
- Ram speed
- Pressure

Where *M* is part material set, which include:

- Part material (i.e., steel, copper, aluminum, …)
- Material properties (i.e., yield strength, young modulus, density, thermal conductivity …)

The mathematic model for calculating similarity percentage between a new case and the previous cases in case library is illustrated in [28]. The equations are shown in equation 2-4. The techniques to retrieve similar cases are inductive indexing and nearest neighbor.

$$S(x,y) = 1 - \frac{[x-y]}{(\beta-\alpha)}; x, y \in [\alpha, \beta] \tag{2}$$

Where α and β are the lower and upper bounds of the range. A crisp value x with a range [a, b], Similarity thisdbetween a crisp value and a range is presented in equation (3)

$$S(a,[b_1,b_2]) \frac{\int_{b_1}^{b_2} S(a,x)\,dx}{b_2-b_1} = \frac{\int_{b_1}^{b_2} (1-\frac{|x-a|}{\beta-\alpha}dx)}{b_2-b_1} \tag{3}$$

And, similarity between two ranges is shown in equation 4.

$$S([a_1,a_2],[b_1,b_2]) = \frac{\int_{a_1}^{a_2}\int_{b_1}^{b_2} S(x,y)\,dydx}{(a_1-a_2)(b_2-b_1)} \tag{4}$$

5 Case study

This paper proposes the case based reasoning for managing and supporting the knowledge base of forging process design by developing the computer program, called ManuSoft. The system can be used for storing, retrieving, revising, and retaining the cases via the case library. The software is coded with Visual Basic whereas database is Microsoft Access. Database consists of forging part, forging press, forging process parameters, materials, forging simulation data, and so on. Furthermore, the software has the module to read forging part attributes via user interface by extracting from API in SolidWorks. The forging part attributes are description of a new case. It contains of part number, part name, type of forging process, part category, material, dimensions, volume, weight, surface area, web width, web height, rib width, rib height, and smallest corner radius. The developed case-based expert system is tested with the sample part from automotive industry, called rear axial shaft, as illustrated in Figure 3.

Figure 3: Rear axial shaft

The sample forging part number TY186543 has dimensions 134 mm in width, 53 mm in length, and 381 mm in height. Part material is low carbon steel S43C grade. It is a component of the rear wheel system of a car. This part is created in CAD system with SolidWorks. The part features and attributes are extracted to capture the part geometry data. This information is a case description, including part volume, mass, dimensions, center of gravity, plane, and so on. In addition, this CAD model is also used to simulate in CAE software.

The new case description includes part volume 550 mm^3, weight 4.03 kilograms, surface area 365.5 mm^2, web length 134 mm, web width 15 mm, rib height 20 mm, rib width 12 mm, and smallest corner radius 2 mm respectively. This part information is extracted from CAD model in SolidWorks by API module and stores this data in to part database. The data is illustrated in Figure 4.

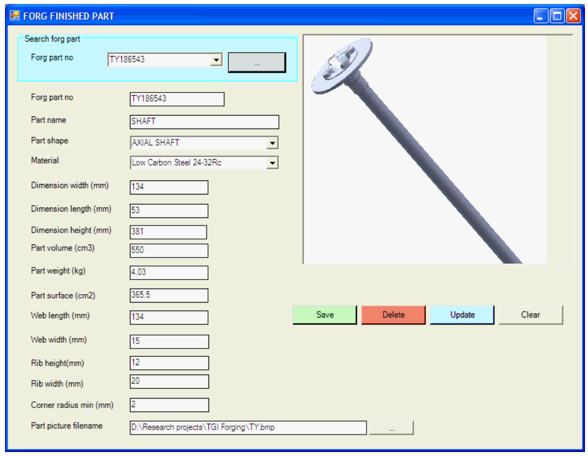

Figure 4: User interface of a new case data

The forging part information is used to search the similar case and calculate similarity percentage of each matched case by the developed case-based expert module. The similar cases are retrieved and displayed as shown in Figure 5.

