*MAT_KINEMATIC_HARDENING_BARLAT89

This is Material Type 226. This model combines Yoshida non-linear kinematic hardening rule (*MAT_125) with the 3-parameter material model of Barlat and Lian [1989] (*MAT_36) to model metal sheets under cyclic plasticity loading and with anisotropy in plane stress condition. Lankford parameters are used for the definition of the anisotropy. Yoshida's theory describes the hardening rule with 'two surfaces' method: the yield surface and the bounding surface. In the forming process, the yield surface does not change in size, but its center moves with deformation; the bounding surface changes both in size and location.

Card 1	1	2	3	4	5	6	7	8
Variable	MID	RO	E	PR	M	R00	R45	R90
Type	I	F	F	F	F	F	F	F
Default	none	0.0	0.0	0.0	0.0	0.0	0.0	none

Card 2	1	2	3	4	5	6	7	8
Variable	CB	Y	SC	K	RSAT	SB	H	HLCID
Type	F	F	F	F	F	F	F	I
Default	0.0	0.0	0.0	0.0	0.0	0.0	0.0	none

Card 3	1	2	3	4	5	6	7	8
Variable	AOPT	IOPT	C1	C2				
Type	F	I	F	F				
Default	none	none	0.0	0.0				

Card 4	1	2	3	4	5	6	7	8
Variable	XP	YP	ZP	A1	A2	A3		
Type	F	F	F	F	F	F		
Default	none	none	none	none	none	none		

Card 5	1	2	3	4	5	6	7	8
Variable	V1	V2	V3	D1	D2	D3	BETA	
Type	F	F	F	F	F	F	F	
Default	none	none	none	none	none	none	none	

VARIABLE	DESCRIPTION
MID	Material identification. A unique number must be specified.
RO	Mass density.
E	Young’s modulus, E.
PR	Poisson’s ratio, ν.
M	m, exponent in Barlat’s yield criterion.
R_{00}	R_{00}, Lankford parameter in 0 degree direction.
R_{45}	R_{45}, Lankford parameter in 45 degree direction.
R_{90}	R_{90}, Lankford parameter in 90 degree direction.
CB	The uppercase B defined in the Yoshida’s equations.
Y	Hardening parameter as defined in the Yoshida’s equations.
SC	The lowercase c defined in the Yoshida’s equations.

VARIABLE	DESCRIPTION
K	Hardening parameter as defined in the Yoshida's equations.
RSAT	Hardening parameter as defined in the Yoshida's equations.
SB	The lowercase b as defined in the Yoshida's equations.
H	Anisotropic parameter associated with work-hardening stagnation, defined in the Yoshida's equations.
HLCID	Load curve ID in keyword *DEFINE_CURVE, where true strain and true stress relationship is characterized. The load curve is optional, and is used for error calculation only.
IOPT	Kinematic hardening rule flag: EQ.0: Original Yoshida formulation, EQ.1: Modified formulation. Define C1, C2 as below.
C1, C2	Constants used to modify R: $R = RSAT\left[(C_1 + \bar{\varepsilon}^p)^{c_2} - C_1^{c_2}\right]$
AOPT	Material axes option (see MAT_*OPTION* TROPIC_ELASTIC for a more complete description): EQ.0.0: locally orthotropic with material axes determined by element nodes 1, 2, and 4, as with *DEFINE_COORDINATE_NODES, and then rotated about the shell element normal by the angle BETA.. EQ.2.0: globally orthotropic with material axes determined by vectors defined below, as with *DEFINE_COORDINATE_VECTOR. EQ.3.0: locally orthotropic material axes determined by rotating the material axes about the element normal by an angle, BETA, from a line in the plane of the element defined by the cross product of the vector v with the element normal. LT.0.0: the absolute value of AOPT is a coordinate system ID number (CID on *DEFINE_COORDINATE_NODES, *DEFINE_COORDINATE_SYSTEM or *DEFINE_COORDINATE_VECTOR). Available with the R3 release of Version 971 and later.
XP, YP, ZP	Coordinates of point **p** for AOPT = 1.
A1, A2, A3	Components of vector **a** for AOPT = 2.
V1, V2, V3	Components of vector **v** for AOPT = 3.
D1, D2, D3	Components of vector **d** for AOPT = 2.

VARIABLE	DESCRIPTION
BETA	Material angle in degrees for AOPT=0 and 3, may be overridden on the element card, see *ELEMENT_SHELL_BETA.

