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THERMAL EXPANSION MISMATCH AND PLASTICITY IN THERMAL BARRIER COATING

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1. INTRODUCTION

The basic objective of this investigation is the quantitative determination of stress states in a model thermal barrier coating (TBC) as it cools in the air to 600°C from an assumed stress-free state at 700°C. This model is intended to represent a thin plasma-sprayed zirconia-yttria ceramic layer with a nickel-chromium-aluminum-yttrium bond coat on a cylindrical substrate made of nickel-based superalloys typically found in gas turbines.

The problem under study is a complex one due to layering, uneven interface between the ceramic and the bond, oxidation, and thermal expansion mismatch, as reported in references 1, 2, and 3. Thus, a concerted effort has been made to use the versatile finite element method to represent a cylindrical model TBC which resembles those that had been tested in a laboratory (refs. 1 and 3). The modeling concept is illustrated in figure 1.

To implement this finite element scheme, a generic code called MARC (ref. 4) has been utilized with the aid of a supercomputer (known as CRAY-XMP) at NASA Lewis Research Center. The latest finite element model which is known as TBCGEP, contains 1316 nodal points and 2140 generalized plane strain elements. This finite element model is now capable of representing both the ceramic layer and the bond coat with classical elastic-perfectly plastic materials.

Numerical results from previous studies have been reported in references 2, 3, 5, and 6. Parameters studied include: (1) variation of material properties involved, (2) oxidation of the bond coat, (3) cracking at the ceramic-bond interface, (4) coefficient of thermal expansion and Poisson's ratio of bond coat, and (5) plasticity in the bond coat.

The newly revised code TBCGEP has been used to study the influence of plasticity in ceramic layer on stress states, particularly on stresses in the "critical zone" shown in figure 2. Detailed results from three lengthly computer runs are presented in section 3 of this paper.

2. FINITE ELEMENT MODELING OF A CYLINDRICAL TBC

The uncoated superalloy cylindrical test specimens used in reference 1 had a radius (R_s) of 0.65 cm and a length of 7.60 cm. The specimens were plasma-sprayed in air with a thin zirconia-yttria (ZrO_2 - 8 wt. % Y_2O_3) layer on a thin nickel-chromium-aluminum-zirconium bond coat. The test specimen is sufficiently long, as compared to its radius, that the problem can be approximated by a two-dimensional generalized plane-strain case in the context of classical elasticity. The resulting finite element model is illustrated in figure 2. Details for an early model (known as TBC) was given in reference 2. That model features a rather sharp sinusoidal interface with an amplitude and a period of 50 micrometers (μm).

The next finite element model known as TBCGEP has a more smooth interface (15μm) than TBC. Detailed finite element discretization has been presented in reference 5.

3. INFLUENCE OF PLASTICITY IN CERAMIC LAYER ON STRESS STATES

With the aid of the latest computer code named TBCGEP, the influence of plasticity in ceramic layer on stress states throughout the TBC has been studied on a preliminary basis. Three cases, i.e. T-17, T-18, and T-19, have been investigated. As shown in Table 1, these three cases are identically the same as that of Case B-2 with the sole exception of varying degree of plasticity. The plastic behavior, as known in the classical theory of plasticity, is controlled by the parameter called YP1 which is the measure in von Mises yeild criterion in an elastic-perfectly-plastic solid.

The stress states have been calculated by using ten increments of -10°C each, starting at an assumed stress-free temperature of 700°C. The results for Case T-18 are presented in figures 6-8. Also presented in figures 9-11 are results for Case T-19. For comparison purposes, corresponding stresses for the perfectly elastic case known as B-2 are also shown in figures 3-5.

From figures 3, 6, and 9, it can be seen that the x-stress in the ceramic layer experiences very significant reduction with increasing plasticity. Furthermore, a rather localized redistribution in stresses is seen to have taken place in the vicinity of the critical zone. These results are expected within the realm of classical plasticity. The same can also be said about the x-stress in the bond coat adjacent to the ceramic-bond interface. Indeed, the experience with y-stress and shearing stress is substantially similar to the x-stress. In short, these results have shown the widespread influence of ceramic plasticity as well as the forgiven nature of plasticity in a solid material.

