The Optimization of Servo Press Method for Sheet Metal Forming

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Abstract

Recently in the field of sheet metal forming, servo press, which can control the speed and position of the tool using a servo motor, is attractive method. Development process of servo press method is accelerated as the capacity of servo motor become bigger. In the future, it's expected as a great alternative plan to replace conventional press method in order to improve quality, increase productivity, maintain integrity of tools, and reduce energy consumption.

Motion control in servo press method has to be effectively optimized depending on the shape and characteristics of the material. However, in the industrial field, the controls of motion relied on experience or intuition of most skilled worker, so the workers can't avoid many trials and errors to find the optimized motion. We try to implement the servo press method using a finite element analysis with LS-DYNA® in order to shorten the trials and errors [1]. And furthermore, we try to find optimal motion with LS-OPT® [2].

The front side member model of Numisheet 2011 BM03 was chosen for the analysis. We carefully consider stress relaxation and time scaling in order to implement servo press method. Then, we try to compare the following three cases to look into utility of optimized motion for the formability and productivity.

- *Conventional press method*
- *Conventional press method controlled by speed*
- *Servo press method*

Finally, we hope that the application of LS-OPT could be effectively used for the optimization of servo press method.

1. Introduction

Sheet metal forming is one of the processes producing the metal product with plastic deformation by machine tools. The traditional method, such as crank press and so on, has been used for sheet metal forming. This method may be restrictive for the control of working speed or load, because it uses the energy of the flywheel having a constant rotational velocity. To resolve this restriction, the development of the press method using a servo motor has been suggested.

In a servo press, the slide motion can be adjusted to optimize the press cycle for different applications and part transfer requirements [3]. This is illustrated in Figure 1, which compares the press cycle of a servo press conceptually with that of a mechanical press [4]. The dotted line shows a conventional press motion, and the solid line indicates an example of the servo press motion to be controlled by speed. The flexible programming of the servo press allows the operator to obtain the most suitable forming velocity for the material and forming operation, dwell in the slide anywhere at the desired stroke position, carry out secondary operations such as painting, punching, or assembly, and provide the necessary time for part transfer. The most important feature of the servo press is a flexible slide movement [5]. Figure 2 presents the typical motions using the servo press [6]. Since a servo press can carry out almost all the motions, a lot of benefits are brought by choosing a motion suitable for each purpose. The formability can be improved by variable change of motion. The productivity can be enhanced by shortening of a forming cycle time. The lifetime of machine tools may be extended by adjusting the touching speeds of the tool to the blank. Servo press is expected to exceed the limit for the difficult working such as high-strength materials.

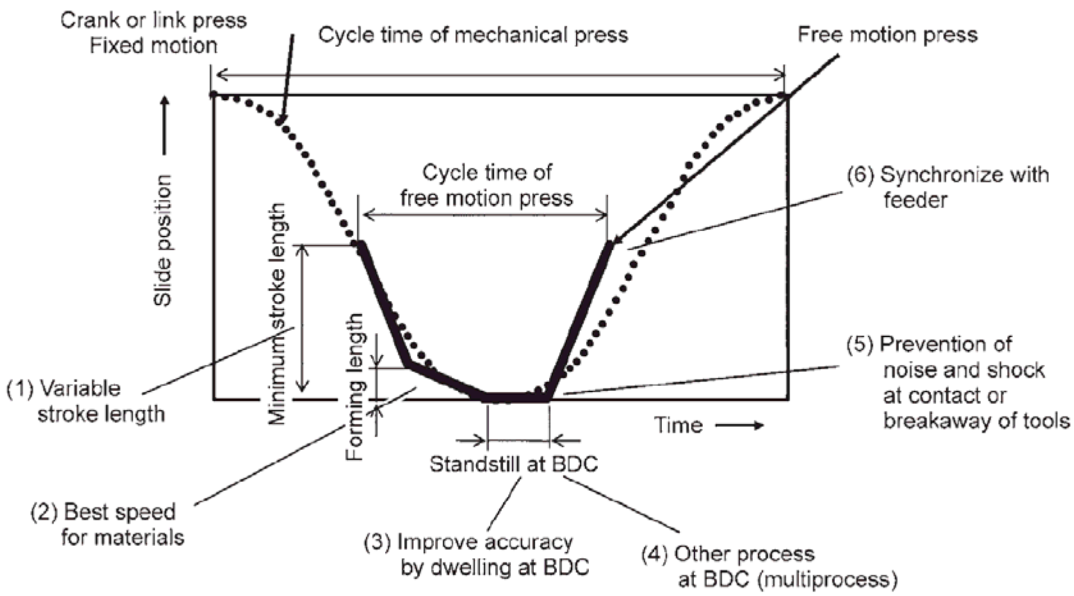


Figure 1: The flexibility of slide motion in servo drive (or free motion) presses [4]

