Recent Advances in Metal Forming Simulation Technology for Automobile Parts by AFDEX

Mansoo Joun
ReCAFT, School of Mechanical and Aerospace Engineering, Gyeongsang National University, 501 Jinjudaero, Jinju, Republic of Korea, 52828
msjoun@gnu.ac.kr

Abstract. In this presentation, hot issues of metal forming simulation are presented, including intelligent remeshing, flow stress modelling and material identification, friction, material model, complete analysis, quality quantification and optimal process design, multi-body forming simulation technology, sheet and plate forging by bulk finite element, etc. Some selected success stories for recent two decades are also introduced with a lot of industrial applications, especially to automobile industries. Finally, some futuristic research works are introduced for weight reduction and maximized life-span of auto-parts to save the global environments and some suggestion of international cooperation for the common pursuit is stated in conclusion.

1. Introduction
Metal forming technology has been everlastingly developed since human beings started to utilize metals about 5000 years ago. It had been occupied by the governing societies even after the Industrial Revolution because it had governed the strength of weapons and life quality. Note that it has still been dominated by the industrialized countries.

Since metal forming industry should be supported by so many infra-structural industries and companies as well as experience-based technologies and techniques, it had been very difficult for the developing or under-developed countries to be competitive in the related business sector. As consequence, limited number of industrialized countries have become independent of metal forming technology. Many countries involved in the global top ten of automobile or electronic industry suffer from the lack of metal forming technology and their automobile or electric industries are much dependent on developed countries.

Metal forming technology is composed of material and/or steel fabrication technology, press and equipment technology, process design technology, die material and making technology, surface and heat treatment technology, lubricant technology, manufacturing and automation technology, etc. From standpoint of engineers in metal forming companies, the process design can be an active source of creativity. Of course, one of obstacles pressing the metal forming companies in the developing countries is the experience-based technology, which can be efficiently come over by the metal forming simulation technology [1]. The metal forming simulation technology has become important in the related industry because it is innovating the costly experience-based approach of process design. In the past, this technology had been used just for being advised while currently it has occupied the major spot of the process design procedure.
Metal forming simulation technology is still growing together with metal forming technology to replace the experience-based approach to process design in metal forming. In this paper, some recent advances in hot issues of metal forming simulation technology are discussed with the state-of-the-art technologies, including solution accuracy, remeshing, modeling technology of material and friction, complete analysis and special applications to plate and sheet metal forming processes and special incremental metal forming process.

2. Hot issues of metal forming simulation technology

2.1. Solution accuracy

The major factors affecting deformation behaviors of material include elastic strain, plastic strain, strain rate, temperature, recrystallization, damage, anisotropy, etc. It is not easy to reflect all the factors in the metal forming simulation. The less influential factors should be thus disregarded from standpoint of engineering solution for the sense of practical application. Plastic strain is a major factor of metal forming at the room temperature while strain rate is a major factor and temperature is the secondary factor at the elevated temperature. In most simulations of bulk metal forming processes, engineers and researchers are interested in solving the material filling phenomena into die cavity affecting the under-filling defect and forming load. In such simulations, the appropriate major factors can give process design engineers and researchers some acceptable sorts of predictions because they are much affected by the volume consistency, that is, even rigid-plastic finite element analysis for cold forging and even rigid-viscoplastic finite element analysis may not discourage them if they are interested in global material flow itself. Typical application examples are shown in Fig. 1. The left figure in Fig. 1(a) is the first application of forging simulation made by industry in Korea [1] and Korea could become independent of forging process design and the related engineering from the developed countries in the mid nineties. The procedure of forging technology development with forging simulation technology in Korea can be seen from the homepage of AFDEX.

![Figure 1. Accuracy of forging simulations](image)
2.2. Remeshing
Remeshing is one of key factors affecting solution accuracy on bulk metal forming simulation [2, 3]. Remeshing is inevitable when the mesh system is too severely distorted or it does not describe the material within acceptable tolerance. It should be noted that the remeshing during metal forming simulation hurts considerably solution accuracy because it causes numerical smoothing of state variables as well as artificial change of the surface of material. Smaller elements near die corners in metal forming simulation can be easily and frequently damaged, causing frequent remeshing. Therefore, in metal forming, there is an appropriate number of finite elements which reduces number of remeshings at a little expense of numerical error. In addition, number of finite elements affects the computational time, implying that mesh density control is also of great importance in metal forming simulation. Fig. 2 shows some typical examples of intelligent finite element mesh systems. Fig. 3 shows the predictions of a coining process with emphasis on mesh density, which is an extreme case in terms of finite element mesh system [4].

