

*MAT_3-PARAMETER_BARLAT_{OPTION}

This is Material Type 36. This model was developed by Barlat and Lian [1989] for modeling sheets with anisotropic materials under plane stress conditions. This material allows the use of the Lankford parameters for the definition of the anisotropy. This particular development is due to Barlat and Lian [1989]. A version of this material model which has a flow limit diagram failure option is *MAT_FLD_3-PARAMETER_BARLAT.

Available options include:

<BLANK>

NLP

The option **NLP** allows for prediction of sheet metal failure using the Formability Index (F.I.), which accounts for the non-linear strain path effect (see **Remarks** below). The variable NLP in card #3 needs to be defined when using the option.

Card 1 1 2 3 4 5 6 7 8

| | | | | | | | | |
|----------|-----|----|---|----|----|----|----|------|
| Variable | MID | RO | E | PR | HR | P1 | P2 | ITER |
| Type | A8 | F | F | F | F | F | F | F |

Card 2 1 2 3 4 5 6 7 8

| | | | | | | | | |
|----------|---|----------|----------|----------|------|----|-----|----|
| Variable | M | R00 / AB | R45 / CB | R90 / HB | LCID | E0 | SPI | P3 |
| Type | F | F | F | F | I | F | F | F |

Define the following card if and only if M<0

Card opt. 1 2 3 4 5 6 7 8

| | | | | | | | | |
|----------|------|------|------|------|------|------|------|------|
| Variable | CRC1 | CRA1 | CRC2 | CRA2 | CRC3 | CRA3 | CRC4 | CRA4 |
| Type | F | F | F | F | F | F | F | F |

Card 3 1 2 3 4 5 6 7 8

| | | | | | | | | |
|----------|------|---|---|-------|--|----|---------|-----|
| Variable | AOPT | C | P | VLCID | | PB | NLP/HTA | HTB |
| Type | F | F | F | I | | F | I/F | F |

Card 4 1 2 3 4 5 6 7 8

| | | | | | | | | |
|----------|--|--|--|----|----|----|-----|-----|
| Variable | | | | A1 | A2 | A3 | HTC | HTD |
| Type | | | | F | F | F | F | F |

Card 5 1 2 3 4 5 6 7 8

| | | | | | | | | |
|----------|----|----|----|----|----|----|------|--------|
| Variable | V1 | V2 | V3 | D1 | D2 | D3 | BETA | HTFLAG |
| Type | F | F | F | F | F | F | F | F |

| <u>VARIABLE</u> | <u>DESCRIPTION</u> |
|-----------------|--|
| MID | Material identification. A unique number or label not exceeding 8 characters must be specified. |
| RO | Mass density. |
| E | Young's modulus, E GT.0.0: Constant value, LT.0.0: Load curve ID = (-E) which defines Young's Modulus as a function of plastic strain. See Remark 1. |
| PR | Poisson's ratio, ν |

| VARIABLE | DESCRIPTION |
|----------|--|
| HR | <p>Hardening rule:</p> <p>EQ.1.0: linear (default),</p> <p>EQ.2.0: exponential (Swift)</p> <p>EQ.3.0: load curve or table with strain rate effects</p> <p>EQ.4.0: exponential (Voce)</p> <p>EQ.5.0: exponential (Gosh)</p> <p>EQ.6.0: exponential (Hockett-Sherby)</p> <p>EQ.7.0: load curves in three directions</p> <p>EQ.8.0: table with temperature dependence</p> <p>EQ.9.0: 3d table with temperature and strain rate dependence</p> |
| P1 | <p>Material parameter:</p> <p>HR.EQ.1.0: Tangent modulus,</p> <p>HR.EQ.2.0: k, strength coefficient for Swift exponential hardening</p> <p>HR.EQ.4.0: a, coefficient for Voce exponential hardening</p> <p>HR.EQ.5.0: k, strength coefficient for Gosh exponential hardening</p> <p>HR.EQ.6.0: a, coefficient for Hockett-Sherby exponential hardening</p> <p>HR.EQ.7.0: load curve ID for hardening in 45 degree direction. See Remark 2.</p> |
| P2 | <p>Material parameter:</p> <p>HR.EQ.1.0: Yield stress</p> <p>HR.EQ.2.0: n, exponent for Swift exponential hardening</p> <p>HR.EQ.4.0: c, coefficient for Voce exponential hardening</p> <p>HR.EQ.5.0: n, exponent for Gosh exponential hardening</p> <p>HR.EQ.6.0: c, coefficient for Hockett-Sherby exponential hardening</p> <p>HR.EQ.7.0: load curve ID for hardening in 90 degree direction. See Remark 2.</p> |
| ITER | <p>Iteration flag for speed:</p> <p>ITER.EQ.0.0: fully iterative</p> <p>ITER.EQ.1.0: fixed at three iterations</p> <p>Generally, ITER=0 is recommended. However, ITER=1 is somewhat faster and may give acceptable results in most problems.</p> |
| M | <p>m, exponent in Barlat's yield surface, absolute value is used if negative.</p> |
| CRCN | <p>Chaboche-Roussiler hardening parameter, see remarks.</p> |
| CRCA | <p>Chaboche-Roussiler hardening parameter, see remarks.</p> |
| R00 | <p>R₀₀, Lankford parameter in 0 degree direction</p> <p>GT.0.0: Constant value,</p> <p>LT.0.0: Load curve or Table ID = (-R₀₀) which defines R value as a function of plastic strain (Curve) or as a function of temperature and plastic strain (Table). See Remark 3.</p> |

