*MAT_KINEMATIC_HARDENING_TRANSVERSELY_ANISOTROPIC

This is Material Type 125. This material model combines Yoshida's non-linear kinematic hardening rule with material type 37. Yoshida's theory uses two surfaces to describe the hardening rule: the yield surface and the bounding surface. In the forming process, the yield surface does not change in size, but its center translates with deformation; the bounding surface changes both in size and location. This model allows the change of Young's modulus as a function of effective plastic strain as proposed by Yoshida [2003]. This material type is available for shells, thick shells and solid elements.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E	PR	R	HLCID	OPT	
Type	A8	F	F	F	F	I	I	
Default	none	none	none	none	none	none	none	

Card 2	1	2	3	4	5	6	7	8
Variable	CB	Y	SC1	K	RSAT	SB	H	SC2
Type	F	F	F	F	F	F	F	F
Default	none	none	none	none	none	none	none	none

Card 3	1	2	3	4	5	6	7	8
Variable	EA	COE	IOPT	C1	C2			
Type	F	F	I	F	F			
Default	none	none	0	none	none			

VARIABLE	DESCRIPTION
MID	Material identification. A unique number or label not exceeding 8 characters must be specified.
RO	Mass density.
E	Young's Modulus
PR	Poisson's ratio
R	Anisotropic hardening parameter
HLCID	Load curve ID in keyword *DEFINE_CURVE, where true strain and true stress relationship is characterized. This curve is used in conjunction with variable OPT, and not to be referenced or used in other keywords.
OPT	Error calculation flag. When OPT=2, LS-DYNA will perform error calculation on the true stress-strain curve from uniaxial tension, specified by HLCID. This variable must be set to a value of '2' if HLCID is specified and stress-strain curve is used.
CB	The uppercase B defined in the following equations.
Y	Hardening parameter as defined in the following equations.
SC1	The lowercase c defined in the following equations, and c1 in **Remarks** #4.
K	Hardening parameter as defined in the following equations.
RSAT	Hardening parameter as defined in the following equations.
SB	The lowercase b as defined in the following equations.
H	Anisotropic parameter associated with work-hardening stagnation.
SC2	The lowercase c defined in the following equations, and c2 in **Remarks** #4. If SC2=0.0 or left blank, then it turns into the basic model.
EA	Variable controlling the change of Young's modulus, E^A in the following equations.
COE	Variable controlling the change of Young's modulus, ζ in the following equations.

VARIABLE	DESCRIPTION
IOPT	Modified kinematic hardening rule flag: EQ.0: Original Yoshida formulation, EQ.1: Modified formulation. Define C1, C2 below.
C1, C2	Constants used to modify *R*: $R = RSAT[(C_1 + \bar{\varepsilon}^p)^{C_2} - {C_1}^{C_2}]$

Remarks:

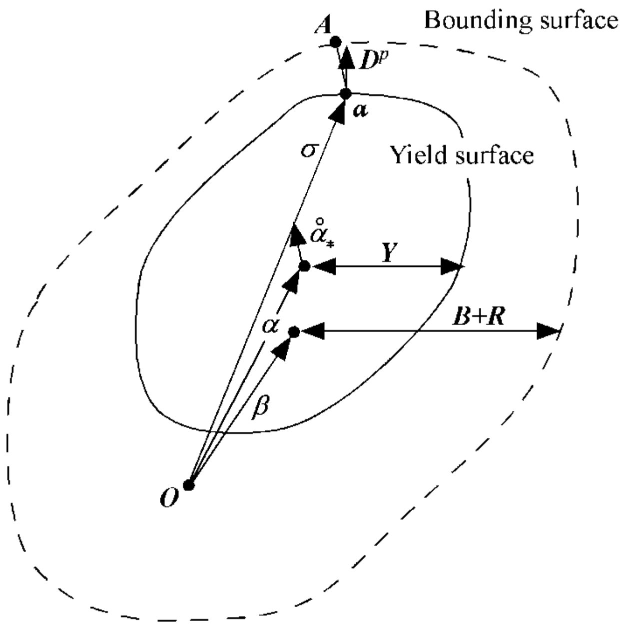


Figure 125.1 Schematic illustration of the two-surface model

1. The above figure 125.1 is a schematic illustration of the two-surface kinematic model. O is the original center of the yield surface, α_* is the current center for the yield surface; α is the center of the bounding surface. β represents the relative position of the centers of the two surfaces. Y is the size of the yield surface and is constant throughout the deformation process. B+R represents the size of the bounding surface, with R being associated with isotropic hardening.

