	to coefficients C7 to C12 in the implicit creep equation (rational polynomial). Then add the primary creep data, release all coefficients, and solve.
Generalized Time Hardening	Generalized time hardening has 6 coefficients. Set C6 to zero if you have temperature independent data. When initializing coefficients set C5σ close to 1 to avoid floating-point overflows.

5.4. Chaboche Material Curve Fitting

Chaboche material curve fitting determines your material constants by relating your experimental data to the Chaboche nonlinear kinematic hardening model.

Curve fitting is performed either interactively or via batch commands. You can fit uniaxial plastic strain vs. stress data, along with discrete temperature dependencies for multiple data sets.

The following topics concerning Chaboche material curve fitting are available:

5.4.1. Understanding the Chaboche Material Curve-Fitting Process

Chaboche material curve fitting determines your material constants by relating your experimental data to the Chaboche nonlinear kinematic hardening model. Isotropic hardening can also be modeled by including a supported isotropic hardening model with the kinematic hardening model in the curve-fitting process.

Following is the general process for using curve fitting to determine the coefficients for the Chaboche material model:

Step	Detailed Information Found Here	Comments
1	Step 1. Prepare Experimental Data (p. 185)	The experimental data must be a plain text file with headers to describe the data types and attributes. The test data must be delimited by a space or a comma.
2	Step 2. Input the Experimental Data (p. 186)	The experimental data can be read into the program by browsing to the file location in the GUI or by specifying the location on the command line.
3	Step 3. Select a Material Model Option (p. 186)	The material options for the applicable curve-fitting regimen are defined (**TBFT**). This step includes selecting the kinematic hardening model.
4	Step 4. Initialize the Coefficients (p. 187)	Chaboche curve fitting is a nonlinear regression; the initial values of the coefficients to be determined is important for a successful solution.

Step	Detailed Information Found Here	Comments
5	Step 5. Specify Control Parameters and Solve (p. 190)	Specify the error norm to be used, the solution control parameters, and perform the nonlinear regression.
6	Step 6. Plot the Experimental Data and Analyze (p. 191)	Review and verify the results by comparing them with the experimental data and the regression errors. If any factor is unacceptable, repeat steps 3 through 5 to obtain a new curve-fitting solution.
7	Step 7. Write Data to the TB Command (p. 191)	Write the curve-fitting results in the **TB** command format to the database.

5.4.2. Step 1. Prepare Experimental Data

Curve fitting requires experimental test data. To use curve fitting with plasticity, the only experimental data supported is uniaxial test data. Uniaxial test data has two columns, plastic strain and true stress. Experimental data for plasticity is path dependent.

Your uniaxial test data must be a plain text file with headers to define the test data. The data file should be in table format, delimited by spaces or commas. Headers can be used to describe the data types that characterize the test data columns or additional attributes of the data.

For Chaboche curve fitting with multiple temperatures, you can evaluate coefficients at each discrete temperature point and write it as a temperature-dependent Chaboche data table. A separate data file is necessary for each discrete temperature.

Issue this command at the top of the experimental data file to specify the temperature for the experiment:

```
/temp,TempValue
```

where *TempValue* is your specified temperature.

Following is a typical data input file:

```
/temp,100 ! define temperature attribute
4.57E-06 2.43E+02
4.89E-04 2.67E+02
1.01E-03 2.83E+02
1.55E-03 2.94E+02
2.11E-03 3.02E+02
2.68E-03 3.09E+02
3.26E-03 3.14E+02
3.84E-03 3.18E+02
4.42E-03 3.22E+02
4.42E-03 7.78E+01
4.41E-03 -1.65E+02
3.54E-03 -2.31E+02
2.51E-03 -2.66E+02
1.40E-03 -2.84E+02
2.49E-04 -2.95E+02
-9.11E-04 -3.03E+02
-2.08E-03 -3.10E+02
-3.24E-03 -3.17E+02
-4.41E-03 -3.24E+02
-4.41E-03 -7.95E+01
-4.40E-03 1.63E+02
-3.53E-03 2.30E+02
-2.50E-03 2.65E+02
-1.39E-03 2.83E+02
-2.44E-04 2.94E+02
9.16E-04 3.02E+02
2.08E-03 3.09E+02
```

```
3.25E-03 3.16E+02
4.41E-03 3.23E+02
4.41E-03 7.87E+01
4.41E-03 -1.64E+02
3.53E-03 -2.31E+02
2.51E-03 -2.66E+02
1.40E-03 -2.84E+02
2.48E-04 -2.95E+02
```

Uniaxial test data can include loading, unloading, and cyclic loading.