| VARIABLE | DESCRIPTION |
|----------|---|
| R45 | R ₄₅ , Lankford parameter in 45 degree direction GT.0.0: Constant value, LT.0.0: Load curve or Table ID = (-R45) which defines R value as a function of plastic strain (Curve) or as a function of temperature and plastic strain (Table). See Remarks 2 and 3. |
| R90 | R ₉₀ , Lankford parameter in 90 degree direction GT.0.0: Constant value, LT.0.0: Load curve or Table ID = (-R90) which defines R value as a function of plastic strain (Curve) or as a function of temperature and plastic strain (Table). See Remarks 2 and 3. |
| AB | a, Barlat89 parameter, which is read instead of R00 if PB>0. |
| CB | c, Barlat89 parameter, which is read instead of R45 if PB>0. |
| HB | h, Barlat89 parameter, which is read instead of R90 if PB>0. |
| LCID | Load curve/table ID for hardening in the 0 degree direction. See Remark 1. |
| E0 | Material parameter HR.EQ.2.0: ϵ_0 for determining initial yield stress for Swift exponential hardening. (Default=0.0) HR.EQ.4.0: b, coefficient for Voce exponential hardening HR.EQ.5.0: ϵ_0 for determining initial yield stress for Gosh exponential hardening. (Default=0.0) HR.EQ.6.0: b, coefficient for Hockett-Sherby exponential hardening |
| SPI | <i>spi</i> , if ϵ_0 is zero above and HR.EQ.2.0. (Default=0.0) EQ.0.0: $\epsilon_0 = (E/k) ** [1/(n - 1)]$ LE.0.02: $\epsilon_0 = spi$ GT.0.02: $\epsilon_0 = (spi/k) ** [1/n]$ If HR.EQ.5.0 the strain at plastic yield is determined by an iterative procedure based on the same principles as for HR.EQ.2.0. |
| P3 | Material parameter: HR.EQ.5.0: p, parameter for Gosh exponential hardening HR.EQ.6.0: n, exponent for Hockett-Sherby exponential hardening |

| VARIABLE | DESCRIPTION |
|----------|--|
| 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 an 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 \mathbf{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. |
| C | C in Cowper-Symonds strain rate model |
| P | p in Cowper-Symonds strain rate model, p=0.0 for no strain rate effects |
| VLCID | Volume correction curve ID defining the relative volume change (change in volume relative to the initial volume) as a function of the effective plastic strain. This is only used when nonzero. See Remark 1. |
| PB | Barlat89 parameter, p. If PB>0, parameters AB, CB, and HB are read instead of R00, R45, and R90. See Remark 4. |
| NLP | Load curve ID of the Forming Limit Diagram (FLD) under linear strain paths (see Remarks below). Define when option _NLP is used. |
| HTA | Load curve/Table ID for postforming parameter A in heat treatment |
| HTB | Load curve/Table ID for postforming parameter B in heat treatment |
| XP YP ZP | Coordinates of point \mathbf{p} for AOPT = 1. |
| A1 A2 A3 | Components of vector \mathbf{a} for AOPT = 2. |
| HTC | Load curve/Table ID for postforming parameter C in heat treatment |
| HTD | Load curve/Table ID for postforming parameter D in heat treatment |
| V1 V2 V3 | Components of vector \mathbf{v} for AOPT = 3. |
| D1 D2 D3 | Components of vector \mathbf{d} for AOPT = 2. |

