The current status of simulation on various heat treatment process

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Abstract

The automotive industry is now in what is called a once-in-a-century period of change. In surrounded by new field CASE (Connected Autonomous Shared Electric), carbon neutral, SDGs, the parts require reduced weight like small size, thin and high strength, producing with low-energy/low-cost. In production process, heat treatment process control is important for product quality. Also CAE is now recognized, and it is used from research to departments closer to the actual site. In fact, we have many situation to measure temperature, dimension, distortion, stress. However heat treatment simulation has also become indispensable as a tool for visualizing and analyzing. There are various process simulations such as deformation and thermal by quenching, carburizing diffusion, induction heating, nitriding, welding, and additive manufacturing, shot peening. The principal of physics, theory, and calculation method is different for each process. Also recently engineer need to expand simulation evaluation field as effect of processes before and after heat treatment, metaphysics like deformation of forming, thermal, diffusion, and magnetic, computational fluid dynamics. And the simulation technique is proceeding such as design of experiments, and machine learning. From this, engineer can get many simulation results easily. The engineer will need to organize important factor from many simulation data and will need to understand the material property and principal of process. Actually some material property is unknown but digitization of real phenomena through simulation is expected to develop. This will introduce using DEFORM for various heat treatment simulations to help your organization.

Keywords: *Simulation, Computer aided engineering, Finite element method, Heat treatment, Quenching, Induction heating, Diffusion, Nitriding, Nitrocarbrization, inverse calculation, shot peening, design of experiment, optimization, data analytics, neural network*

1. Introduction

In the manufacturing industry, computer aided engineering (CAE) is recognized for its practicality. The usage is shifting from university laboratory to research & development department and closer to the design department. This many engineers is using simulation for low cost, shorten lead time as a tool like CAD. This explanation introduce DEFORM as one of the CAE software.

In the 1970s, it was development with rigid plastic finite element method for large deformation prediction at the Kobayashi Laboratory at Berkeley University. ALPID as the solver core was developed at the Laboratories of Battelle with funded by the U.S. Air Force. The developer established Scientific Forming Technologies Corporation (SFTC) in 1991, DEFORM has been commercially software and is still under development. This application is for large deformation simulations such as forging as the first stage, and currently implemented various process like extrusion, cogging, cutting, distortion after machining, shape rolling, ring rolling, mechanical joining, quenching with transformation, welding, and additive manufacturing.

Also post-processor has some tool with material sciences. Integrated manufacturing of pre-processor can chain each process and support design of experiment (DOE), optimization, and data analytics with machine learning.

In heat treatment simulation with transformation, the solver support it from 1997. Volume changes due to thermal gradients and phase transformation are modeled for evaluation. It was used for analysis by visualizing phenomena during heat treatment that are difficult to measure. The parameters and models of the product interface have a large effect on phase transformation and deformation. It has been quantified by inverse calculation of heat transfer coefficient and using Computational Fluid Dynamics (CFD). The parameter of material property will impact the final result. The expanding material properties will be a key challenge, but some support tool is developing like TTT prediction from chemical composition, converting TTT from CCT, graph digitizer. The quantified simulation data of the heat treatment state will be analyzed along with the experimental results, and Machine learning has the potential to make great strides. Further applied simulation technology development can be expected to improve heat treatment technology.

2. Software function

2.1 Integrated multiple process of manufacturing

When the process changes, such as heating, heat radiation, molding, and heat radiation, the input parameter also change. For over two decades ago, engineers repeated the setting and calculation of one process. DEFORM provided the integration of process chain modeling in Fig.1. GUI support intuitive operation for settings and each process has wizard in a menu tree. Multiple process is handled one plat home like heat treatment process and machining process. The continuous simulation of multiple process is possible using resetting automatically.

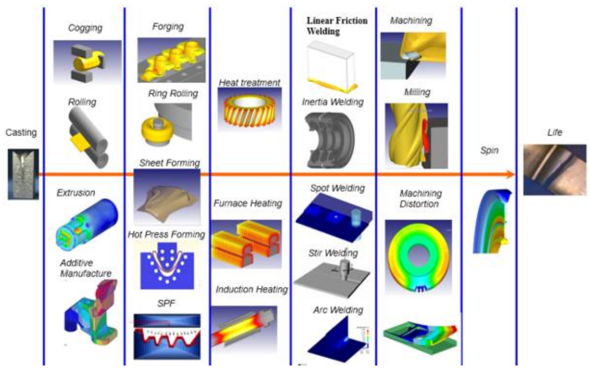

Fig.1 Integrated manufacturing process

2.2 Mesh generation

DEFORM has a mesh generation function powerfully. Mesher can generate fine mesh in critical areas under certain conditions such as geometry curvature, strain, and temperature. Coining example show 1.9 million element in Fig.2. It is possible to specify a spatial area and generate a thin layer coating mesh on the surface layer. In recent years, by 64-bit hardware and software, it possible to perform large-scale calculations involving millions of elements.