For plasticity, experimental data is path-dependent and the stress-strain behavior depends on the history of the loading and/or unloading.

5.4.3. Step 2. Input the Experimental Data

The experimental data must be read in from a plain text file (**TBFT**,EADD). Prepare this file as described in Step 1. Prepare Experimental Data.

Each file is viewed as a data set, and can be a complete set of experimental test data or a part of a series of files of experimental test data. You can include several data sets, such as tests performed at different stress levels and/or temperatures, when you perform creep curve fitting.

Input your experimental data using either the batch method or the GUI method.

5.4.3.1. Batch Method

Issue this command to identify and specify the location of a data file:

```
TBFT,EADD,ID,Option1,Option2,Option3,Option4
```

where:

ID = Index corresponding to the material number
Option1 = Experimental data type UNIA (uniaxial test data)
Option2 = Experimental data file name
Option3 = File name extension
Option4 = File directory

5.4.3.2. GUI Method

Click on **Add Data Set** and enter the experimental data file name in the field provided. You can also browse to a file in a specified location. Separate input is performed for each data type (*Option1* = SDEC or BDEC) /

5.4.4. Step 3. Select a Material Model Option

The **TBFT** command provides the curve-fitting tools for Chaboche material modeling.

To define the material model, you must specify a case name, the order of Chaboche kinematic model, and finally the isotropic hardening option if needed.

After you create a case, the number of Chaboche terms or the isotropic hardening options cannot be changed without deleting the case. Additional cases with different case names can be created to model Chaboche kinematic hardening with different orders.

5.4.4.1. Batch Method

Define a Chaboche material model by defining a case (**TBFT**,FCASE), then specifying the order of kinematic hardening model. The case is created only *after* the **TBFT**,FCASE,*ID*,FINISH command executes.

The following syntax example and argument descriptions illustrates a complete case definition:

```
TBFT,FCASE,ID,NEW,Option2,Option3   ! define case
```

where:

ID = Index corresponding to the material number
Option2 = CPLA
Option3 = Your specified case name

```
TBFT,FADD,ID,Category,Option2,Option3   ! specify kinematic hardening model
```

where:

ID = Index corresponding to the material number
Category = PLAS
Option2 = One of the following: CHABOCHE, BISO, MISO, VOCE, or POWER
Option3 = Dependent on *Option2*, as follows:

When *Option2* = CHABOCHE, *Option3* = 1 to N
When *Option2* = MISO, *Option3* = 1 to N_{iso}
When *Option2* = BISO, VOCE, or POWER, *Option3* is not used

```
TBFT,FCASE,ID,FINISH   ! create case
```

5.4.4.2. GUI Method

Interactively navigate the tree structure of the curve-fitting window. Select the order of the Chaboche model, select the isotropic hardening option if needed, then specify the appropriate case name in the text box field. As you select the options, the coefficient table is created automatically.

5.4.5. Step 4. Initialize the Coefficients

The initial values chosen for your coefficients (**TBFT**,SET) determines the success of the curve-fitting operation.

The number of parameter depends on the order of the Chaboche model. For a Chaboche model of order N, there are 2*N+1 coefficients. Coefficients 1 through 2*N are Chaboche parameters, and coefficient 2*N+1 is the yield stress. The odd coefficients in the Chaboche model refer to the slope of the curve and the even coefficients are decay function parameters. The number of terms depend on the complexity of the curve. Evenly distributed estimates of the slope over the range of the curve can be used as initial guesses for the curve-fitting process. Different terms can dominate at different parts of the curve. Initial guesses for the decay parameters can typically be chosen one or two orders less than odd coefficients (slope).

5.4.5.1. Including Isotropic Hardening Models with Chaboche Kinematic Hardening

When isotropic hardening models are included with Chaboche kinematic hardening, the number of coefficients is 2*N+N_{iso}, where N_{iso} is:

- 2 for the BKIN option
- 2*N_i for the MISO option (where N_i is the number of MISO terms)
- 3 for the NLISO POWER option
- 4 for the NLISO VOCE option

The third coefficient for the power law is shear modulus, which must be set to the correct value and fixed before solving.