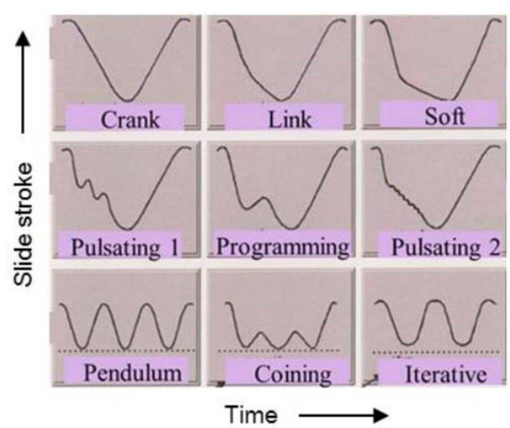


Figure 2: Typical motions of servo press [6]

2. Feasibility Study for Simulation of Press Methods

Press forming of sheet metal, often called stamping, includes bending, deep drawing, stretching, shearing, and so on [5]. We only focus the deep drawing in sheet metal forming, and look into the some issues to proceed with the analysis setup.

The analysis model is used for the front side member model in Numisheet 2011 BM03 as shown in Figure 3. The stamping process of this model is constructed with three sequences that are punch forming (OP10), trimming (OP20), and springback (OP30). The punch forming is only carried out for the servo press. In order to set up finite element analysis (FEA) method, forming conditions of this model are referred to the listed description in the benchmark [7]. The shape and location of machine tools, such as upper die, blank holder, and lower punch, are given as the CAD data. In the punch forming process, the motion of a punch is stationary, and upper die and blank holder are moving tools. The shape of the blank is made up to the maximum size allowed by the configuration, and the material is used by a high-strength steel (DP590) provided by POSCO in Korea. The speed of upper die is arbitrarily applied because it's not given in this benchmark.

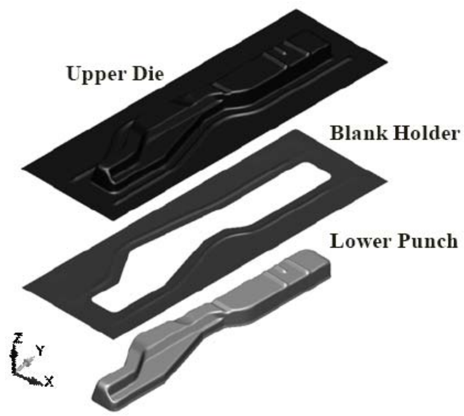


Figure 3: Front side member model in Numisheet 2011 BM03 [7]

We should discuss how to express the material properties of the blank among the many kind of material model in LS-DYNA. So, we searched the material model of LS-DYNA in order to use the information given in the benchmark. Among the material models, *MAT_HILL_3R (material type 122) of Hill's 1948 planar anisotropic material model with 3 R values can be considered. The exponential (swift) hardening can be chosen for hardening rule like description of benchmark. And the R-value determined from experiments is applied to the Lankford parameter. It seems to be reasonable to set up forming analysis according to forming conditions of the benchmark.

However, in the case of a servo press method, the phenomenon of stress relaxation is observed through re-draw motion. So, we need to consider a kinematic hardening in order to represent the characteristics of material. Among the material models which can represent this phenomenon, *MAT_KINEMATIC_HARDENING_TRANSVERSELY_ANISOTROPIC (material type 125) to combine Yoshida's non-linear kinematic hardening rule with the change of young's modulus during the simulation can be implemented.