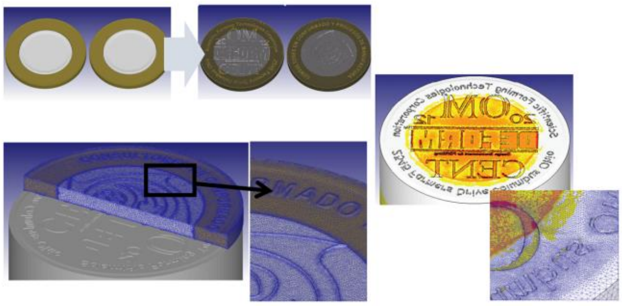

Fig.2 A large number of element simulation example

2.3 Simulation technic

As a more advanced function, this MO also implements DOE and optimization functions. Specifies the upper and lower ranges of the design variable.

In DOE, simulation conditions is planned by like Latin hypercube method or Taguchi method. After starting the simulation, the input values are automatically set, is performed in order. Any specified output values are also automatically outputted.

In optimization, target objective function is needed. The other is same as almost operation of DOE. After performing some conditions, the input values for the next job are determined based on the previous the objective function value.

DOE post processors can show the result from many simulation results automatically. This result show the tendency of results and major influencing factors due to design variables. Engineers can be evaluated simply by opening the file. Inputs for DOE, optimization can be numerical values, functions, geometry shape, and shape changes by CAD API. Outputs can output many variables such as temperature, stress, strain, load, dimensions, etc.

In addition, data analysis tools can load easily the necessary input and output information from many simulation data such as DOEs, and can be machine-learned. This learning model can predict the result of new conditions in seconds.

3. Theoretical base concept

DEFORM is calculated by finite element method (FEM). Generally, FEM calculate deformation using stress, strain and heat transfer for elast-plastic object. Heat treatment process is a complex, non-linear, non-equilibrium property-structure-process dynamic. Heat treatment simulation for steel consider transformation, diffusion. It is expressed by their coupling in Fig.3. In transformation, changing microstructure in each element is expressed using volume fraction. And diffusion of carbon is for carburization process. Changed each phase like ferrite, austenite, martensite is defined by TTT curve with JMAK model. The kinematic between each phase in material property is defined on diffusion like TTT curve and non-diffusion transformation. The kinematic of phase depend on temperature, time, and stress. Also latent heat and changed volume and transformation plasticity is also considered when transformation is occurred at element. Strain can be categorized into elastic, plasticity, thermal, transformation, transformation plasticity, and creep. In induction hardening, magnetic field simulation is added. Heat generation will be simulate between coil and work. In nitiriding, Precipitation of compounds is calculate transformation algorithm.

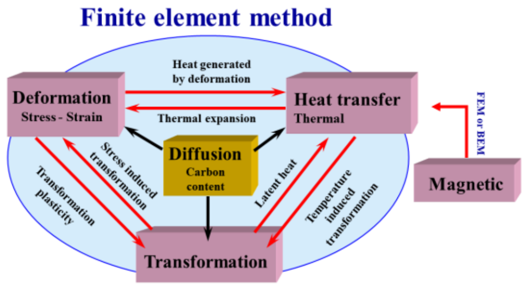

Fig.3 Inter-relation between each simulation models

4. Simulation example of various process

4.1 Quenching

Test piece is a hole of inner diameter 10 mm, outer diameter 30 mm and thickness 5 mm. After heating 790 degree, it is cooling in a water bath. Quenching cracks occurred after 5.3 sec from started cooling. In the heat treatment simulation, maximum principal stress was observed at the failure position in Fig.4(a). Another case is quenching using a diameter 10 mm shaft with a keyway and 100 mm in length. The tip of the shaft sways to the left and then to the right. This deformation was observed in experiments and simulations in Fig.4(b).

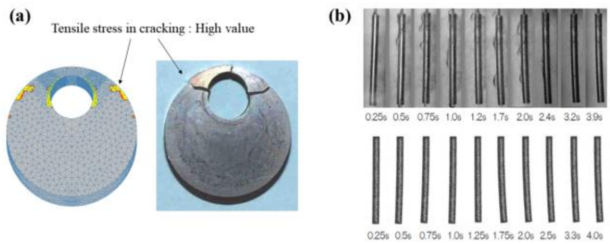

Fig.4 Crack and deformation of quenching

4.2 Diffusion

This is example of carburizing and quenching of a helical pinion. Material is chromium steel with low carbon.