| <u>VARIABLE</u> | <u>DESCRIPTION</u> |
|-----------------|--|
| BETA | Material angle in degrees for AOPT=0 and 3, may be overridden on the element card, see *ELEMENT_SHELL_BETA. |
| HTFLAG | Heat treatment flag (see remarks): HTFLAG.EQ.0: Preforming stage HTFLAG.EQ.1: Heat treatment stage HTFLAG.EQ.2: Postforming stage |

Remarks:

1. The effective plastic strain used in this model is defined to be plastic work equivalent. A consequence of this is that for parameters defined as functions of effective plastic strain, the rolling (00) direction should be used as reference direction. For instance, the hardening curve for HR=3 is the stress as function of strain for uniaxial tension in the rolling direction, VLCID curve should give the relative volume change as function of strain for uniaxial tension in the rolling direction and load curve given by -E should give the Young's modulus as function of strain for uniaxial tension in the rolling direction. Optionally the curve can be substituted for a table defining hardening as function of plastic strain rate (HR=3) or temperature (HR=8).
2. Exceptions from the rule above are curves defined as functions of plastic strain in the 45 and 90 directions, i.e., P1 and P2 for HR=7 and negative R45 or R90. The hardening curves are here defined as measured stress as function of measured plastic strain for uniaxial tension in the direction of interest, i.e., as determined from experimental testing using a standard procedure. Moreover, the curves defining the R values are as function of the measured plastic strain for uniaxial tension in the direction of interest. These curves are transformed internally to be used with the effective stress and strain properties in the actual model. The effective plastic strain does not coincide with the plastic strain components in other directions than the rolling direction and may be somewhat confusing to the user. Therefore the von Mises work equivalent plastic strain is output as history variable #2 if HR=7 or if any of the R-values is defined as function of the plastic strain.
3. The R-values in curves 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:

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

4. The anisotropic yield criterion Φ for plane stress is defined as:

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

where σ_Y is the yield stress and $K_{i=1,2}$ are given by:

$$K_1 = \frac{\sigma_x + h\sigma_y}{2}$$

$$K_2 = \sqrt{\left(\frac{\sigma_x - h\sigma_y}{2}\right)^2 + p^2\tau_{xy}^2}$$

If PB=0, the anisotropic material constants a, c, h, and p are obtained through R₀₀, R₄₅, and R₉₀:

$$a = 2 - 2\sqrt{\frac{R_{00}}{1+R_{00}} \frac{R_{90}}{1+R_{90}}} \quad c = 2 - a$$

$$h = \sqrt{\frac{R_{00}}{1+R_{00}} \frac{1+R_{90}}{R_{90}}}$$

The anisotropy parameter p is calculated implicitly. According to Barlat and Lian the R value, width to thickness strain ratio, for any angle ϕ can be calculated from:

$$R_\phi = \frac{2m\sigma_Y^m}{\left(\frac{\partial\Phi}{\partial\sigma_x} + \frac{\partial\Phi}{\partial\sigma_y}\right)\sigma_\phi} - 1$$

where σ_ϕ is the uniaxial tension in the ϕ direction. This expression can be used to iteratively calculate the value of p. Let $\phi=45$ and define a function g as

$$g(p) = \frac{2m\sigma_Y^m}{\left(\frac{\partial\Phi}{\partial\sigma_x} + \frac{\partial\Phi}{\partial\sigma_y}\right)\sigma_\phi} - 1 - R_{45}$$

An iterative search is used to find the value of p.

If PB>0, material parameters a (AB), c (CB), h (HB), and p (PB) are used directly.