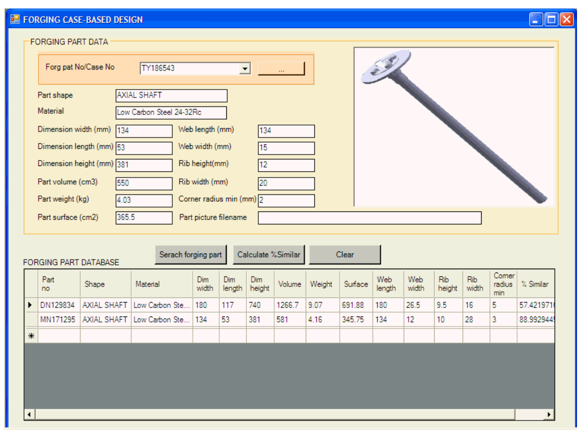

Figure 5: Searching similar cases interface

There are two forging parts number DN129834 and MN171295 from case base library, which matched with the new case. The forging parts data and similarity percentage are shown in Table 1.

Table 1: Similar percentage of the similar cases

Part No	**DN129834**	**MN171295**
Shape (Category)	Axial shaft	Axial shaft
Material	S43C	S43C
Dim width (mm)	180	134
Dim length (mm)	117	53
Volume (mm^3)	1,267	581
Weight (Kg)	9.07	4.16
Surface (mm^2)	692	346
Web length (mm)	180	134
Web width (mm)	26.5	12
Rib height (mm)	9.5	10
Rib width (mm)	16	28
Corner radius (mm)	5	3
Similarity (%)	57	89

From table 1, we found that the maximum similarity percentage of the part number MN17129 is 89%. The solution of this case is the parameters of forging process from the retrieved case. These parameters of forging process are shown in Table 2, including work piece material, punch material, die material, work piece temperature, punch and die temperatures, type of press machine, lubricant, ram speed, and forging stroke.

Table 2: Forging process parameters

Parameter	**MN171295**
Work piece material	S45C
Punch upper material	SKD61
Die lower material	WC
Work piece temperature	1,200
Punch and die temperatures	120
Press machine	HYDRALIC
Lubricant	GRAPHITE
Ram speed (mm/s)	0.5
Forging stroke (s)	52

These forging parameters are shown in forging process window as illustrated in Figure 6.

Furthermore, the forging processes are 3 steps: initial billet, preform, and finish forging, which are also represented to guide a forger to define the number of forming dies, press machines, and processes. The metal forming steps of forging are depended on the complexity of part geometry. In case library, the forging parameters are not only stored, but it is included the forging process simulation based on by FEM with MSC.SuperForge software in case library.

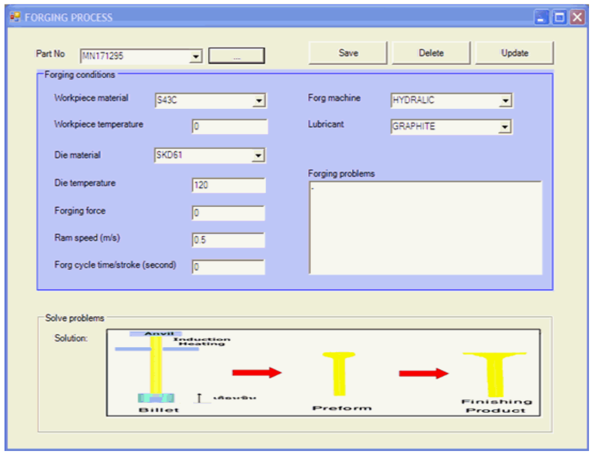

Figure 6: Case representation

The information for forging process simulation consists of material's properties, process parameters, meshing form, and etc. For this case study, the mechanical properties at high temperature between 900 and 1200 °C of forging part carbon steel grade that are illustrated in Table 3. This data set is input in forging simulation with FEM software.