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

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

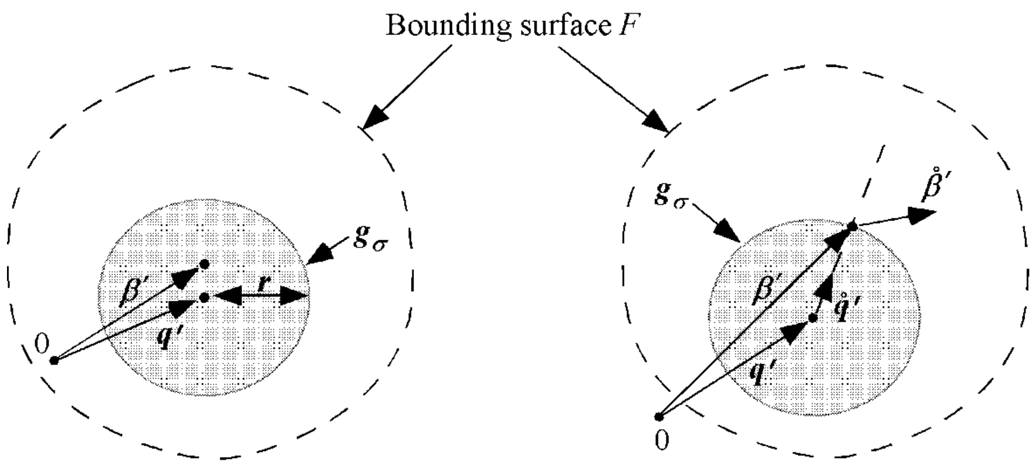
$$a = B + R - Y$$

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, this is work-hardening stagnation in the unloading process, and it is described as:

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



(a) when $\dot{R} = 0$ (b) when $\dot{R} > 0$

Young's modulus is defined as a function of effective strain:

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

2. Further improvements in the original Yoshida's model, as described in a paper "*Determination of Nonlinear Isotropic/Kinematic Hardening Constitutive Parameter for AHSS using Tension and Compression Tests"*, by Ming F. Shi, Xinhai Zhu, Cedric Xia, Thomas Stoughton, in *NUMISHEET 2008 proceedings*, 137-142, 2008, included modifications to allow working hardening in large strain deformation region, avoiding the problem of earlier saturation, especially for Advanced High Strength Steel (AHSS). These types of steels exhibit continuous strain hardening behavior and a non-saturated isotropic hardening function. As described in the paper, the evolution equation for R (a

part of the current radius of the bounding surface in deviatoric stress space), as is with the saturation type of isotropic hardening rule proposed in the original Yoshida model,

$$\dot{R} = m(R_{\text{sat}} - R)\dot{p}$$

is modified as,

$$R = RSAT[(C_1 + \bar{\varepsilon}^p)^{C_2} - C_1{}^{C_2}]$$

For saturation type of isotropic hardening rule, set IOPT=0, applicable to most of Aluminum sheet materials. In addition, the paper provides detailed variables used for this material model for DDQ, HSLA, DP600, DP780 and DP980 materials. Since the symbols used in the paper are different from what are used here, the following table provides a reference between symbols used in the paper and variables here in this keyword:

B	Y	C	m	K	b	h	e^0	N
CB	Y	SC	K	Rsat	SB	H	C1	C2

Using the modified formulation and the material properties provided by the paper, the predicted and tested results compare very well both in a full cycle tension and compression test and in a pre-strained tension and compression test, according to the paper.