For face centered cubic (FCC) materials m=8 is recommended and for body centered cubic (BCC) materials m=6 may be used. The yield strength of the material can be expressed in terms of k and n:

$$\sigma_y = k\varepsilon^n = k(\varepsilon_{yp} + \bar{\varepsilon}^p)^n$$

where ε_{yp} is the elastic strain to yield and $\bar{\varepsilon}^p$ is the effective plastic strain (logarithmic). If SIGY is set to zero, the strain to yield is found by solving for the intersection of the linearly elastic loading equation with the strain hardening equation:

$$\sigma = E\varepsilon$$

$$\sigma = k\varepsilon^n$$

which gives the elastic strain at yield as:

$$\epsilon_{yp} = \left(\frac{E}{k}\right)^{\left[\frac{1}{n-1}\right]}$$

If SIGY yield is nonzero and greater than 0.02 then:

$$\epsilon_{yp} = \left(\frac{\sigma_y}{k}\right)^{\left[\frac{1}{n}\right]}$$

The other available hardening models include the Voce equation given by

$$\sigma_Y(\epsilon_p) = a - be^{-c\epsilon_p},$$

the Gosh equation given by

$$\sigma_Y(\epsilon_p) = k(\epsilon_0 + \epsilon_p)^n - p,$$

and finally the Hocket-Sherby equation given by

$$\sigma_Y(\epsilon_p) = a - be^{-c\epsilon_p^n}.$$

For the Gosh hardening law, the interpretation of the variable SPI is the same, i.e., if set to zero the strain at yield is determined implicitly from the intersection of the strain hardening equation with the linear elastic equation.

To include strain rate effects in the model we multiply the yield stress by a factor depending on the effective plastic strain rate. We use the Cowper-Symonds' model, hence the yield stress can be written

$$\sigma_Y(\epsilon_p, \dot{\epsilon}_p) = \sigma_Y^S(\epsilon_p) \left\{ 1 + \left(\frac{\dot{\epsilon}_p}{C}\right)^{1/p} \right\}$$

where σ_Y^S denotes the static yield stress, C and p are material parameters, $\dot{\epsilon}_p$ is the effective plastic strain rate.

- 5. A kinematic hardening model is implemented following the works of Chaboche and Roussilier. A back stress α is introduced such that the effective stress is computed as

$$\sigma_{\text{eff}} = \sigma_{\text{eff}}(\sigma_{11} - 2\alpha_{11} - \alpha_{22}, \sigma_{22} - 2\alpha_{22} - \alpha_{11}, \sigma_{12} - \alpha_{12})$$

The back stress is the sum of up to four terms according to

$$\alpha_{ij} = \sum_{k=1}^4 \alpha_{ij}^k$$

and the evolution of each back stress component is as follows

$$\delta\alpha_{ij}^k = C_k \left(a_k \frac{S_{ij}}{\sigma_{\text{eff}}} - \alpha_{ij}^k \right) \delta\epsilon_p$$

where C_k and a_k are material parameters, s_{ij} is the deviatoric stress tensor, σ_{eff} is the effective stress and ϵ_p is the effective plastic strain.

- 6. When the option `_NLP` is used, a necking failure criterion is activated to account for the non-linear strain path effect in sheet metal forming. Based on the traditional Forming Limit Diagram (FLD) for the linear strain path, the Formability Index (F.I.) is calculated for every element in the model throughout the simulation duration and the entire history is stored in history variable #9 in D3PLOT files, accessible from *Post/History* menu in LS-PrePost v3.1. The time history of the index can be plotted for each element under the menu. It is therefore necessary to set NEIPS to 10, in the second field of card 1 in keyword `*DATABASE_EXTENT_BINARY`, to output the history variable to the D3PLOT files. The index can also be plotted as a color contour map on the formed sheet blank, accessible from *Post/FriComp/Misc* menu. The index has a value ranging from 0.0 to 1.2, with the onset of necking failure at 1.0. The F.I. is calculated based on critical effect strain method, as illustrated in the Figure in **Remarks** in *MAT_037. The theoretical background can be found in two papers also referenced in **Remarks** section in *MAT_037.

D3PLOT files can be used to plot the history variable #9 (the F.I.) in color contour. The value in the “Max” pull-down menu in *Post/FriComp* needs to be set to “Min”, meaning that the necking failure occurs only when all integration points through the thickness have reached the critical value of 1.0. It is suggested to set the variable ‘MAXINT’ in `*DATABASE_EXTENT_BINARY` to the same value as the variable ‘NIP’ in `*SECTION_SHELL`. In addition, the value in the “Avg” pull-down menu in *Post/FriRang* needs to be set to “None”. The strain path history (major vs. minor strain) of each element can be plotted with radial dial button *Strain Path* in *Post/FLD*.

