Simulation-aided application of advanced sheet steels to automotive parts

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Abstract. To promote our advanced steel to lightweight crashworthy automotive bodies, the authors’ group has developed practical technologies which improve the reliability of sheet-forming simulations from the viewpoint of material behaviour. For cold forming, simple-shear testing has been used to obtain the material data for the simulations of springback and edge cracking. For hot stamping, we developed the temperature-dependent forming simulations coupled with thermal analyses, computational fluid dynamics and phase-transformation models. We have also applied multi-scale simulations to understand the effects of steel microstructures on the deformation and fracture behaviour.

1. Introduction
The strong demand both for weight reduction and for crash safety of automotive bodies has increasingly promoted the application of high-strength steels to automotive parts. The strength levels of major structural parts have already reached 1.2 GPa for cold forming and 1.8 GPa for hot stamping. This trend from the late 1990s has fortunately come along with the progress and industrial spread of sheet-forming simulations which are truly helpful to obtain good solutions for many problems in the forming of these high-strength parts.

In cold forming of high-strength steels, major problems are springback and edge cracking [1], whereas hot stamping requires the stability of product properties and dimensions, as well as the improvement of productivity. In what follows, the activities in the field of forming simulations to overcome these difficulties will be introduced. As a steel supplier, the authors’ group focused attention to material-related issues including the basic understandings of the relationship between the microstructures and the deformation behaviour of real materials.

2. Cold forming

2.1. Springback
A good countermeasure for sipingback generally requires the good springback simulation which provide a sufficiently accurate stress distribution at the dead point of punch stroke, because this stress distribution is the driving force of springback when the constraints by tools are removed at the end of a stamping operation. The curl of vertical walls in a hat-section column, which is one of the typical springback phenomena observed in draw bending of high-strength steel sheets, is caused by the
combination of compression on the top surface and tension on the opposite surface of the walls. As the sheet material in the walls is first bent at the entry of die cavity and then unbent at the end of die radius, the stress at the walls is lower than the stress estimated based on the isotropic hardening hypothesis which neglects the Bauschinger effect. Such phenomena can be reproduced by a simulation into which a mixed hardening model, such as the Chaboche model [2] and the Yoshida-Uemori model [3], is implemented. As a matter of course, the appropriate material testing for the identification of material parameters is another important factor.

The authors’ group mainly uses simple-shear tests to experimentally observe the Bauschinger effect for parameter identification [4]. Because of the lack of work hardening and of the high yield strength, ultra-high strength steel sheets suffer from necking in tension and buckling in compression. The latter is pronounced by the reduction of thickness for weight-reduction purpose in automotive parts. Therefore, uniaxial tension and compression tests generally limit the strain given to the material. To obtain plastic strains as high as those in general sheet forming applications, the simple-shear testing is one of the best solutions. A good choice of specimen geometry and constraints enable to avoid necking and buckling. A large shear strain equivalent to a uniaxial strain of 0.1 or higher can, thus, be given both before and after loading reversal, as shown in figure 1. The equivalency between uniaxial loading and simple shear has already been confirmed [5].

Our simulation technologies have been applied to many ultra-high-strength steel parts practically used. We generally use simulations to minimize the springback deformation by adjusting and optimizing stress distribution [6]. This first step allows small dimensional errors to be compensated by the tool dimensions and, therefore, leads to stable high-volume production even under the variations of manufacturing conditions, such as temperature, lubrication, tool wearing, and materials.

2.2. Edge cracking in hole expanding and stretch flanging

The edge cracking in the forming of high-strength steel sheets is significantly influenced by the state of cut edge and the materials properties such as plastic anisotropy and flow-stress evolution. The former can be optimized by choosing a good shearing condition, for which the shearing simulations described in the next subsection is helpful. In this subsection, the materials aspects in the simulations of hole expanding and stretch flanging will be discussed.