Now, figure 12 presents data on stresses in the critical zone in a model TBC as a function of temperature and plasticity. Stresses in x-direction increased linearly with decreasing temperature in Case B-2. These stresses, however, tend to increase with decreasing temperature at a rate much slower than that of Case B-2 as more plasticity is involved. At 600°C, the x-stress in Case T-19 is only about 40 percent of the corresponding stress in the elastic case, B-2.

Similar reductions in y-stresses can be seen as a function of plasticity as well. The magnitudes of reduction, however, are even more pronounced than that of Case B-2. Much of the same can be said of shearing stresses as shown in figure 12.

In short, data shown in figure 12 clearly illustrates the very significant influence ceramic plasticity has on stresses in the critical zone. Given the nature of plasticity in a medium, the results are entirely expected.

4. CONCLUDING REMARKS

In the present work, the computer code TBCGEP has been used to generate numerical solutions to the model thermal barrier coating, as shown in figures 3 to 12.

In section 3, nine stress-field contours and figure 12 illustrate the very important influence ceramic plasticity has on the stresses in the critical zone as a coating system is cooled from an assumed stress free temperature. The importance is in marked contrast with the slight impact bond coat plasticity had on stresses in the critical zone or elsewhere in the model TBC (ref. 6). Nonetheless, additional data will have to be generated and analyzed before a firm conclusion can be drawn.

The question of combined influence of plasticity in both ceramic layer and the bond coat, is of significant interest at present. Of equal importance is the determination of the effect of bond coat oxidation on stress states, in the presence of plasticity. Such are some of the major directions for future TBC investigations.

REFERENCES

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2. Chang, G. C.; Phucharoen, W.; and Miller, R. A.: Thermal Expansion Mismatch and Oxidation in Thermal Barrier Coatings. NASA CP-2405, 1985, pp. 405-425.

3. Chang, George C.; Phucharoen, Woraphat; and Miller, Robert A.: Behavior of Thermal Barrier Coatings for Advanced Gas Turbine Blades. Surface and Coatings Technology, 30, 1, 1987, pp. 13-28.

4. Anonymous, MARC Finite Element Program User Manual, Version K-2, MARC Analysis Research Corporation, 1986.

5. Chang, George C.; Phucharoen, Woraphat; and Miller, Robert A.: A Study on Thermal Barrier Coatings including Thermal Expansion Mismatch and Bond Coat Oxidation. NASA-CP-2444, 1986, pp. 415-434.

6. Chang, G. C.; Phucharoen, W.; and Miller, R. A.: Finite Element Thermal Stress Solutions for Thermal Barrier Coatings. Paper presented at the 14th International Conference on Metallurgical Coatings, San Diego, CA., March 23-27, 1987.

TABLE 1 MATERIAL AND OTHER PARAMETERS

Parameters	Case A-2	Cases B-2, T-17, T-18, T-19
Young's Modulus (MPa)		
Substrate	0.1758×10^6	0.1758×10^6
Bond	0.1379×10^6	0.1379×10^6
Ceramic	0.0276×10^6	0.0276×10^6
Poisson's Ratio		
Substrate	0.25	0.25
Bond	0.27	0.27
Ceramic	0.25	0.25
Coefficient of Thermal Expansion (/°C)		
Substrate	13.91×10^{-6}	13.91×10^{-6}
Bond	15.16×10^{-6}	15.16×10^{-6}
Ceramic	10.01×10^{-6}	10.01×10^{-6}
YP1 - value (MPa)		
Substrate	0.069×10^6	0.069×10^6
Bond	0.069×10^6	0.069×10^6
Ceramic	0.069×10^6	(B-2) 0.069×10^6 (T-17) 34.48* (T-18) 17.24 (T-19) 8.62
Oxidation	NO	NO
Interface Roughness Amplitude (μm)	50	15

*5,000 psi.