Table 3: Mechanical properties of carbon steel at 900 °C - 1200 °C

Material Property	**Value**
Minimum Yield Stress (MPa)	25
Young's Modulus (MPa)	203,395
Poisson's Ratio	0.29
Density (Kg/m^3)	7,833
Thermal Conductivity (Watt/m*K)	46.729
Specific Heat Capacity (Joule/Kg*K)	419
Coefficient of Thermal Expansion (1/K)	1.49e-005

The metal deformation behavior of carbon steel is Viscoplastic that can be expressed in term of relation between effective stress and effective strain as illustrated in equation 5.

$$\bar{\sigma} = \max(S, C\dot{\bar{\varepsilon}}^{M}) \tag{5}$$

where $\bar{\sigma}$ = FlowStress

S = Maximum Yield Stress

C = Yield Constant

$\dot{\bar{\varepsilon}}$ = Strain Rate

M = Strain Rate Hardening Exponent

Furthermore, C and M values that are depended on strain and temperature of carbon steel grade S45C. The results form simulation have a played role for a die designer and a forger to make a decision in each forging die design and forging process design phases. This information from forging process simulation is stored in database as shown in Figure 7. It consists of forging effective stress, effective plastic strain, and temperature in the process. Forging process simulation by finite element method can be used to simulate and test the forging process parameters before applying in the production line. In addition, the results from finite elements simulation will be employed to modify the die geometry and to define the forging sequences. It can reduce forging process design times and costs. Moreover, the forging process data from simulation can be compared with the results from the forging case in the production. It can be used to redesign the forging process parameters and restored in the case library.

Although, case based reasoning and FEM are suitable for forging process design, however, the developed system can be enhanced the efficiency in knowledge learning by applying and integrating with other artificial intelligence such the neuron networks, fuzzy logics, and so on to support an adaptive forging knowledge base management.

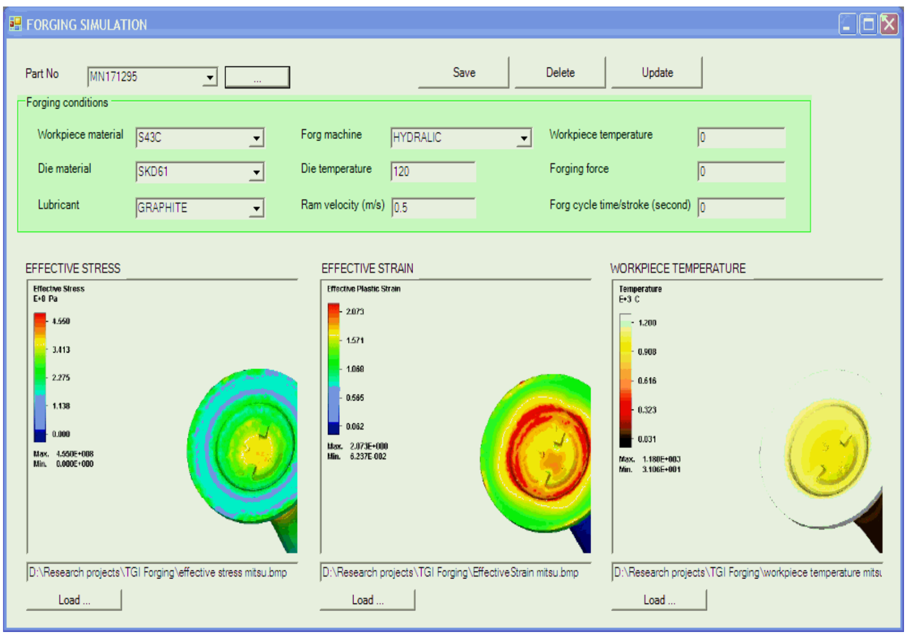

Figure 7: Case representation the results from simulation by finite element method

6 Conclusions

The case-based expert system can be used to support a forging process design. The previous cases are stored in case library, which have been prepared to retrieve for solving a new case. The integrated system for forging process design includes user interface, CAD, CBR, and FEM modules. Nearest Neighbor Method (NNM) is applied in CBR module for calculating case similarity percentage. The similar cases are retrieved and revised based on the knowledge base of the forging process design experts. In addition, forging process simulation by finite element method with CAE software can analyses the effective stress, effective strain, temperature, and other parameters in forging process to support forging tools and process design. The developed system can assist a forger to enhance forging process design efficiency. Forging design process time and cost can be reduced and to meet forging part quality. Finally, the knowledge base of forging process design is managed and manipulated in term of case-based expert system to be a knowledge asset of forging process design in organization.

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