The material information given in the benchmark has limitation to implement material type 125. So, we look into the papers related to the relaxation of stress. There are "Pre-strain effect on springback of 2-D draw bending" in Numisheet 2011 BM04 and "Effects of variable elastic modulus on springback predictions in stamping advanced high-strength steels" in ICTP 2011. We can consider the dual-phase (DP) 780 material contained in these papers. First in Numisheet 2011 BM04, it was explained to update Young's modulus according to the change of the equivalent plastic strain in order to evaluate the springback behavior [8]. This material of blank was a DP780 steel sheet, and the pre-strain effect was reported. Second in ICTP 2011, the effect of variable elastic modulus on springback was investigated by using various stamping tests [9].

The cyclic loading-unloading tensile tests were conducted to determine the variations of elastic modulus for DP780 sheet steel. The non-linear reduction of elastic modulus for increasing the plastic strain was formulated by using the Yoshida model that was implemented in the FEA method for springback.

Based on these data, DP780 seems to be appropriate as a blank material rather than DP590. The relational functions used in the material type 125 are listed below.

The Yoshida kinematic hardening model [1]:

According to F. Yoshida and T. Uemori's paper titled "A model of large-strain cyclic plasticity describing the Bauschinger effect and work hardening stagnation" in 2002 International Journal of Plasticity 18, 661-686,

$$\alpha_* = \alpha - \beta$$

$$\alpha_* = c\left[\left(\frac{a}{Y}\right)(\sigma - \alpha) - \sqrt{\frac{a}{\overline{\alpha_*}}}\alpha_*\right]\bar{\varepsilon}^p$$

$$a = B + R - Y$$

The change of size and location for the bounding surface is defined as,

$$\dot{R} = k(R_{\text{sat}} - R)\dot{\bar{\varepsilon}}^p,$$

$$\overset{o}{\beta}' = k(\frac{2}{3}bD - \beta'\dot{\bar{\varepsilon}}^p)$$

$$\sigma_{\text{bound}} = B + R + \beta$$

In Yoshida's model, there is work-hardening stagnation in the unloading process, and it is described as,

$$g_\sigma(\sigma', q', r') = \frac{3}{2}(\sigma' - q'):(\sigma' - q') - r^2$$

$$\overset{o}{q}' = \mu(\beta' - q')$$

$$r = h\Gamma, \Gamma = \frac{3(\beta' - q'):\overset{o}{\beta}'}{2r}$$

Change in Young's modulus is defined as a function of effective strain,

$$E = E_0 - (E_0 - E_A)(1 - \exp(-\zeta\bar{\varepsilon}^p))$$

Application of the modified Yoshida's hardening rule in the metal forming industry has shown significant advantage in springback prediction accuracy, especially for advanced high-strength steels (AHSS) type of sheet materials [1]. In our case, for the DP780 material using material type 125, hysteretic plasticity with a multiple cycle tension and compression simulation is done on one single shell element and the result is shown in Figure 4.

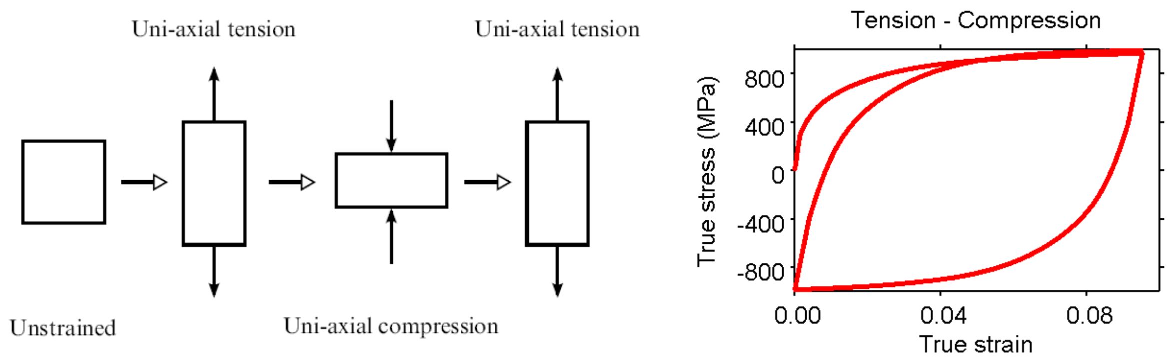


Figure 4: Multiple cycle plasticity motion and result

If the tool speed is identically set up with the physical speed applied to sheet metal forming in the FEA method, it will take considerably long CPU time. We should use the time scaling about forming speed of machine tool for this material. Therefore, the effect of strain rate may be an issue in the servo press method because of variable tool speed. In the case of DP780 material, the tensile strength increases slightly with strain rate as shown in Figure 5 [10]. But the strain rate has little effect on uniform elongation and total elongation as shown in Figure 6. It seems to be negligible to reflect the effect of strain rate for DP780 material.