An example of a partial input for the material is provided below, where the FLD for the linear strain path is defined by the variable NLP with load curve ID 211, where abscissa values represent minor strains and ordinate values represent major strains.

```

*MAT_3-PARAMETER_BARLAT_NLP
$-----1-----2-----3-----4-----5-----6-----7-----8
$      MID      RO      E      PR      HR      P1      P2      ITER
$      1 2.890E-09 6.900E04 0.330 3.000
$      M      R00      R45      R90      LCID      E0      SPI      P3
$      8.000      0.800      0.600      0.550      99
$      AOPT      C      P      VLCID      NLP
$      2.000      211
$      A1      A2      A3
$      0.000      1.000      0.000
$      V1      V2      V3      D1      D2      D3      BETA

$-----1-----2-----3-----4-----5-----6-----7-----8
$ Hardening Curve
*DEFINE_CURVE
  99
      0.000      130.000
      0.002      134.400
      0.006      143.000
      0.010      151.300
      0.014      159.300
...
      0.900      365.000
      1.000      365.000

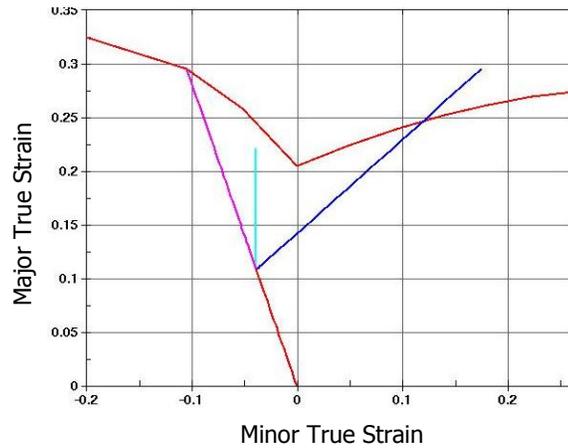
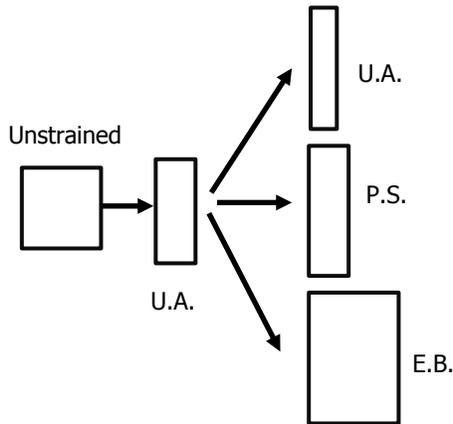
```

```

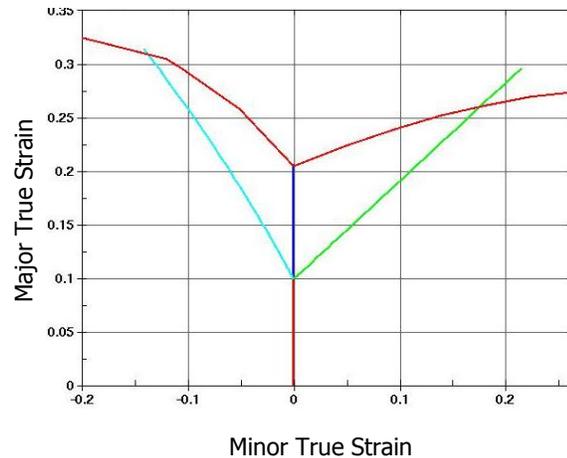
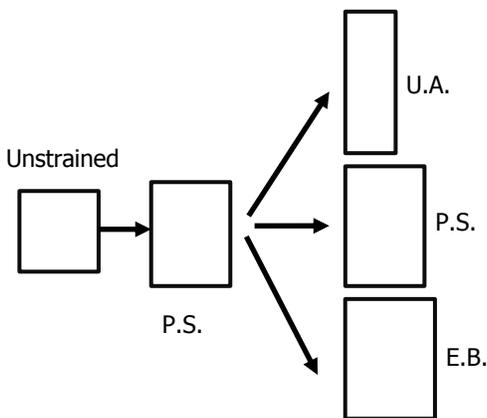
$ FLD Definition
*DEFINE_CURVE
211
      -0.2          0.325
    -0.1054        0.2955
    -0.0513        0.2585
     0.0000        0.2054
     0.0488        0.2240
     0.0953        0.2396
     0.1398        0.2523
     0.1823        0.2622
...