The index of the isotropic hardening coefficients start from 2*N+1. Initial yield stress is generally estimated from separate experiments outside of curve fitting and is generally fixed in the curve-fitting process.

For the BKIN, VOCE, and POWER options, the first isotropic hardening coefficient refers to yield stress.

5.4.5.2. General Process for Initializing MISO Option Coefficients

The MISO option used here is same as the **TB**,PLAS,,,MISO option. It has N_i coefficients, and the second isotropic hardening coefficient refers to the yield stress. Odd isotropic coefficients are plastic strain values and the even coefficients are stress values. The actual index of the coefficient is 2*N+N_{iso}, where N is the order of the Chaboche model.

If the experiment has a maximum accumulated plastic strain of $\varepsilon_{pl,max}$, set the odd coefficients to values equally distributed from 0 to $\varepsilon_{pl,max}$. These values are then fixed (**TBFT**,FIX) before solving (**TBFT**,SOLVE). If you require greater accuracy at certain strain ranges, you can distribute the strain values unevenly as you wish.

To fix (hold constant) your coefficients (**TBFT**,FIX), specify a value for a coefficient and keep it unchanged, while allowing the other coefficients to be operated on. You can then release the fixed coefficient later if desired. By default, all of the coefficients are free to vary.

Estimate coefficients for temperature-dependent data by setting the temperature-dependency flag and setting a reference temperature before solving for the coefficients. You can set the reference temperature only to values specified via the **`/temp,TempValue`** header line in the experimental data.

You can also specify **`tref = all`** and initiate multiple solves to evaluate coefficients at all available discrete temperature values. In this case, for data at three temperatures (t1, t2, and t3), a single **TBFT**,SOLVE command initiates three separate solve operations at those three discrete temperature values, and generates data at three corresponding discrete temperatures.

With temperature dependency specified and the reference temperature set to a specific value, a **TBFT**,SOLVE command solves for coefficients only at that discrete temperature. To solve for coefficients at other temperatures, set the reference temperature to each of the desired discrete temperature values and solve again.

You can initialize the coefficients before or after activating temperature dependency. If the coefficients initialize before setting temperature dependency, the specified coefficients become the initial coefficients for all future solves for that particular model. These coefficients are, however, overridden when temperature dependency is active and another set of values is specified at a discrete temperature value. The curve-fitting tool looks for the initial coefficients at a particular temperature. If no coefficients are specified at discrete temperature values, the initial coefficients set before temperature dependency was activated are used.

5.4.5.2.1. Batch Method

The following syntax example and argument descriptions illustrate coefficient initialization:

```
TBFT,SET,ID,CASE,Option2,Option3,Option4,Option5
```

where:

ID = Index corresponding to the material number
Option2 = Case name
Option3 = (Blank--not applicable)
Option4 = Index of coefficient
Option5 = Value of coefficient

Example 5.3: Initialize Coefficients

```
TBFT,SET,1,case1,,1,1.2 ! Initialize the first coefficient to 1.2
TBFT,SET,1,case1,,2,1.5 ! Initialize the second coefficient to 1.5
```

By default, coefficients are not fixed. To fix a coefficient to a value (p. 188) set via the **TBFT**,SET command, or to release a previously fixed coefficient, issue the **TBFT**,FIX command.

```
TBFT,FIX,ID,CASE,Option2,Option3,Option4,Option5
```

where:

ID = Index corresponding to the material number
Option2 = Case name
Option3 = (Blank--not applicable)
Option4 = Index of coefficient
Option5 = 1 to fix, 0 to vary (default)

Temperature dependency uses Option4 and references your specified data files with the appropriate "temp" header:

```
TBFT,SET,ID,CASE,Option2,Option3,Option4,Option5
```

where:

ID = Index corresponding to the material number
Option2 = Case name
Option3 = (Blank--not applicable)
Option4 = tdep or tref
Option5 = If *Option4* = tdep, then 1 activates temperature dependency 0 deactivates it. If *Option4* = tref, this value is either a specific temperature or all temperatures (ALL (p. 188)).