Application of the modified Yoshida's hardening rule in the metal forming industry has shown significant improvement in springback prediction accuracy, especially for AHSS type of sheet materials. In the figure shown below, predicted springback shape of an automotive shotgun (also called: upper load path) using *MAT_125 is compared with experimental measurements of a DP780 material. Prediction accuracy achieved over 92% with *MAT_125 while about 61% correlation is found with *MAT_037.

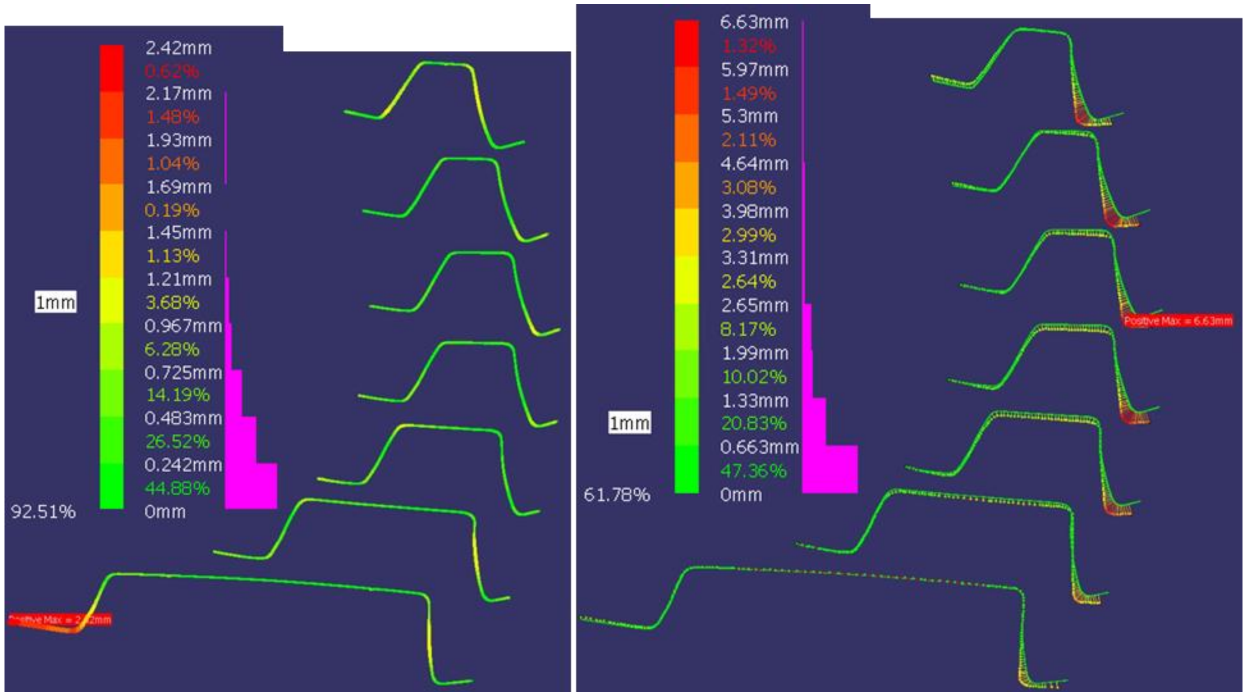


Figure Comparison of springback prediction of *MAT_125 (left) and *MAT_037 (right) on A/S P load beam *(Courtesy of Chrysler LLC and United States Steel)*

3. NUMISHEET 2011 BM4 is used below to demonstrate the application of the Young's modulus variations as a function of effective strain in prediction of springback. The sheet blank is a DP780 material with an initial thickness of 1.4mm. The simulation process is shown as pre-straining(to 8%), springback, trimming, draw and springback. Young's modulus variations with effective strains are accounted for by curve fitting the provided experimental data to obtain the variables EA and COE. Final springback shapes of the sectional view are compared with measurement provided, along with benchmark results from participants X and Y. In addition, springback with no pre-straining is also conducted and correlated. Furthermore, hysteretic plasticity result on one element with a full cycle tension and compression test is examined with experimental test.