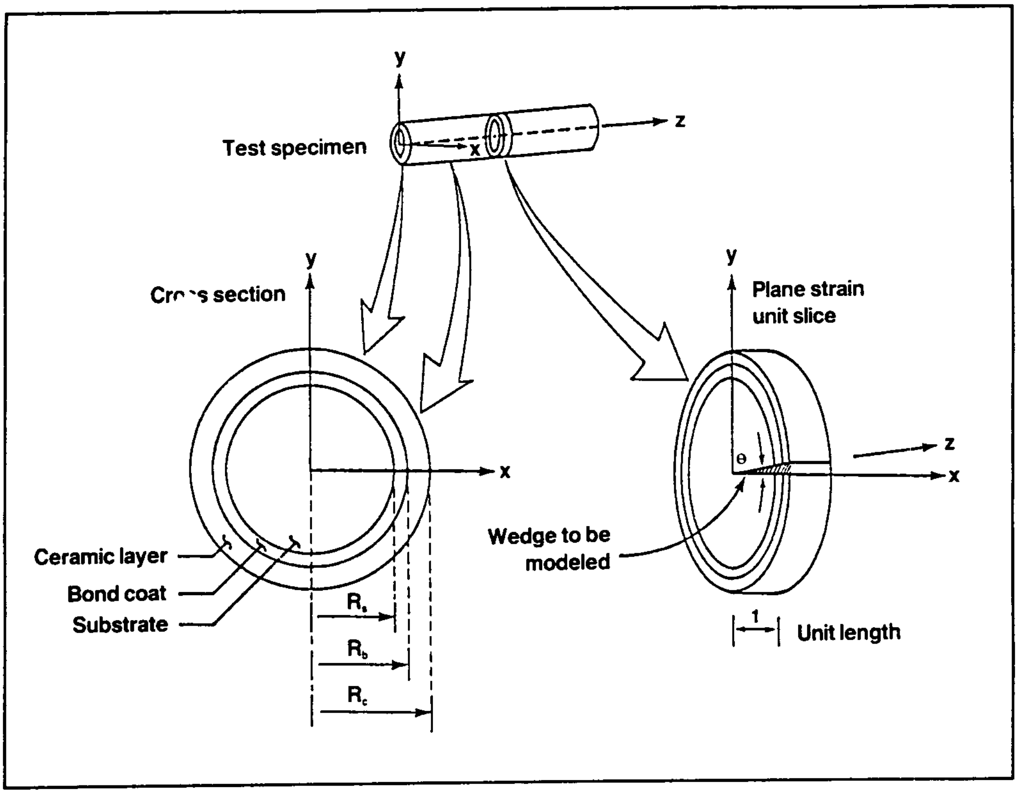

Figure 1. CYLINDRICAL TBC TEST SPECIMEN

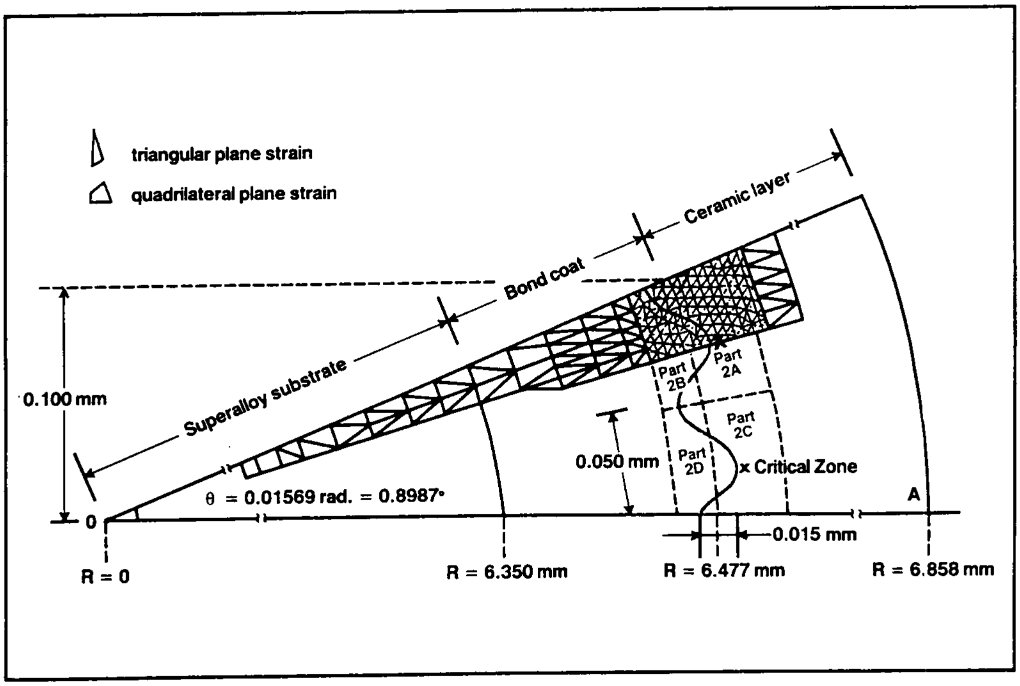

Figure 2. THE TBCGEP FINITE ELEMENT MODEL