![Intelligent finite element mesh systems for metal forming simulation](image1)

**Figure 2.** Intelligent finite element mesh systems for metal forming simulation

![Coining process](image2)

**Figure 3.** Coining process

2.3. Material identification
Remeshing is one of key factors affecting solution accuracy on bulk metal forming simulation. Particularly, plastic behavior of the material at the elevated temperature is very complicated. Its features involve strain softening due to recrystallization. When the coefficient and exponent in the power-law of flow stress with respect to effective strain rate are formulated as functions of strain and temperature, its unique features can be described as can be seen in Fig. 4 in which Voce model [5, 6], its variants including Ebrahimi et al. model [7], CFF and PLF models proposed by Razali et al. [8] and Hensel-Spittel model [9] are compared with experiments. However, these models except Voce model are weak in expressing the flow stress at extremely low strain rate which occurs in deal metal zone, etc. and cannot be neglected in many cases, for example, rolling with front and back tensions. A systematic approach to identify the flow stress of commercial metals at room temperature and to understand the plastic deformation behaviors of materials can be referred to the related works done by the author’s group [10, 11].
2.4. Friction model
Traditionally, laws of Coulomb friction and constant shear friction have been employed for metal forming simulation \cite{12}. It is noted that Coulomb friction and its variants are better for both cold and hot metal forming processes. For well-lubricated cases in cold metal forming, both friction models can be helpful for revealing the grain flow or metal flow lines. To the contrary, for example, when a metal forming process of a pancake shape of material at the elevated temperature is predicted, two laws show much difference from each other and the law of Coulomb friction is better in terms of metal flow lines.

Recently, a new concept of critical surface strain was presented by the author’s group, which is used to explain drastic change of frictional phenomena. Fig. 5(a) shows an experiment. Fig. 5(b) is one of unacceptable solutions. It should be noted that all the predictions were wrong when they were obtained using law of Coulomb friction with constant friction coefficients or law of constant shear friction with constant friction factors.

![Figure 5. Comparison of experiment and predictions](image)

2.5. Complete simulation
In most cases of practical metal forming simulation, dies or tools have been assumed rigid in metal forming simulation. With much better information about material and friction models, the solution accuracy has been much enhanced and metal forming simulation without any assumption or with minimized assumption on material and die deformation, called complete simulation has been becoming more and more important. However, the numerical complexity has hindered the advance in the complete simulation technology. Recently fully complete simulation of forging processes became realized and Fig. 6 is a typical example of complete simulation of a cold forging process considering pre-stressed dies owing to shrink fit. It is noted that the die deflection is coupled with deformation of material.
2.6. Quantification of grain flow or metal flow lines
Grain flow has been predicted by a finite element method for practical use by forging simulation technologies [1,13] for nearly 25 years. Traditionally, in the finite element method, the desired mesh defined on a planar section is traced to show the grain flow. It should be noted that traditional numerical approaches do not give a solution to quantify the quality of grain flow. The quantification of grain flow will become of great importance in the near-future because it will become essential for realizing process design optimization to meet strict quality specifications in simulation analyses. Recently the author of this work presented a unique method [14] of predicting grain flow or metal flow lines, which are contour lines of grain flow functions and new concepts of grain flow density and grain flow density gradient are presented to quantify the grain flow and its quality. A typical application example is given in Fig. 7, which shows the change of grain flow lines and the overlapping index. Fig. 7(a) and Fig. 7(b) are grain flow lines and overlapping index in the cross-section A-A defined in Fig. 7(c), respectively. Fig. 8 shows an example of optimal design considering normality of grain flow lines to the surface where taper rollers contact in service.
Optimized process design

Comparison of initial design (left) and optimized design (right)

Figure 8. Optimal process design in terms of normality of grain flow to the surface

2.7. Multi-body metal forming process simulation

Metal forming of multi-body processes, especially for assembling mechanical parts into assemblies, is one of hottest issues. Because residual interfacial stresses are important in these cases, elastoplastic finite element method is essential. These sorts of simulation will be becoming more and more important to guarantee the quality of assembly and optimize structural design of the assembly by the numerical way.

Process of assembling three parts

Stresses due to increase in lateral force

Figure 9. Simulation of multi-body metal forming and mechanical processes
Fig. 9 shows two typical examples of multi-body metal forming process. Fig. 9(a) is an assembly process of three metal parts in which the residual interfacial stresses are of great importance and Fig. 9(b) shows the change of contact stresses owing to lateral force in ball bearing assembly.

2.8. Thick plate blanking simulation

Shearing, piercing, trimming and blanking processes are essential in metal forming. However, their simulation techniques are not so easy because of fracture phenomena and complicated remeshing during the process. Traditional theory of ductile fracture can be employed to separate the material. To the contrary, remeshing is not so simple in these cases. An example of typical blanking simulation is given in Fig. 10.

![Figure 10. Blanking simulation](image)

2.9. Sheet metal forming simulation by solid element

Traditionally sheet metal forming processes have been solved by finite element methods with shell or plate finite-elements, which give quite reliable solutions especially when the processes rely on the stretching of thin sheet materials. However, these conventional approaches have shown decisive defects when thickness change of sheet or plate due to forming is one of major issues in the process design. In these cases, solid elements can give much better solutions and they can be inevitable in many cases. Fig. 11 shows a typical application of solid element approach to sheet metal forming of an oil pan.