Remarks:

1. The R-values are defined as the ratio of instantaneous width change to instantaneous thickness change. That is, assume that the width W and thickness T are measured as function of strain. Then the corresponding R-value is given by:

$$R = \frac{\frac{dW}{d\varepsilon}/W}{\frac{dT}{d\varepsilon}/T}$$

Input R00, R45 and R90 to define sheet anisotropy in the rolling, 45 degree and 90 degree direction.

2. Barlat and Lian’s [1989] anisotropic yield criterion Φ for plane stress is defined as:

$$\Phi = a\left|K_1 + K_2\right|^m + a\left|K_1 - K_2\right|^m + c\left|2K_2\right|^m = 2\sigma_Y^m$$

For face centered cubic (FCC) materials exponent m=8 is recommended and for body centered cubic (BCC) materials m=6 may be used. Detailed description on the criterion can be found in *MAT_036 manual pages.

3. The Yoshida’s model accounts for cyclic plasticity including Bauschinger effect and cyclic hardening behavior. For detailed Yoshida’s theory of nonlinear kinematic hardening rule and definitions of material constants CB, Y, SC, K, RSAT, SB, and H, refer to **Remarks** in *MAT_125 manual pages and in the original paper, “*A model of large-strain cyclic plasticity describing the Baushinger effect and workhardening stagnation”*, by Yoshida, F. and Uemori, T., *Int. J. Plasticity*, vol. 18, 661-689, 2002.

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 Shi, M.F., Zhu, X.H., Xia, C., and Stoughton, T., in *NUMISHEET 2008 proceedings*, 137-142, 2008, included modifications to allow work 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,

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

is modified as,

$$R = RSAT\left[(C_1 + \bar{\varepsilon}^p)^{c_2} - C_1^{c_2}\right]$$

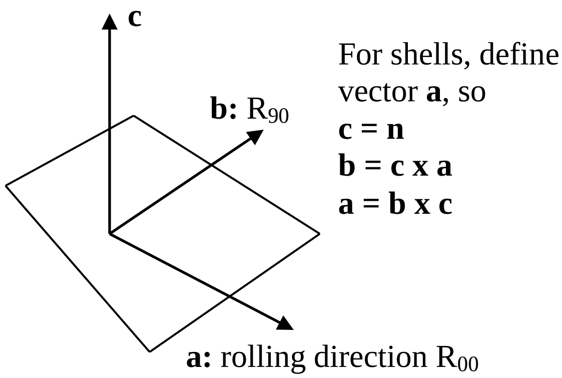
For saturation type of isotropic hardening rule, set IOPT=0, applicable to most of Aluminum sheet materials. In addition, the paper provides detailed variables used for this material model for DDQ, HSLA, DP600, DP780 and DP980 materials. Since the symbols used in the paper are different from what are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

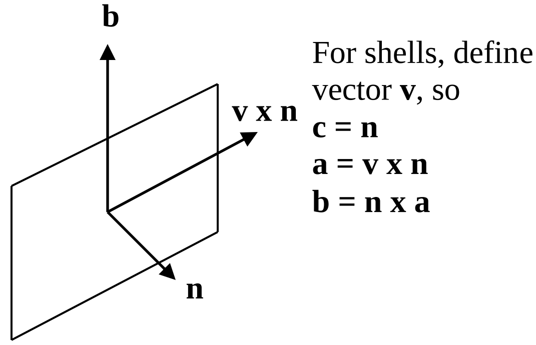
Using the modified formulation and the material properties provided by the paper, the predicted and tested results compare very well both in a full cycle tension and compression test and in a pre-strained tension and compression test, according to the paper. A set of experiments are required to fit (optimize) the Yoshida material constants, and these experiments include a uniaxial tension test (used for HLCID), a full cycle tension and compression test and a multiple cycle tension and compression test.

Application of the modified Yoshida's hardening rule in the metal forming industry has shown significant improvement in springback prediction accuracy, which is a pre-requisite for a successful stamping tool compensation, especially for AHSS type of sheet materials.

4. The variable AOPT is used to define the rolling direction of the sheet metals. For shells, AOPT of 2 or 3 are relevant. When AOPT=2, define vector components of **a** in the direction of the rolling (R_{00}); when AOPT=3, define vector components of **v** perpendicular to the rolling direction, as shown in the following Figure.