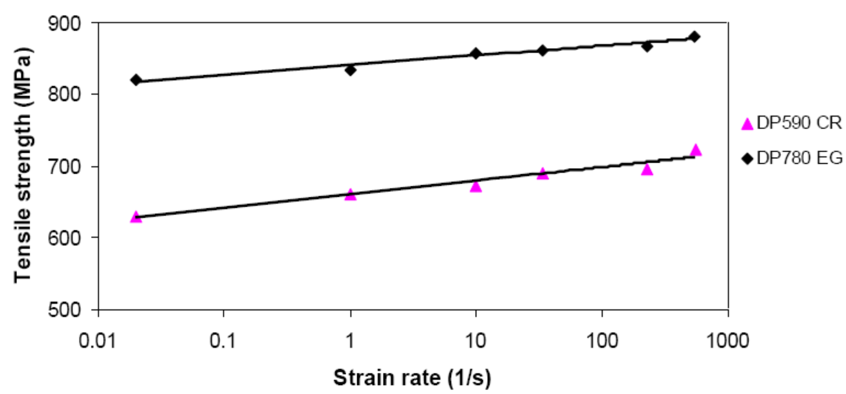


Figure 5: Relation between tensile strength and strain rate [10]

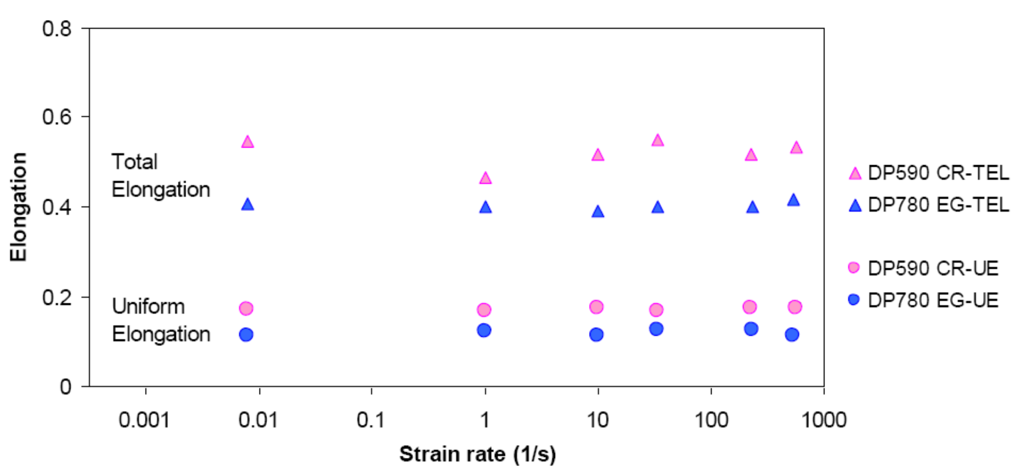


Figure 6: Uniform elongation and total elongation with respect to strain rate [10]

3. Simulation of Press Methods

The cross section of model chosen for simulation is shown in Figure 7. Also, common conditions to be applied for the three cases of methods are shown in Table 1. We modified size of the blank because of serious wrapping at the end of material. The cutting position is about 30mm from the trim line. The blank size is 1308mm * 460mm.

