Example 4b: SiC/Ti-21S Composite with Residual Stresses

This is an example of a MAC/GMC 4.0 simulation for a metal matrix composite in which residual stresses due to fabrication have been included. The composite configuration is identical to that of Example 1d. The changes lie in the loading section of the input file, wherein, prior to application of the simulated mechanical loading, a simulated stress-free cool-down from 900 °C is performed. Thus, when the simulated mechanical loading is applied, the composite contains internal local stresses within each constituent resulting from property mismatch of the composite phases and the simulated cool-down. The stress-strain curve that results from the subsequent applied mechanical loading can then be shifted such that the origin corresponds to the onset of the mechanical loading. This then simulates an actual composite tensile test in which it is assumed that the zero global strain condition corresponds to the start of the mechanical test.

MAC/GMC Input File: **example_4b.mac**

```
MAC/GMC 4.0 Example 4b - SiC/Ti-21S composite w/ residual
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*RUC
  MOD=2 ARCHID=1 VF=0.25 F=1 M=2
*MECH
  LOP=1 REFTIME=57600.
#  LOP=2 REFTIME=57600.
  NPT=3 TI=0.,57600.,57800. MAG=0.,0.,0.02 MODE=2,1
*THERM
  NPT=3 TI=0.,57600.,57800 TEMP=900.,23.,23.
*SOLVER
  METHOD=1 NPT=3 TI=0.,57600.,57800 STP=40.,1.
*PRINT
  NPL=6
*XYPLOT
  FREQ=5
  MACRO=4
   NAME=example_4b_11  X=1   Y=7
   NAME=example_4b_22  X=2   Y=8
   NAME=example_4b_TH1 X=100 Y=1
   NAME=example_4b_TH2 X=100 Y=2
  MICRO=0
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (***CONSTITUENTS**) [KM_2]:
Number of materials: 2 (NMATS=2)

Materials:	SiC fiber	(MATID=E)
	Ti-21S	(MATID=A)
Constitutive models:	SiC fiber: linearly elastic	(CMOD=6)
	Ti-21S matrix: Isotropic GVIPS	(CMOD=4)

3) Analysis type (***RUC**) → Repeating Unit Cell Analysis [KM_3]:

Analysis model:	Doubly periodic GMC	(MOD=2)
RUC architecture:	square fiber, square pack	(ARCHID=1)
Fiber volume fraction:	0.25	(VF=0.25)
Material assignment:	SiC fiber	(F=1)
	Ti-21S matrix	(M=2)

4) Loading:

a) Mechanical (***MECH**) [KM_4]:

Loading option:	1 or 2	(LOP=1 or LOP=2)
Strain reference time:	57600. sec.	(REFTIME=57600.)
Number of points:	3	(NPT=3)
Time points:	0., 57600., 57800. sec.	(TI=0.,57600.,57800.)
Load magnitudes:	0., 0., 0.02	(MAG=0.,0.,0.02)
Loading mode:	stress control, strain control	(MODE=2,1)

The mechanical loading profile now contains three time-magnitude pairs. For the first segment of the mechanical loading, the magnitude is kept at zero, then, during the second segment, the mechanical loading progresses to a magnitude of 0.02. Since there are now three time-magnitude pairs, and thus two loading segments, two loading modes (one for each segment) must be specified. During the first segment, it is the stress that is held at zero, while during the second segment, it is the strain that is applied up to a level of 0.02.

The strain reference time (REFTIME) is the time taken to be the zero strain point for subsequent specified strains. Thus, the strain that results at time = 57600. sec. from the cool-down is taken as the reference strain. Then, the subsequent applied 0.02 strain is taken with respect to this reference strain such that a total increment in strain of 0.02 is applied. This mimics a tensile stress-strain test on a specimen containing an unknown residual strain. The unknown residual strain is the reference (thought to be zero at the beginning of the tensile test) and the amount of strain applied during the test is on top of this reference strain. If it is not specified, the strain reference time defaults to zero. For additional information on the strain reference time, see the MAC/GMC 4.0 Keywords Manual Section 4.

b) Thermal (***THERM**) [KM_4]:

Number of points:	3	(NPT=3)
Time points:	0., 57600., 57800. sec.	(TI=0.,57600.,57800.)