AOPT=2

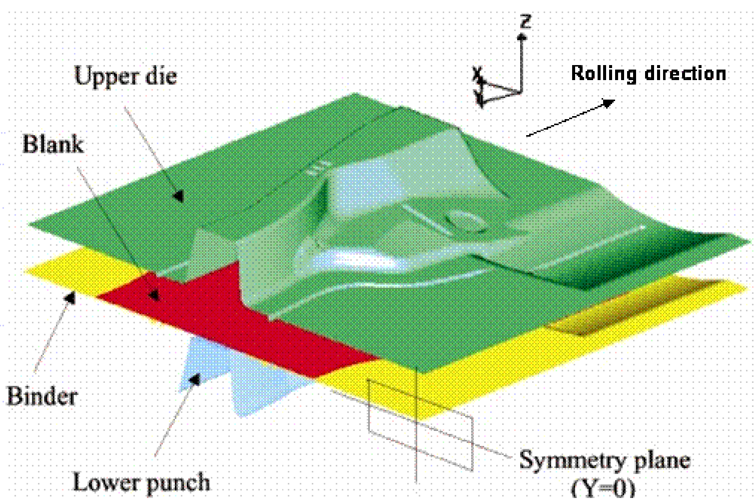


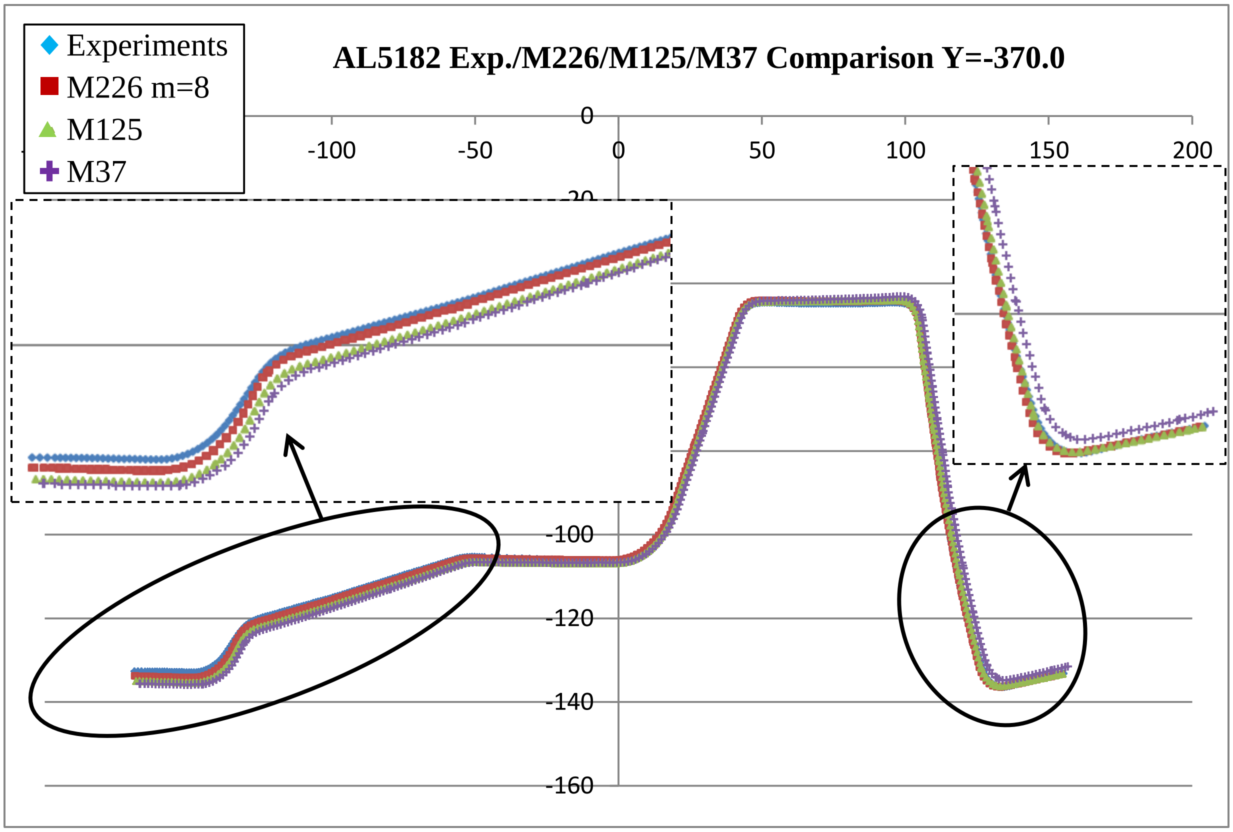
AOPT=3

5. To improve convergence, it is recommended that *CONTROL_IMPLICIT_FORMING type ‘1’ be used when conducting springback simulation.

6. In an example below, springback simulation results on the section Y=-370 mm from the NUMISHEET 2005 cross member using *MAT_226 show better springback correlation with measurements than *MAT_125 and *MAT_37.

7. This material model is available in LS-DYNA R5 Revision 57717 or later releases.





Springback prediction with *MAT_226 (Material properties courtesy of Ford Motor Company)