The carbon concentration was measured at the depth from the surface, the tooth tip and tooth bottom in section by experiment after quenching. The similar distribution of carbon was observed between experiment and simulation.

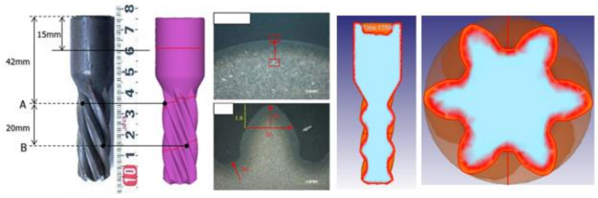

Fig.5 Comparing carbon distribution

4.3 Heat transfer coefficient

In quenching, the cooling rate by the media is important.

It effect for the transformation to martensite and the depth of product hardness. During quenching, the product surface undergoes vapor film stage, boiling stage, and convection stage, with different cooling rates. Cooling in the vapor film stage is slow, after the vapor film is broken, the cooling of the product progresses as the coolant boils. When the temperature reaches around the Ms point, the convection stage occurs and martensite transformation occurs. In the simulation, the cooling rate of water, oil, polymer, etc. is specified as a function of the heat transfer coefficient, which depends on the temperature. Surface heat transfer coefficient is an important parameter in quenching. In order to match the temperature history actually measured at multiple locations, DEFORM module run simulation repeatedly and optimizations to find the heat transfer coefficient. Fig6 shows an example. The heat transfer coefficient is optimized to match the temperature histories of the two measurement points.

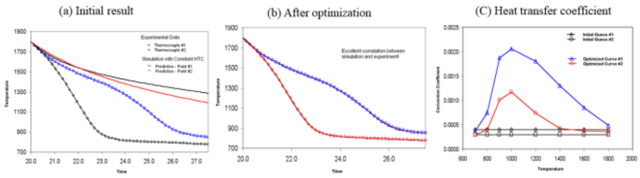

Fig.6 Inverse heat transfer coefficient calculation

4.4 Induction heating

Induction heating process uses an alternating electrical current through an induction coil to create a magnetic field. When ferromagnetic steel is placed in this magnetic field, an induced current is generated in the product, and the product is heated by Joule heat generated from the current. In the simulation, magnetic field analysis is also performed in addition to phase transformation. Magnetic field simulation is supported by FEM and boundary element method. It is need for material property such as electrical resistance coil property such as current densities, frequency. An example is shown in Fig.7. In (a), material is chromium molybdenum steel. Work is heated by high-frequency heating with a 40-turn coil, the heated part was formed, and the region of phase transformation was evaluated. In (a), a wire rod is moved and transformed into austenite by high-frequency heating. After passing through the coil, cooling was performed by water quenching, and depth of martensite transformation were evaluated.

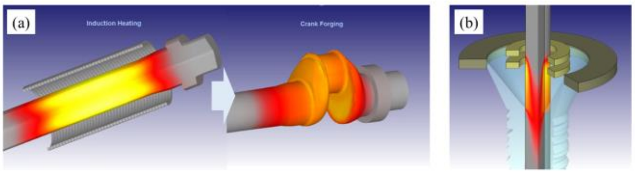

Fig.7 Induction heating simulation

4.5 Furnace

Heating with a furnace may cause some issue depending on time and placement. It is uninform temperature and scale occurrence, deterioration of mechanical properties, and excessive growth of grain size. In addition, heating time longer than necessary will result in extra energy. In the furnace module, the appropriate arrangement of the products to minimize the heating time, the delay in the heating rate of the products due to radiation and convection heating in Fig.8. It can be evaluated by simulation. The heating cycle and energy consumption can be optimized.

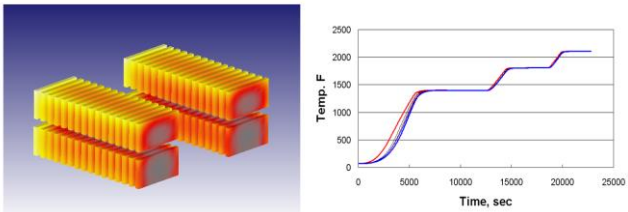

Fig.8 Furnace heating simulation

4.6 Predict distortion after heat treatment

Residual stress in the product occurs after forging or quenching. If a part of the product is removed by machining, residual stress also changes to a stable state and distortion of product will occurs. Using the results of heat treatment simulation, the cutting part and arrange the fixture is specified. And simulation has process of material removal with Boolean for machining and the fixture released process for distortion. It can be investigated the position of the fixture, the cutting area, the order of cutting, previous heat treatment condition, the distortion of product can be optimized.