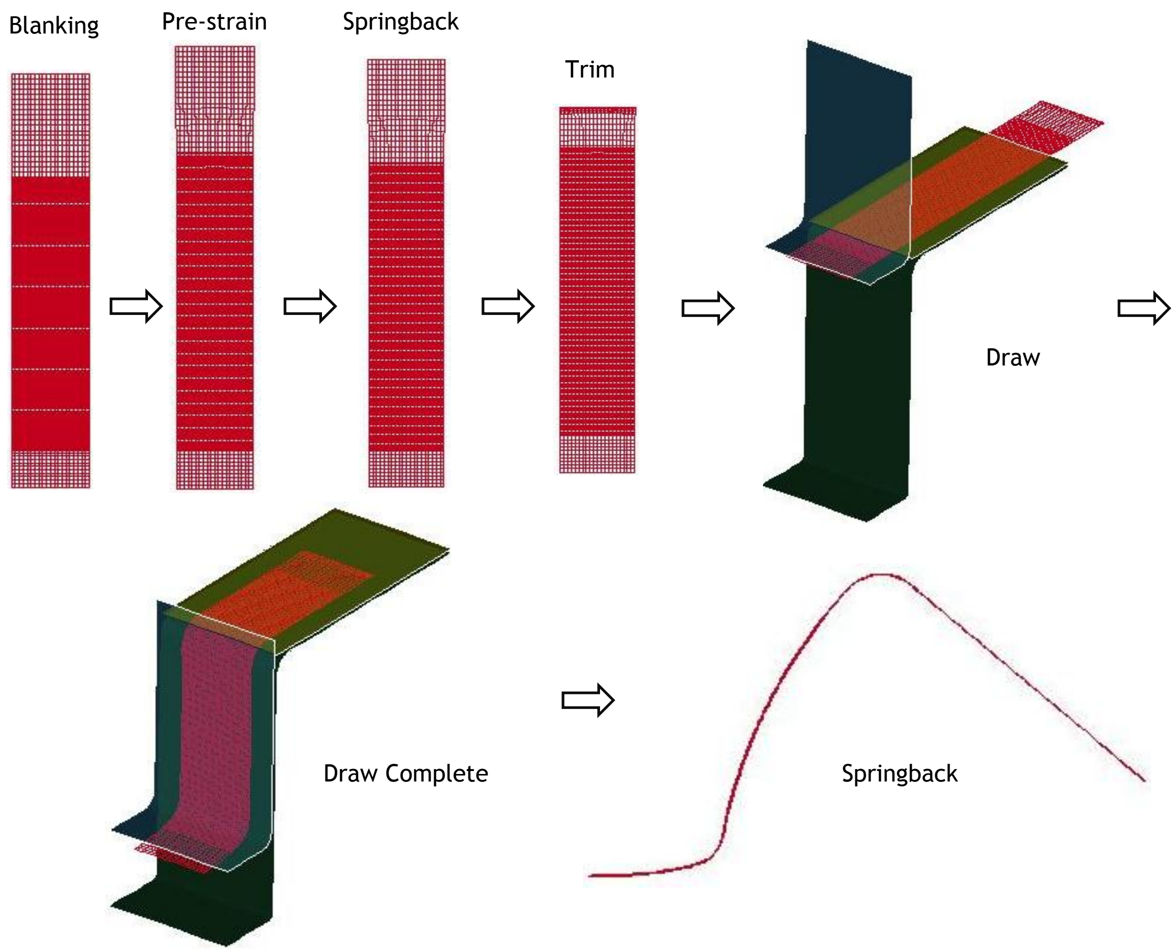


Figure NUMISHEET2011 Benchmark 4 Simulation process

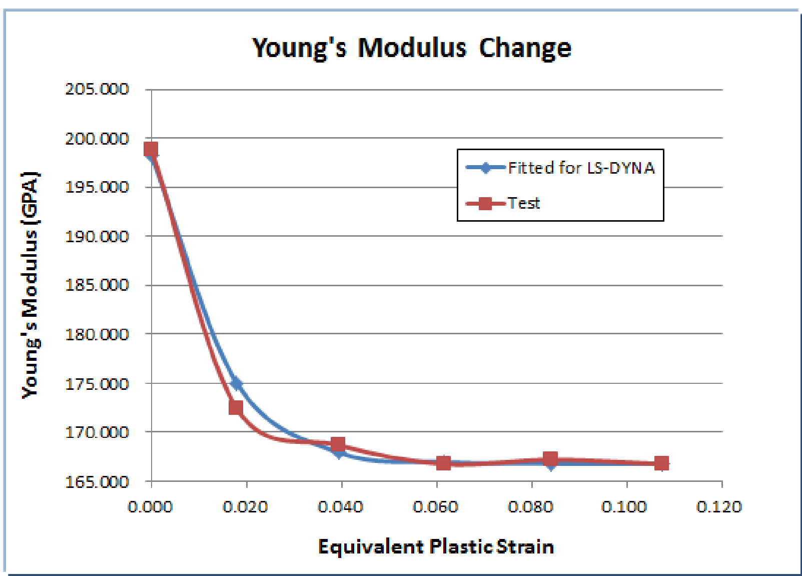


Figure Curve fitting with