Plastic anisotropy and flow-stress evolution are important materials properties which affect the strain localization in sheet forming. In hole expanding for a circular initial hole with axisymmetric tools, the plastic anisotropy and its evolution cause anisotropic strain distribution along the hole edge.
The simulations with 6-order polynomial yield function of which parameters evolutionarily changes as a function of effective plastic strain provided a good agreement with the experiments [7].

For the identification of material parameters, stress-and-strain curves in the strain range larger than uniform elongation in uniaxial tensile testing are required, because the strain gradient in hole expanding and stretch flanging delays the onset of necking and the strains at edge thus reach such high values. The simple-shear testing, as well as hydraulic-bulge testing and in-plane stretch-bend testing, is applicable to measure the evolution of flow stress at large strains [5]. The equivalency of stress-and-strain curves by simple-shear testing, by uniaxial tensile testing and by hydraulic-bulge testing is shown in figure 2. Furthermore, some models for the flow-stress evolution were proposed [5, 7].

![Figure 2. Stress-and-strain curves obtained by various mechanical tests for a 590-MPa-grade high-strength steel [5].](image)

One of the applications of the stretch-flanging simulations is an automotive part without notches in its curved flanges [8]. The end flanges of a cross member, for instance, generally have notches at corners. The flange with notches can avoid the edge cracking, since such flanges can be formed easily by bending. However, the notches in a flange reduce the rigidity of automotive body structures. In order to obtain a continuous curved flange without having the edge cracks in stretch flanging, strains are widely distributed and the peak height of strain along the edge line is lowered. The tools and forming process which can realize such strain distribution were optimized by using forming simulations as shown in figure 3. Ultra-high-strength-steel cross members with the continuous flanges have already contributed to the rigidity, the light weight, and the crashworthiness of automotive body structures.

![Figure 3. Schematic drawing of developed forming method for a continuous flange [8].](image)
2.3. Shearing
The state of a sheared edge produced in blanking, trimming or piercing process is influenced by tool conditions such as the clearance between punch and die, the shapes of punch head and die entry, and the angle between the punch stroke direction and the normal of sheet material. It is well known that the hardness distribution of the material around pierced edge, for instance, depends on the clearance. The simulations of such property changes in shearing are also of interest. A piercing simulation with the Hancock and Mackenzie criterion for ductile fracture leads to a good agreement between the distributions of experimentally measured hardness and of the calculated equivalent plastic strain \[9\]. The shearing simulations may also contribute to the estimation of residual stresses which affect the fatigue and the hydrogen embrittlement of sheared edge.

![Figure 4](image)

**Figure 4.** Development of calculated equivalent plastic strain after the crack initiation \[9\].

3. Hot stamping

3.1. Coupling with thermal analyses
The formability of hot stamping strongly depends on the distribution of deformation resistance caused by the temperature difference between areas with and without tool contact. Therefore, forming simulations coupled with thermal analyses are required. By the detailed analysis of heat transfer coefficient in hot drawing of cylindrical cup, we developed a technique to take thermal boundary conditions into consideration adequately \[10\]. This method, as well as the temperature-dependent material and friction models, can improve the accuracy of practical hot-stamping simulations. The forming simulations of centre-pillar part, for instance, provided a good agreement with experimental results as shown in figure 5.

![Figure 5](image)

**Figure 5.** Comparison of measured and simulated results for a model product of centre-pillar outer reinforcement \[10\].
3.2. Coupling with computational fluid dynamics for hot stamping with direct-water quenching
To improve the low productivity due to the time for complete martensitic transformation, we
developed a direct-water-quenching method using special tools with spout and vacuum nozzles [11].
For the simulations of hot stamping with this rapid-cooling method, computational fluid dynamics was
additionally applied to estimate the heat-transfer coefficient. We obtained a good agreement with
experiments in temperature distribution and in shape accuracy for a hat-section column model.

3.3. Coupling with phase-transformation models
For a further accurate prediction of product dimension, the effect of phase transformation should be
taken into consideration. We introduced not only the martensitic transformation in quenching but also
the ferritic transformation in slow cooling into the material model of hot-stamping simulations. This
allows considering the strains by phase transformation, which can be crucial in hot stamping with a
material excessively cooled before the start of quenching.