Temperature points:	900., 23., 23.	(TEMP=900.,23.,23.)

Three time-temperature pairs are used to specify the two thermal loading segments – a cool-down from 900 °C to 23 °C followed by a hold at 23 °C. The second segment corresponds to the application of the non-zero simulated mechanical loading.

c) Time integration (***SOLVER**) [KM_4]:

Time integration method:	Forward Euler	(METHOD=1)
Number of time points:	3	(NPT=3)
Time points:	0., 57600., 57800. sec.	(TI=0.,57600.,57800.)
Time step size:	40., 1. sec.	(STP=40.,1.)

5) Damage and Failure: None

6) Output:

a) Output file print level (***PRINT**) [KM_6]:

Print level:	6	(NPL=6)

b) x-y plots (***XYPLOT**) [KM_6]:

Frequency:	5	(FREQ=5)
Number of macro plots:	4	(MACRO=4)
Macro plot names:	example_4b_11	(NAME=example_4b_11)
	example_4b_22	(NAME=example_4b_22)
	example_4b_TH1	(NAME=example_4b_TH1)
	example_4b_TH2	(NAME=example_4b_TH2)
Macro plot x-y quantities:	ε_{11}, σ_{11}	(X=1 Y=7)
	ε_{22}, σ_{22}	(X=2 Y=8)
	Temperature, ε_{11}	(X=100 Y=1)
	Temperature, ε_{22}	(X=100 Y=2)
Number of micro plots:	0	(MICRO=0)

In this example, four macro (repeating unit cell level) plots are generated; two represent the mechanical response of the composite, two represent the thermal response of the composite

7) End of file keyword: (***END**)

Results

Figure 4.3 shows the strain that results from the simulated stress-free cool-down applied to the SiC/Ti-21S composite. It should be noted that, due to the fact the Ti-21S matrix undergoes inelastic deformation during the cool-down, the overall or global strain plotted in Figure 4.3 is not the global thermal strain. Rather, it is the sum of the global thermal strain and the global inelastic strain. Examining the output file for this example reveals the following global strain state at the conclusion of the simulated cool-down (but before application of the simulated mechanical loading):

```
 1440 TIME:   5.7600D+04      TEMP:  2.3000D+01      TSTEP:  4.0000D+01
-----------------------------------------------------------------------------------------------
         STRESS:  0.0000D+00   0.0000D+00   0.0000D+00   0.0000D+00   0.0000D+00   0.0000D+00
         STRAIN: -5.5186D-03  -8.7271D-03  -8.7271D-03   0.0000D+00   0.0000D+00   0.0000D+00
     IN. STRAIN:  7.1719D-04  -4.2385D-04  -4.2385D-04   0.0000D+00   0.0000D+00   0.0000D+00
     TH. STRAIN: -6.2358D-03  -8.3033D-03  -8.3033D-03   0.0000D+00   0.0000D+00   0.0000D+00
```

Clearly, there is an inelastic strain contribution to the total strain, in addition to the thermal strain. An interesting ramification of this observation is that, it would be erroneous to use Figure 4.3 to determine tangential coefficients of thermal expansion (CTEs) for the composite by taking slopes of the curves at different temperatures. This would give the slope of the total strain with respect to temperature, while the definition of tangent CTE is the slope of thermal strain with respect to temperature. Taking the slope of an experimental composite thermal expansion curve as a tangential CTE is similarly erroneous if the composite has undergone any inelastic deformation during the test, consequently micromechanics is needed to extract the true composite CTE.

Figure 4.4 shows that the effect of residual stresses on the SiC/Ti-21S composite (at 23 °C) is greater in the longitudinal direction compared to the transverse direction. The composite yields sooner longitudinally for the case that includes residual stresses. In the transverse direction, the simulation with residual stresses exhibits yielding slightly sooner, but the differences in the predicted stress-strain curves is minor. Clearly, the presence of the continuous fibers causes greater residual effects in the longitudinal direction as these fibers have a significant restraining effect on the matrix during the cool down.