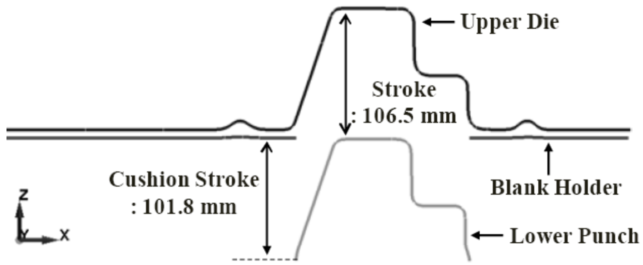


Figure 7: Stroke description for punch forming [7]

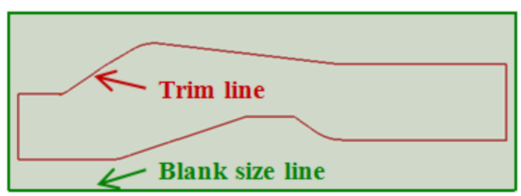
Upper die stroke	106.5mm
Working direction	Upper die: moving (-z direction) Blank holder: moving (-z direction) Lower punch: stationary
Stamping process	Punch forming (OP10)
Blank material	DP780 using material type 125
Blank thickness	1.8mm
Blank element	Quadrilateral shell element
Analysis solver	LS-DYNA V971 R7.0
Blank size	

Table 1: Common conditions of analysis model

The individual conditions are also needed for three cases of methods. Please refer following Table 2.

	1) Conventional press method	**2) Conventional press method controlled by speed**	**3) Servo press method**
Velocity of upper die	2,000mm/s (triangular)	3 Design variables	8 Design variables
Blank holding force	1,000kN	1,000kN	5 Design variables

Table 2: Conditions for velocity of upper die and BHF

1) Conventional press method:
The velocity of upper die is 2,000mm/sec at the vertex of triangular curve. So, the stroke of upper die has crank motion represented as quadratic function of time. The upper die moves from top dead center (TDC) to bottom dead center (BDC). And, blank holding force (BHF) is 1,000kN.

2) Conventional press method controlled by speed:
The velocity of upper die is optimized by LS-OPT with only 3 variables. So, the stroke of upper die has crank motion to be controlled by speed. And BHF is 1,000kN. The optimum approach can be summarized as follows.

- Optimization strategy: Sequential
- Sampling scheme: Radial basis function network (RBF) with space filling
- Objective components: Thinning, End time
- Optimization constraint: Forming limit diagram (FLD)
- Design variables: 3 items

Variable name	Description
drawvel1	Initial velocity
drawvel2	2nd velocity after initial movement
drawdis2	2nd displacement after initial movement

3) Servo press method:
Both velocity of upper die and BHF are optimized by LS-OPT. Especially, the velocity of upper die is optimized with 8 variables. So, the stroke of upper die has much variable motion than the others. It seems to take too much time to implement the optimization including all of 13 variables. But we can’t reduce the design variables because we don’t know which of variables are more sensitive to objective of optimization. So, we need to find most sensitive variables with ANOVA or GSA. Single iteration was implemented with 180 experimental points currently. The optimum approach can be summarized as follows.

- Optimization strategy: Single iteration
- Sampling scheme: RBF with space filling
- Objective components: Thinning, End time
- Optimization constraint: FLD
- Design variables: 13 items

Variable name	Description
drawvelo	Initial velocity
backfreq	Frequency of stepwise motion
backvelo	Backward velocity for stepwise motion
backdist	Backward displacement for stepwise motion
redrvelo	Re-draw velocity after backward movement
redrdist	Re-draw displacement after backward movement
finalvel	Velocity after last backward movement
finaldis	Displacement after last backward movement
bindfor1	Initial BHF
binddis1	displacement of upper die while the initial BHF is applied
bindfor2	2nd BHF after initial BHF
binddis2	2nd displacement of upper die while the 2nd BHF is applied
bindfor3	3rd BHF after 2nd BHF

LS-OPT is used to set up the optimization of servo press method. The development of LS-OPT has continued with an emphasis on the integration with LS-DYNA [2]. The main focus of Version 5 has been the development of a new graphical pre-processor to accommodate design processes as shown in Figure 8, in which the design stages are dependent on one another, as well as the improvement of the job scheduling system to enable handling of job dependencies. Transparency of the job scheduling process has also been improved.