coefficients: EA=1.668E+05; COE=95.0

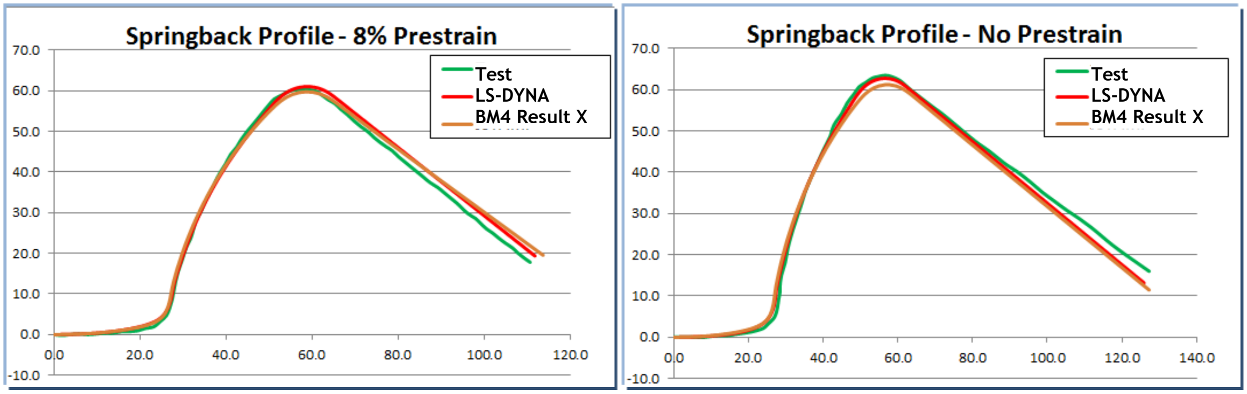


Figure Comparison with participant X with 8% prestrain(left) and 0% prestrain(right)