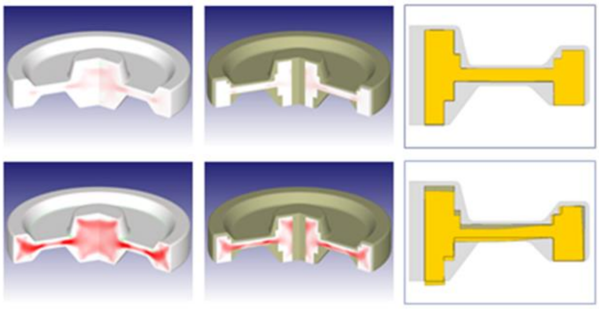

Fig.9 Predict distortion after heat treatment

4.7 Nitriding and Nitrocarburizing

Nitriding and Nitrocarburizing are processes in which activated nitrogen permeates the surface of steel to harden the surface. Similar to carbon, Fick's law is used to calculate the diffusion and penetration of nitrogen. Using volume fractions as for phase transformation, precipitation of epsilon, gamma prime is calculated from the solubility curve and Lehrer diagram. In order to represent the nitriding depth of the surface layer, a mesh of a thin layer is generated on the surface layer.

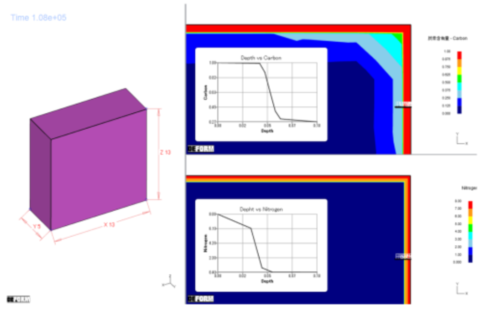

Fig.10 The depth of nitrogen and carbon

4.8 Shot peening

Shot peening process is generally difficult for FEM to appear real phenomena. Shot peening module can simulate using high technic. In micro model, the impact stress, residual stress is calculated from impact angle, number of hits, efficiency. Based on this relation of depth and radial stress, the model is trained. In next, hit count, impact angle and exposure time, etc is the simulated by particle simulation for 3D real model. From the trained model and particle simulation, this simulation can predict residual stress.

5. Simulation technical example

5.1 DOE for decreasing hoop stress on quenching

An example of disk parts using DOE shows in Fig.11. The material is a nickel-based alloy. The evaluation is the residual hoop stress after quenching by heat treatment. Design variables is the heat transfer coefficient at three area. It can be confirmed that the heat transfer coefficient of the inner diameter surface has the greatest effect on the internal hoop stress. The magnitude of the temperature gradient causes plastic deformation.

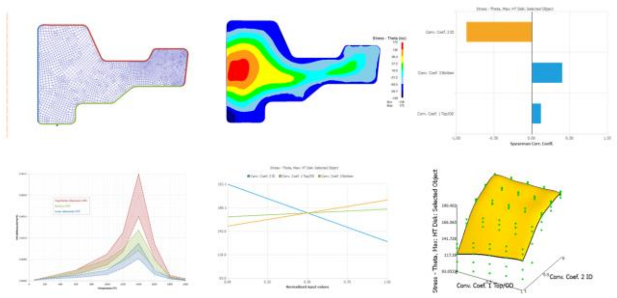

Fig.11 Heat transfer coefficient by DOE results

5.2 Data analytics for hardening prediction

Data analytics tool is for analyze and train the data with machine learning model like neural network. And it can predict output for new input data. For heat treatment example, data Analytics is used to model the hardness vs. cooling rate relationship from reference. The hardness values measured on production parts was compared to the predicted hardness using Data Analytics validation capability. After analyze, this model is trained from this data. The predicted hardness distribution using this model was displayed on the work mesh in post processing.

6. Conclusions

Various processes related to heat treatment can be simulated. Each process can be analyzed to understand the materials property, process conditions and principles. The scope of simulation field is to link all processes related to product manufacturing. In the future, many engineers simulate heat treatment process, then the understanding of material properties will be expanded, and the knowledge obtained by simulation and measurements by experiment will increase. It is expected that the prediction accuracy will be improved. Also, once a confidence dataset is built, rapid predictions by machine learning. Then, by providing feedback to equipment, it expect to control the fracture, dimensions and strength of the product as it is called a digital twin. To achieve, we use simulations to understand and analyze each process, and it is necessary to organize data of important factor conditions from a huge amount of information.

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