4. Multi-scale simulations

4.1. Anisotropic hardening and surface roughening in interstitial-free steel
The crystal-plasticity finite-element analyses coupled with the in-situ observation of deformation
textures revealed that the latent hardening possibly increases the work hardening in biaxial tension
[12]. Furthermore, it was found that the surface roughening depends on the combination of crystal
orientation and loading mode [13]. The plane strain, for instance, provides higher surface roughening
than the equi-biaxial tension in interstitial-free steel. This was supported by the distribution of the
Taylor factor experimentally observed and by the heterogeneous deformation simulated by crystal-
plasticity finite-element analyses.

4.2. Ductile fracture in dual-phase high-strength steel
The problem of edge cracking in high-strength steels has drawn our attention to the microstructural
effects on ductile fractures. For the void nucleation in dual-phase steel, image-based finite-element
simulations with the models for martensite fracture and for decohesion at the ferrite-martensite
interface were precisely compared with the microstructural evolution observed in tensile tests [14]. A
good agreement was obtained for martensite fracture, whereas further study was desired for the
behaviour of interface.

Figure 6. Comparison of in-situ observations with simulation results, (a) at 0.1 gauge strain, and (b) at 0.28 gauge strain. The
locations of martensite fracture are highlighted by elliptical markers [14].
5. Conclusions

The problems in forming of high-strength sheet steels can be overcome by the aid of forming simulations with reliable material data. The material data obtained by the simple-shear testing are useful for the simulations of cold forming in which springback or edge cracking is of major interest. The hot-stamping simulations coupled with thermal analyses including phase transformation and fluid dynamics can efficiently optimize the condition of forming and cooling to achieve the good qualities and the dimensional accuracies of products, as well as the high productivity. Moreover, the multi-scale simulations with finite-element models of microstructures can deepen the fundamental understandings on deformation and fracture of materials. Further development of simulation technologies will promote the applications of more advanced steels to higher-performance parts for automotive bodies.

References

[1] Yoshida T, Sato K, Isogai E, Nitta J and Yoshida H 2013 Proc. Int. 2nd Int. Symp. on Automobile Steel (China Machine Press) p 29
[2] Chaboche J L 1991 Int. J. Plasticity 7 661
[3] Yoshida F and Uemori T 2002 Int. J. Plasticity 18 661
[4] Suzuki N, Hiwatashi S, Uenishi A, Kuwayama T, Kuriyama Y, Lemoine X and Teodosiu C 2005 J. Japan Society for Tech. Plasticity 46 636
[5] Shirakami S, Yoshida T and Kuwabara T 2017 Tetsu-to-Hagané 103 589
[6] Yoshida T, Uenishi A, Isogai E, Sato K and Yonemura S 2013 Nippon Steel Tech. Rep. 102 63
[7] Suzuki T, Okamura K, Capilla G, Hamasaki H and Yoshida F Int. J. Mech. Sci. in press (available online 28 October 2017)
[8] Nishimura R, Nakazawa Y, Hama T and Takuda H 2017 J. Japan Society for Tech. Plasticity 58 304
[9] Matsuno T, Seto A, Suehiro M, Kuriyama Y and Murakami H 2012 Lightweighting: Possibilities & Challenges ed A Tewari, K Narasimhan and P P Date (IDDRG 2012) p 134
[10] Kusumi K, Nomura N and Maki J 2013 Nippon Steel Tech. Rep. 103 47
[11] Nomura N, Fukuchi H and Seto A 2015 5th Int. Conf. Proc. Hot Sheet Metal Forming of High Performance Steel (CHS²) p 549
[12] Tsunemi Y, Kubo M, Yonemura S and Uenishi A 2017 Procedia Engineering 207 2095
[13] Kubo M, Hama T, Tsunemi Y, Nakazawa Y and Takuda H 2018 ISIJ Int. 58 704
[14] Matsuno T, Teodosiu C, Maeda D and Uenishi A 2015 Int. J. Plasticity 74 17