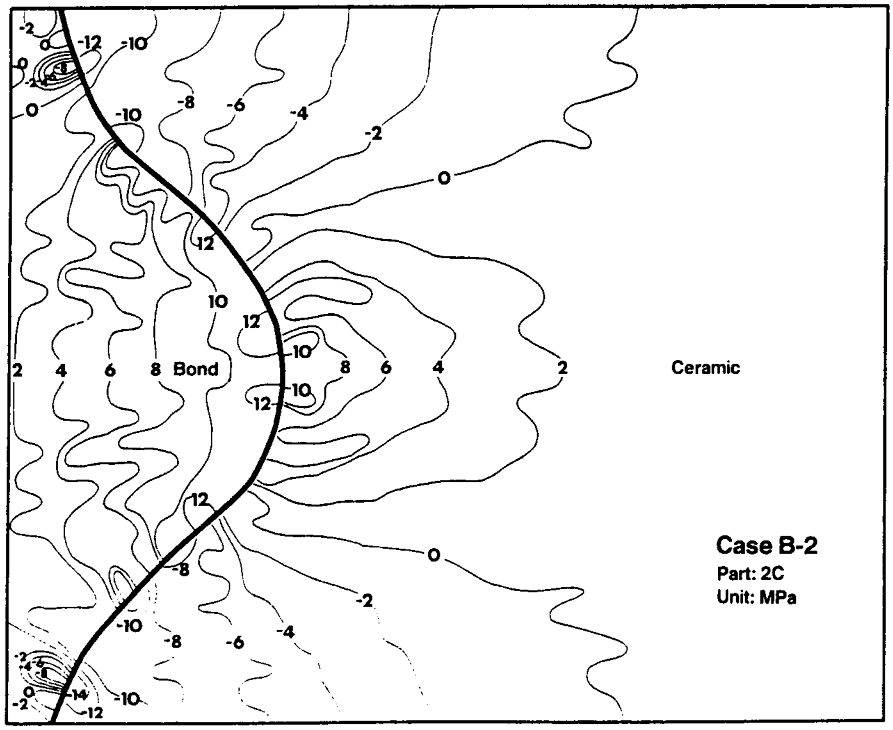

Figure 3. STRESS IN X-DIRECTION DUE TO THERMAL EXPANSION MISMATCH

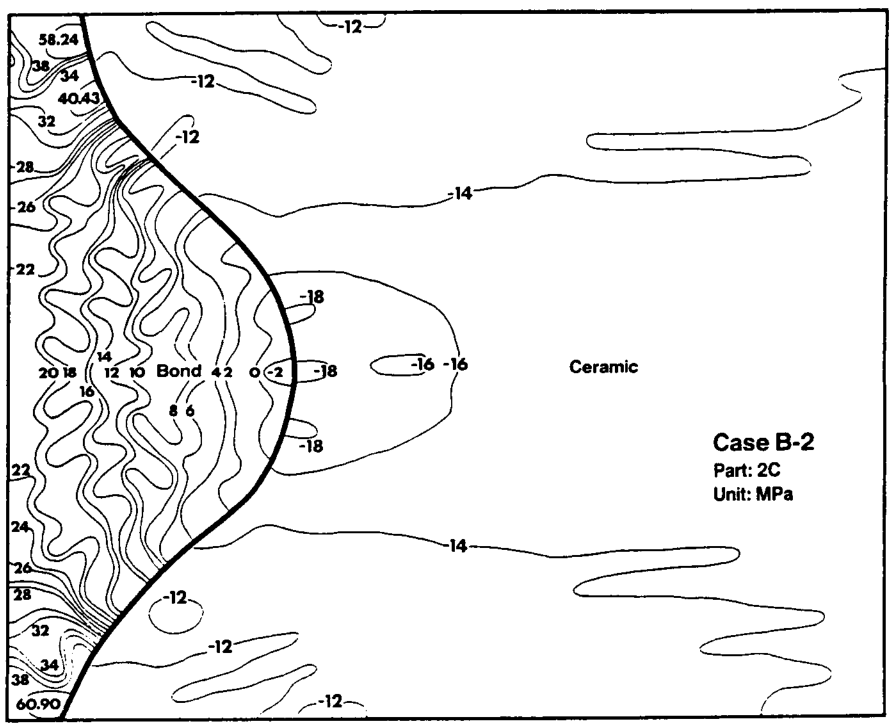