It should also be noted that in Figure 4.4, the simulated stress-strain curves with residual stresses have been shifted from the strain value at the completion of the cool-down to a strain value of zero. That is, for example, the composite exhibited a longitudinal strain of -0.00552 upon completion of the cool-down. The longitudinal stress-strain curve with residual in Figure 4.4 was thus shifted to the right by a strain value of +0.00552. Therefore, as is the case in an experimental tensile stress-strain test on a composite, it appears that, at the beginning of the test, the composite starts at zero macro strain. In reality, of course, during manufacture, the composite has experienced some strain, but the as delivered, room-temperature composite state is commonly used as the zero strain reference.

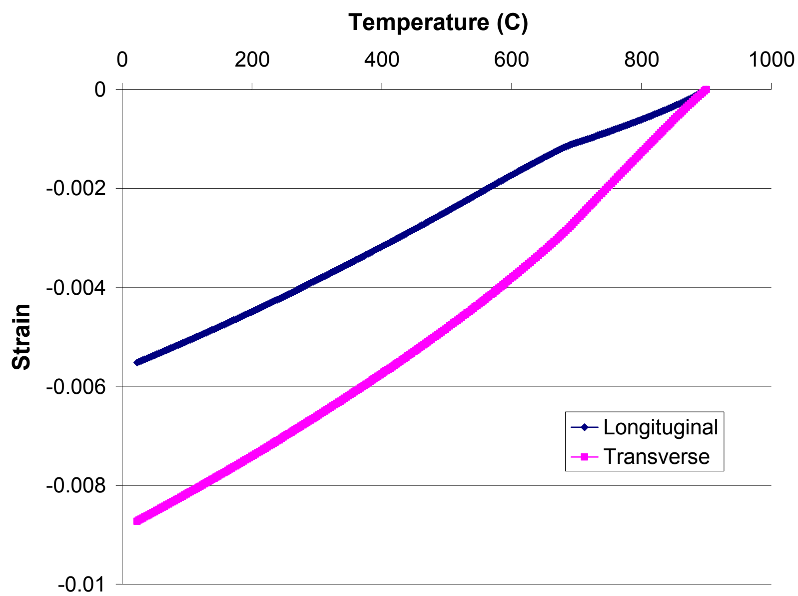

Figure 4.3 Example 4b: plot of the simulated longitudinal and transverse thermal response of a 25% SiC/Ti-21S composite to a stress-free cool-down from 900 °C to 23 °C.

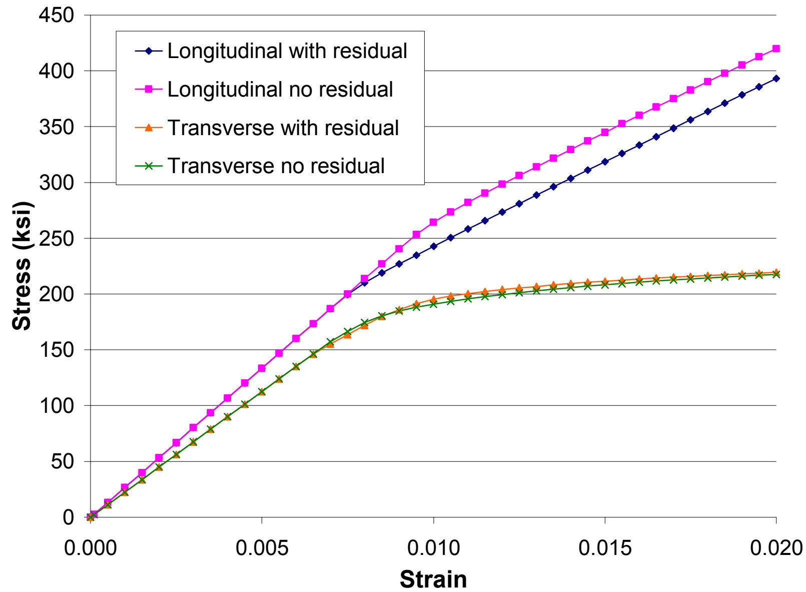

Figure 4.4 Example 4b: plots of the simulated longitudinal and transverse tensile response of a 25% SiC/Ti-21S composite with and without residual stresses included. The plots for the cases without residual stresses are the results from Example 1d.