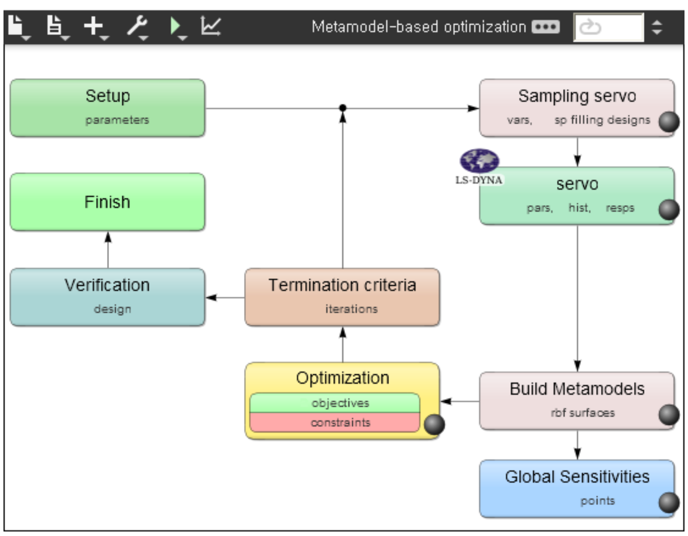


Figure 8: The LS-OPT GUI window to visualize the optimization process flow

The simulation results are shown in Table 3.

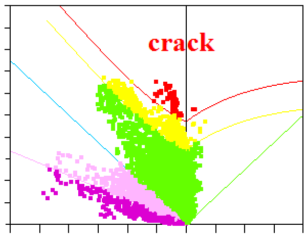
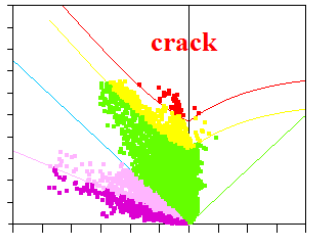
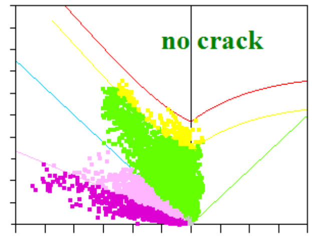
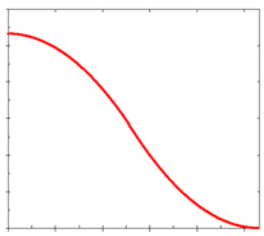
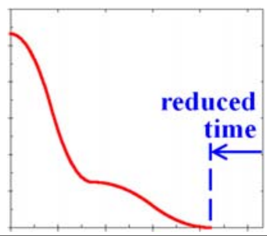
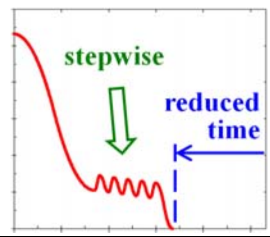
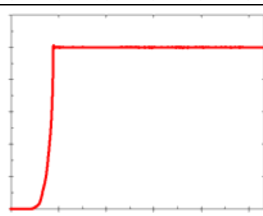
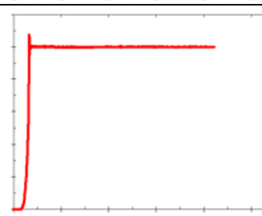
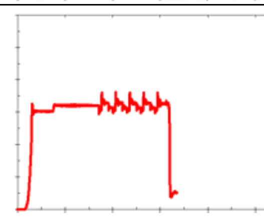
	case 1	case 2	case 3
FLD			
Thinning (max)	25.7%	24.4%	19.7%
Thickening (max)	19.4%	16.7%	20.1%
Die stroke			
Blank holding force			

Table 3: Comparison of simulation results

The following figures represent FLD results.