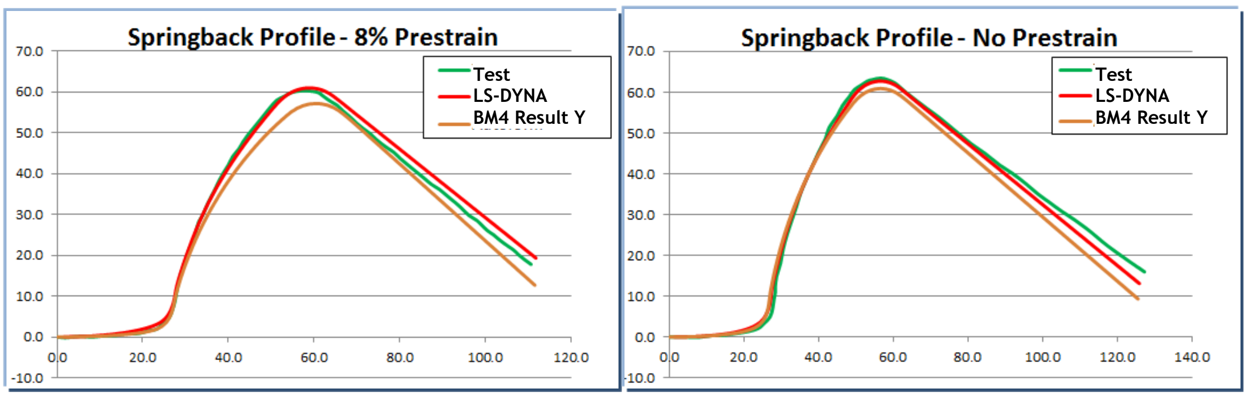
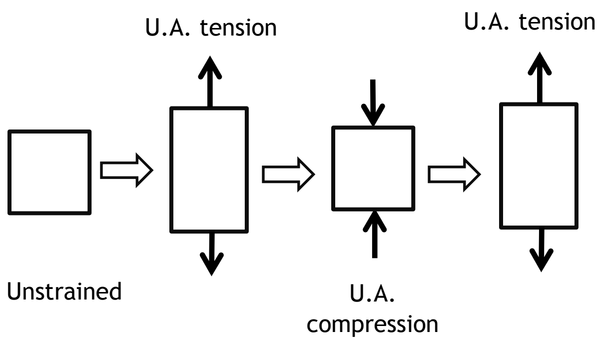


Figure Comparison with participant Y with 8% prestrain(left) and 0% prestrain(right)



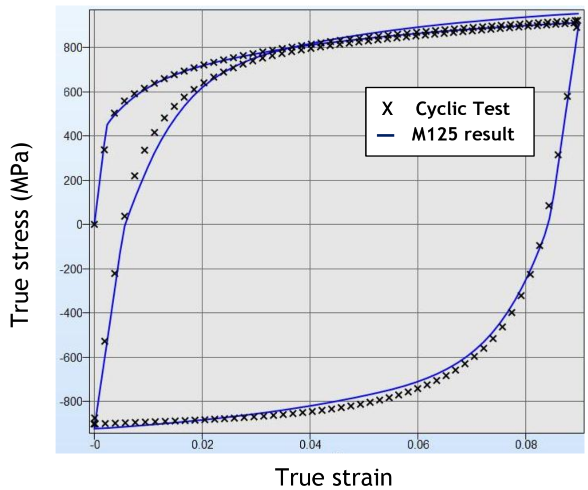


Figure Cyclic tension/compression modeling on one shell element

Figure Cyclic plasticity verification

4. To improve convergence, it is recommended that *CONTROL_IMPLICIT_FORMING type '1' be used when conducting a springback simulation.

5. F. Yoshida and T. Uemori introduced variables SC1 and SC2 in their publication of the 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.* According to the paper, variables SC1 and SC2 are used to describe the forward and reverse deformations of the cyclic plasticity curve, respectively. It allows for a more rapid change of work hardening rate in the vicinity of the initial yielding (~0.5% equivalent plastic strain), in the form of the following equations:

$$SC = SC_1 \text{ when } \mathrm{Max}(\bar{\alpha}_*) < B - Y, \quad (1a)$$
$$SC = SC_2, (C_1 > C_2), \text{ otherwise.} \quad (1b)$$

where $\mathrm{Max}(\bar{\alpha}_*)$ is the maximum value of $\bar{\alpha}_*$, and,

$$\bar{\alpha}_* = \sqrt{\frac{3}{2}\alpha_* : \alpha_*}$$

The figure below shows the effect of a curve fitting for a high strength steel (SPFC) using both SC1 and SC2, in comparison with a fitting using only SC1, from Yoshida & Uemori's original paper:

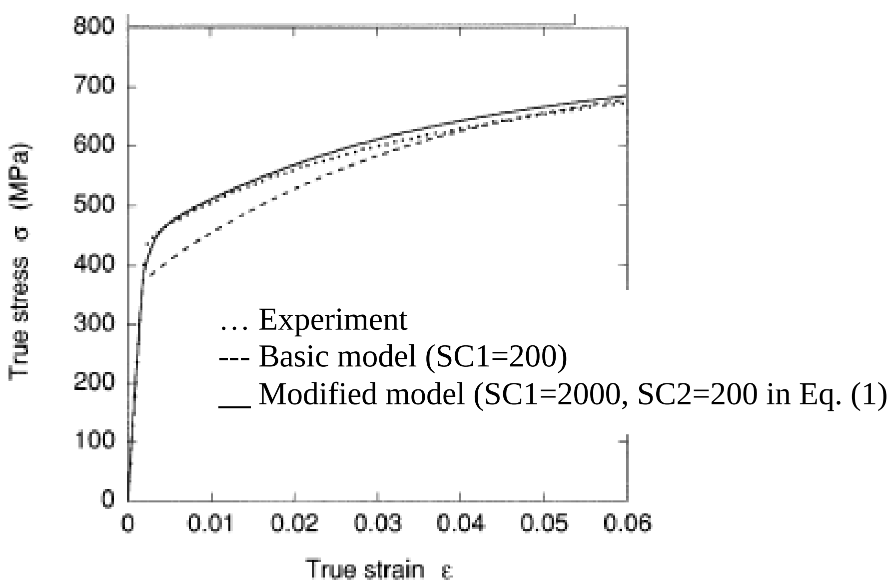


Figure Effect of SC1 and SC2
(copy from original Yoshida & Uemori paper)

The following figures show a much better fitting with SC1/SC2 than with SC1 only for a DP980 material.

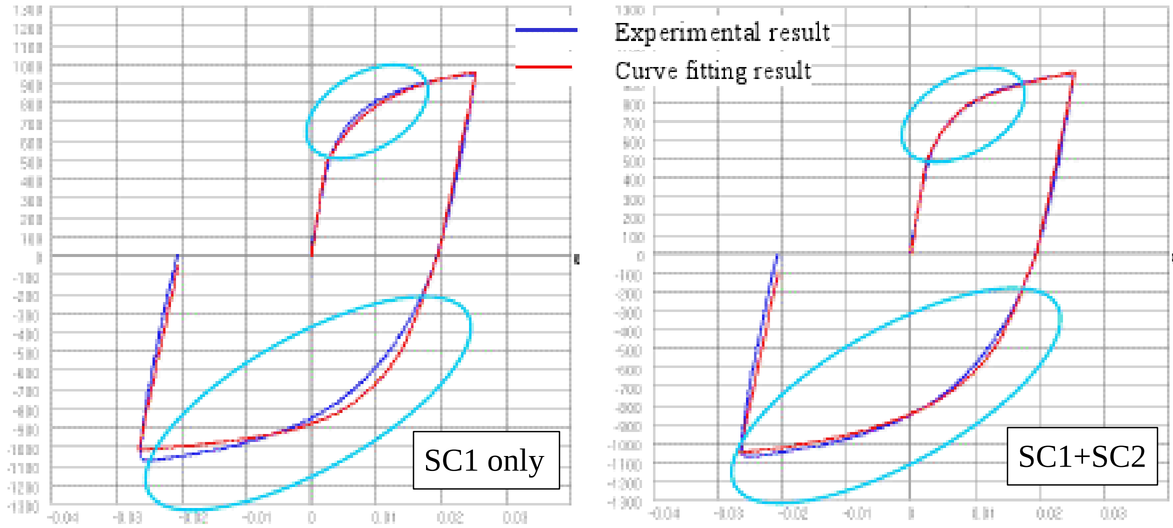


Figure Material curve fitting comparison
(*Courtesy of CYBERNET SYSTEMS CO., LTD.*)

6. The HLCID, OPT, IOPT, C1, and C2 variables are available in LS-DYNA R4 Revision 46217 or later releases. The variables SC1 and SC2 are available in LS-DYNA R6 Revision 74884 and later releases.