```

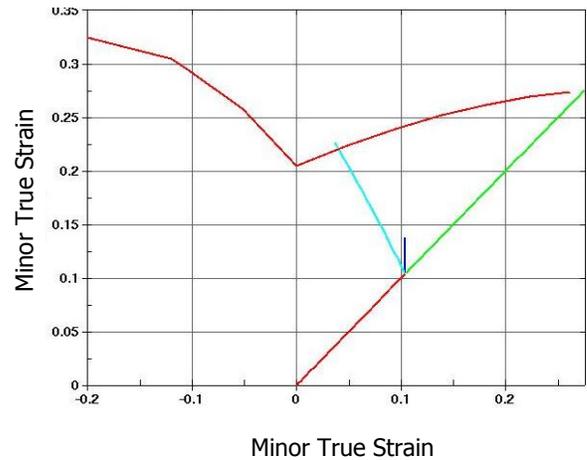
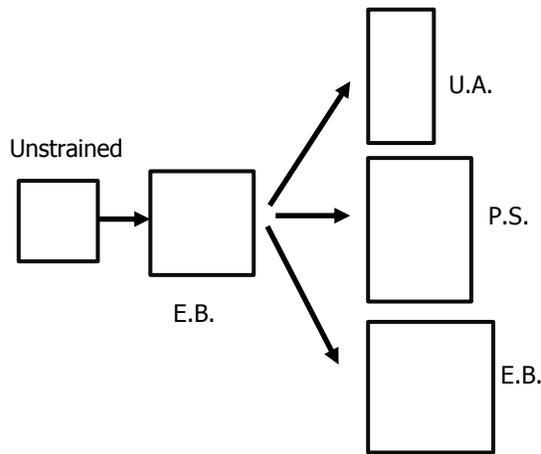
The following FLD prediction of non-linear strain paths on a single element was done using this new option, for an Aluminum alloy with $r_{00}=0.8$, $r_{45}=0.6$, $r_{90}=0.55$, and yield at 130.0 MPa. In each case, the element is further strained in three different paths (uniaxial - U.A., plane strain - P.S., and equi-biaxial - E.B.) separately, following a pre-straining in uniaxial, plane strain and equi-biaxial strain state, respectively. The forming limits are determined at the end of the further straining for each path, when the F.I. has reached the value of 1.0.



Nonlinear FLD prediction with pre-straining in uniaxial strain state



Nonlinear FLD prediction with pre-straining in plane strain state



Nonlinear FLD prediction with pre-straining in equi-biaxial mode

Typically, to assess sheet formability, F.I. contour of the entire part should be plotted. Based on the contour plot, non-linear strain path and the F.I. time history of a few elements in the area of concern can be plotted for further study. These plots are similar to those shown in manual pages of *MAT_037.

It is noted that the option `_NLP` is implemented for Explicit Dynamic analysis and is available pending a release soon.

7. Heat treatment for increasing the formability of prestrained aluminum sheets can be simulated through the use of HTFLAG, where the intention is to run a forming simulation in steps involving preforming, springback, heat treatment and postforming. In each step the history is transferred to the next via the use of `dynain` (see `*INTERFACE_SPRINGBACK`). The first two steps are performed with `HTFLAG=0` according to standard procedures, resulting in a plastic strain field ϵ_p^0 corresponding to the prestrain. The heat treatment step is performed using `HTFLAG=1` in a coupled thermomechanical simulation, where the blank is heated. The coupling between thermal and mechanical is only that the maximum temperature T^0 is stored as a history variable in the material model, this corresponding to the heat treatment temperature. Here it is important to export all history variables to the `dynein` file for the postforming step. In the final postforming step, `HTFLAG=2`, the yield stress is then augmented by the Hockett-Sherby like term

$$\Delta\sigma = b - (b - a)\exp\left(-c[\epsilon_p - \epsilon_p^0]^d\right)$$

where a , b , c and d are given as tables as functions of the heat treatment temperature T^0 and prestrain ϵ_p^0 . That is, in the table definitions each load curve corresponds to a given prestrain and the load curve value is with respect to the heat treatment temperature,

$$a = a(T^0, \epsilon_p^0) \quad b = b(T^0, \epsilon_p^0) \quad c = c(T^0, \epsilon_p^0) \quad d = d(T^0, \epsilon_p^0)$$

The effect of heat treatment is that the material strength decreases but hardening increases, thus typically

$$a \leq 0 \quad b \geq a \quad c > 0 \quad d > 0$$