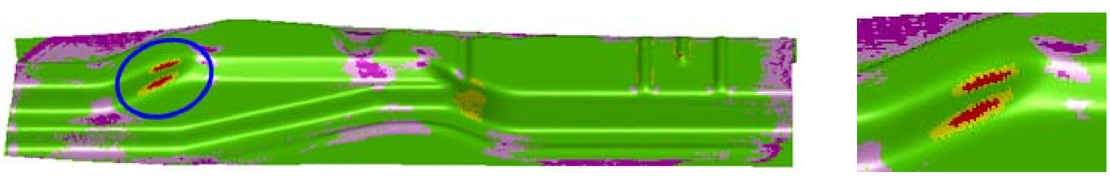


Figure 9: FLD result from case 1

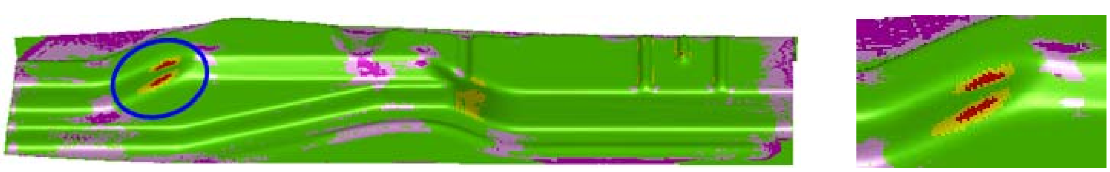


Figure 10: FLD result from case 2

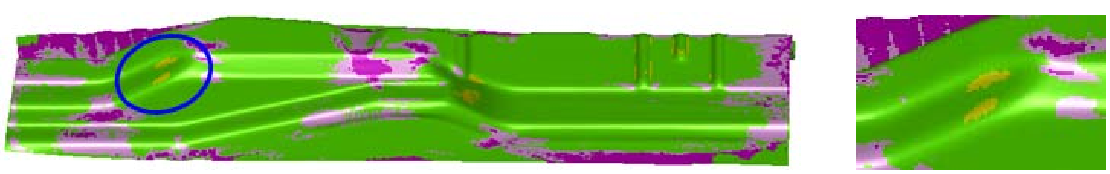
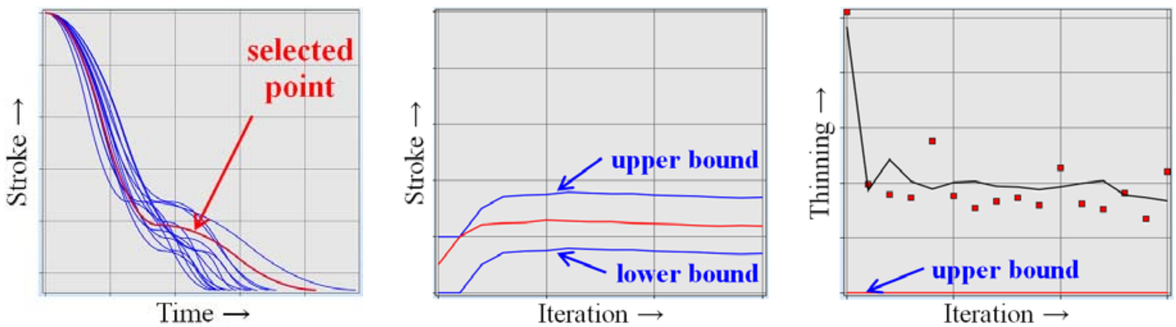


Figure 11: FLD result from case 3

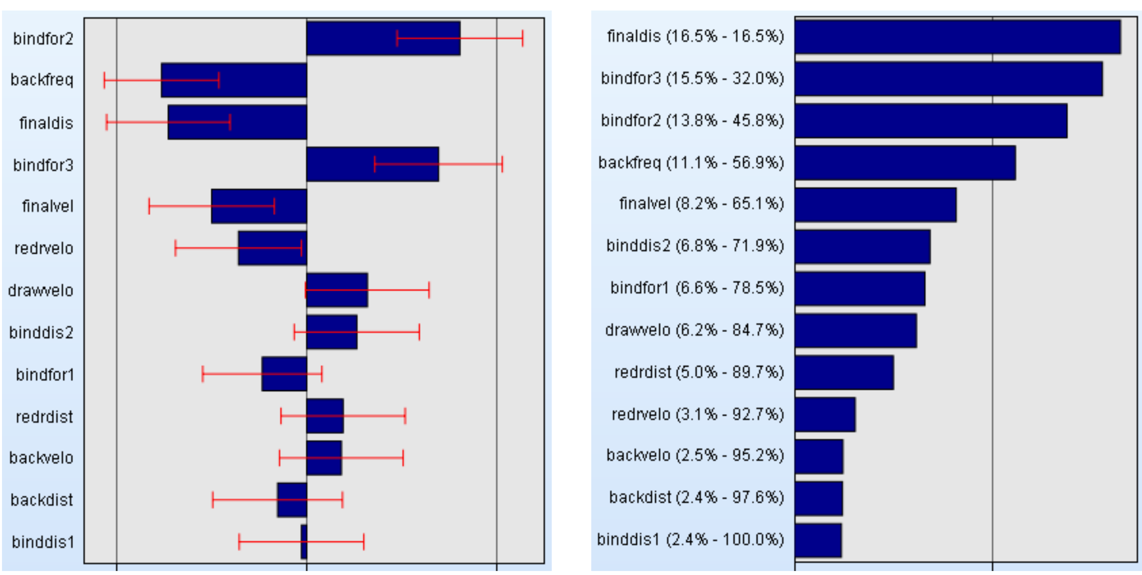
In case 1:
The cracks occur as shown in Figure 9. Because inflow of the blank may be relatively less in the curved locations of lower punch, it is likely that cracks occurred. We suppose that the crank motion has the limitation on improving the formability.