![Figure 11. Sheet metal forming simulation by solid finite-element](image)

Fig. 12 shows comparison of experiments and predictions of a sheet metal forming process. It is noteworthy that the material is a sheet of titanium-clad aluminum. The experimental dimensions of $a$ and $b$ were 126.9 and 67.9 mm, respectively while their predictions were 126.7 and 68.3 mm, respectively.
2.10. Incremental metal forming process simulation

Incremental metal forming processes are attractive because they can form very complicated shapes of product with reduced stages in a quite creative way. From standpoint of their simulation, they are very characterized by long computational time and special functions which should be user-friendly.

A typical example is shown in Fig. 13, which forms the stepped bar and the end spline. The stepped bar was formed by around 1000 blows in the lateral forging or swaging while the spline at an end is formed by the punch with oscillatory motion which is aimed to reduce the forming load.

3. Summary

In this study, some recent hot issues and special topics in metal forming simulation were presented with typical examples, which show some advances and/or characteristics related with accuracy, remeshing, material and friction modeling, multi-body process simulation, complete simulation considering effects of die elastic deformation, solid-element approach to sheet metal forming simulation, process design optimization and extreme case of incremental forming process. The hottest interests from standpoint of developers of metal forming simulators for engineers and researchers include process optimal design and sheet metal forming process simulation using the solid-elements.

The importance of metal forming technologies were emphasized in terms of automobile and electronic industries together with the difficulties in developing the nationwide metal forming industry. The characteristics of metal forming technologies were explained, revealing that nationwide cooperation is essential to develop the metal forming industry because it should be supported by so
many infra-structural industries and companies. The importance of the role of academic sides to
develop the metal forming industry in the developing countries was also emphasized.
In Korea, AFDEX was started to be used by the leading Korean forging companies in the middle of
nineties when most commercial software could be applied mainly for academic purposes by
universities and research institutes and they have been able to innovate the imported or dead-copies
forging processes by themselves. It should be noted that the forging process design engineers could
not dare to change the traditional forging processes in those days. Nowadays most forging companies
are using forging simulation technology and web services are also being given to small-sized forging
companies by Korea Institute of Industrial Technology established by Korean government.
The examples shown in this study showed how Korean metal forming societies have been
everlastingly evolving and how academic side can prepare or lead the potential development of metal
forming industry in the developing countries. International cooperation for sharing experiences in this
field is needed for saving global environments because metal forming is the most influential green
manufacturing technology.

Acknowledgement
This work is carried out by the support of the BK 21 PLUS project and Industrial Core Technology
Development Project (2003950) from KEIT.

References
[1] Joun MS (Ed.), 1996, Workshop on metal forming CAE technology, Jinju Korea.
[2] Joun MS and Lee MC, 1997, Quadrilateral finite-element generation and mesh quality control
for metal forming simulation, Int. J. Num. Meth. Eng. 40(21) 4059-4075.
[3] Lee MC, Lee JK and Joun MS, 2007, Adaptive tetrahedral element generation and refinement to
improve the quality of bulk metal forming simulation, Finite Elem. Anal. Des. 43(10) 788-802.
[4] Jeong SW, Eom JG, Lee MC, Lee JE, Joun MS, Finite element analysis of a coining process
with extreme number of finite elements, Proc. KSTP, Joun MS, Daegu, Korea.
[5] Meyer LW, Weise A, Hahn F, 1997, Comparison of constitutive flow curve relations in cold
and hot forming, J. Phys. 7 3-20.
[6] Razali MK, Irani M, Joun MS, 2018, Consideration of Voce’s flow stress model and its
variants, Proc. KSTP, Joun MS, Seoul, Korea 138–139.
[7] Ebrahimi R, Zahiri SH, Najafizadeh A, 2006, Mathematical modelling of the stress–strain
curves of Ti-IF steel at high temperature, J. Mater. Process. Technol. 171 301–305.
[8] Razali MK, Irani M, Joun MS, 2019, General modelling of flow stress curves of alloys at
elevated temperatures using bi-linearly interpolated or closed-form functions for material
parameters, J. Mater. Res. Technol. 8(3) 2710-2720.
[9] Opela P, Schindler I, Kawulok P, Kawulok R, Rusz S, Petrek T, 2015, Hot flow stress models
of the steel C45, Metallurgical 54 469-472.
[10] Joun MS, Eom JG, Lee MC, 2008, A new method for acquiring true stress–strain curves over a
large range of strains using a tensile test and finite element method, Mech. Mater. 40(7) 586-593.
[11] Eom JG, Son YH, Jeong SW, Ahn ST, Jang SM, Yoon DJ, Joun MS, 2014, Effect of strain
hardening capability on plastic deformation behaviors of material during metal forming,
Mater. Design. 54 1010-1018.
[12] Joun MS, Moon HG. Choi IS, Lee MC, Jun BY, 2009, Effects of friction laws on metal forming
processes, Tribol. Int. 42(2) 311-319.
[13] Joun MS, Lee SW, Jung JH, 1998, Finite element analysis of a multi-stage axisymmetric
forging process having a spring-attached die for controlling metal flow lines, Int. J. Mach.
Tools Manu. 38(7) 843-854.
[14] Joun MS, Lee MC, Eom JG, 2016, Simulation device for object to be plastically deformed,
Japanese patent.