Example 5.4: Fixing Coefficient Values

```
TBFT,FIX,1, case1,,1,1 ! Fix the first coefficient to a value set via TBFT,SET
TBFT,FIX,1, case1,,2,1 ! Fix the second coefficient to a value set via TBFT,SET
```

5.4.5.2.2. GUI Method

The coefficients table is updated automatically in the Chaboche curve-fitting window when the order of kinematic hardening model is specified. Specify values for your coefficients in the coefficients table in the curve-fitting GUI window, and check the appropriate boxes to fix them or allow them to vary.

5.4.6. Step 5. Specify Control Parameters and Solve

Chaboche curve fitting is a nonlinear regression process. Only the non-normalized error norm is available for the regression.

The solution control parameters for nonlinear regression include number of iterations, residual tolerance, and coefficient change tolerance. The solution stops when both residual tolerance of the error norm and coefficient change tolerance is met, or if the number of iterations criteria is met. The coefficients are updated when the solution is completed.

5.4.6.1. Temperature-Dependent Solutions

Separate coefficients at each temperate must be calculated to account for temperature dependency. Perform the regression as follows:

1. Set the temperature-dependency flag (**TBFT**,SET,,,,,TDEP,1).
2. Solve for all (tref = ALL) coefficients.
   a. Set the reference temperature at which your partial solution should be performed (**TBFT**,SET,,,,,TREF,TX). Only data at temperature TX is used to estimate the combined plasticity coefficients.
   b. Initialize the coefficients.
   c. Solve (**TBFT**,SOLVE).

Repeat the regression process for all desired temperatures.

5.4.6.2. Batch Method

The following syntax examples and argument descriptions illustrate how to set control parameters and solve:

```
TBFT,SET,ID,CASE,Option2,Option3,Option4,Option5
```

where:

ID = Index corresponding to the material number
Option2 = Case name
Option3 = (Blank--not applicable)
Option4 = tdep
Option5 = 1 to activate temperature dependency, 0 to deactivate (default)

```
TBFT,SET,ID,CASE,Option2,Option3,Option4,Option5
```

where:

ID = Index corresponding to the material number
Option2 = Case name
Option3 = (Blank--not applicable)
Option4 = tref
Option5 = Valid temperature values found in the experimental data

The SOLVE option allows you to specify procedure types, tolerances, and the number of iterations:

```
TBFT,SOLVE,ID,CASE,Option2,Option3,Option4, ... , Option7
```

where:

ID = Index corresponding to the material number
Option2 = Case name
Option3 = (Blank--not applicable)
Option4 = Curve-fitting procedure: 0 = non-normalized least squares
Option5 = Maximum number of iterations
Option6 = Residual change tolerance
Option7 = Coefficient change tolerance

Other parameters for solving are available. See the **TBFT** command for more information.

5.4.6.3. GUI Method

The GUI allows you to choose your error norm, solution control parameters, and solver options. After you complete these specifications and solve, you can go back and modify your parameters as necessary to obtain a good curve fit.

5.4.7. Step 6. Plot the Experimental Data and Analyze

The best method for ensuring a good fit between your experimental data and the provided curves is to plot your curves and visually inspect them via the GUI. The **Graph** button provides a direct means for plotting the data.

5.4.7.1. Analyzing Your Curves for Proper Fit

All of your data is plotted as a function of column 1 (X axis). Column 2 (Y axis) and the corresponding fitted data are plotted as a function of column 1. Two or more fitted functions can be compared in the same plot.

Take advantage of the right-mouse-button (RMB) functions to zoom, fit, save your plot to a file, view or hide objects, toggle between log scale and regular scale, and so on. With the middle mouse button, you can eliminate specific curves from each window's display in order to view the remaining data more clearly.

After plotting the curve-fitting results, you can then review multiple plots and also verify the error norm/residual value displayed in the curve-fitting GUI window. This information helps you to determine the quality of a curve fit and decide whether or not to accept the results.

If the curve-fitting results are unsatisfactory, you may want to go back to Step 3. Select a Material Model Option and solve again by changing the order of the Chaboche model or other options, redefining certain initial values of the coefficients, and possibly redefining other control parameters. You can continue to use your original data, repeating step 3 through step 6 until you are satisfied with the solution.

5.4.8. Step 7. Write Data to the TB Command

After a successful curve fitting, the last step is to write the curve-fitting data as a Chaboche data table (**TB**,CHABOCHE) to the database. The program converts the coefficients to the appropriate form before writing to the database.