In case 2:
Optimized motion was converged as shown in Figure 10 after some iteration. Also, optimization history of displacement variable appears as shown in Figure 12. The progress time of work was decreased than previous case. But, there is on feasible experimental points. The constraint violation appears as shown in Figure 12. So, we also suppose that the crank motion optimized with a few design variables has the limitation on improving the formability.



(a) Motion: upper die (b) Variable: drawdis2 (c) Constraint: FLD
Figure 12: Optimization histories in LS-OPT viewer

In case 3:
The cracks do not occur as shown in Figure 11. And the progress time of work is decreased. The cracks are improved, but on the other hand the wrinkles are increased. We can suppose that the wrinkles also need to be included to objectives of optimization. We tried to find which variables are most sensitive to objectives of optimization in order to remove the unnecessary variables. The Figure 13 shows the ranking of each variable for sensitivity to thinning.



(a) Linear ANOVA (b) GSA/Sobol
Figure 13: Sensitivities in LS-OPT viewer

Global sensitivity analysis (GSA) is widely used to study the importance of different variables for higher order models. The five variables chosen from the GSA are as following.

- finaldis > bindfor3 > bindfor2 > backfreq > finalvel

The variable, finaldis, represents the displacement after last backward movement, and determines the position of stepwise motion. After this position, upper die will have the final velocity, finalvel. The both variables are very sensitive to thinning because the most severe thinning is found within this period of time. Blank holding force is very important for inflow of blank. The well controlled BHF is necessary when upper die move during the whole process. The whole process was divided with three stages to apply the different BHF. The last two BHF, bindfor2 and bindfor3, are more sensitive to thinning. The frequency of stepwise motion, backfreq, is also sensitive to thinning. The Bauschinger effect and work hardening stagnation in the material type 125 vary according to the frequency. So, we suppose that the cumulative re-draw motions contribute the change of thickness. The other variables, such as binddis1 and so on, are not relatively sensitive to thinning.

We suppose that the more desirable results can be obtained by reducing the number of variables and applying the sequential method for optimization. Also, wrinkles can be included for objective of optimization because thickening is some increase. We expect that the next optimization can be set up as follows.

- Optimization strategy: Sequential
- Sampling scheme: RBF with space filling
- Objective components: Thinning, End time, Thickening
- Optimization constraint: FLD
- Design variables: 5 items

4. Conclusions

The phenomenon of stress relaxation is observed in servo press method. The kinematic hardening model must be considered to realize the stress relaxation. The material type 125 was chosen for simulation. While the strength of DP780 increases slightly with strain rate, the elongation shows little difference. So, it seems to be negligible to consider the effect of strain rate for DP780 material.

We tried to compare three cases in order to look into benefits of servo press method. The optimized motion could be found in case 3. The simulation of case 3 confirm that the complex motion of servo press method help the distribution of thickness to be more uniformly spread out where the severe thinning is found. The ranking of sensitivity can make a judgment that which variables need to be removed. The five variables could be chosen by level of sensitivity. Each variable represents as follows.

- The position of stepwise motion
- The velocity after stepwise motion
- The frequency of stepwise motion
- BHF (two variables were chosen)

The more desirable results will be obtained by complementary optimization. The reasonable number of variables needs to be chosen as above. The sequential strategy helps the variables to be optimized more effectively. The sequential strategy has the advantage that the iterative process can be stopped as soon as optimum points have achieved sufficient accuracy. Wrinkle need to be included for objective of optimization.

The FEA can reduce huge amount of trials and errors in the industrial field. The development of LS-OPT will be continued to help this kind of strong industrial demand.

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