Figure 4. STRESS IN Y-DIRECTION DUE TO THERMAL EXPANSION MISMATCH

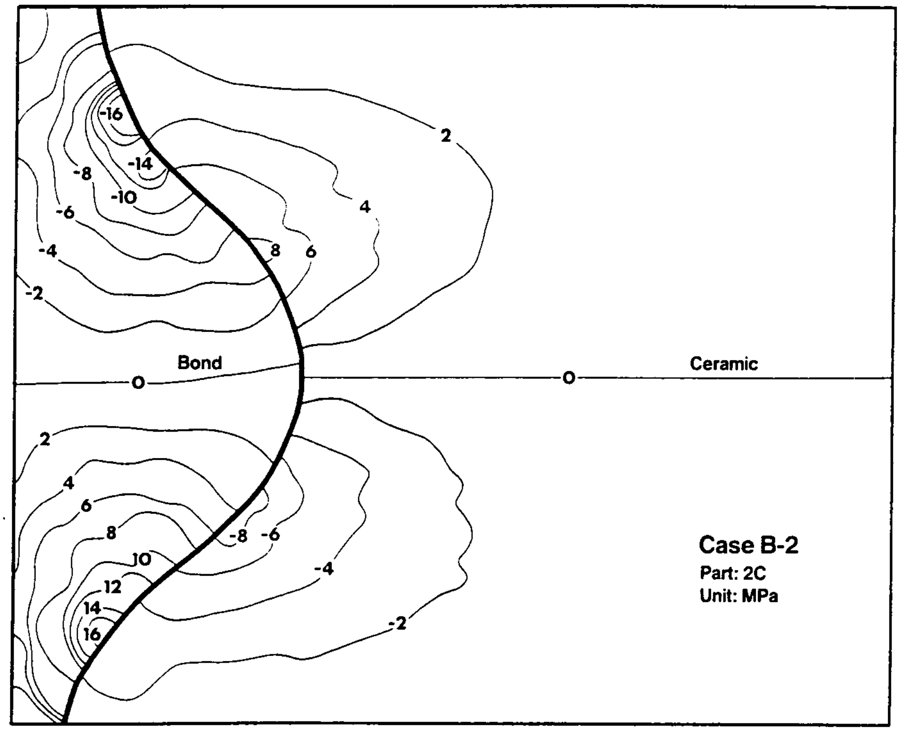

Figure 5. SHEARING STRESS DUE TO THERMAL EXPANSION MISMATCH

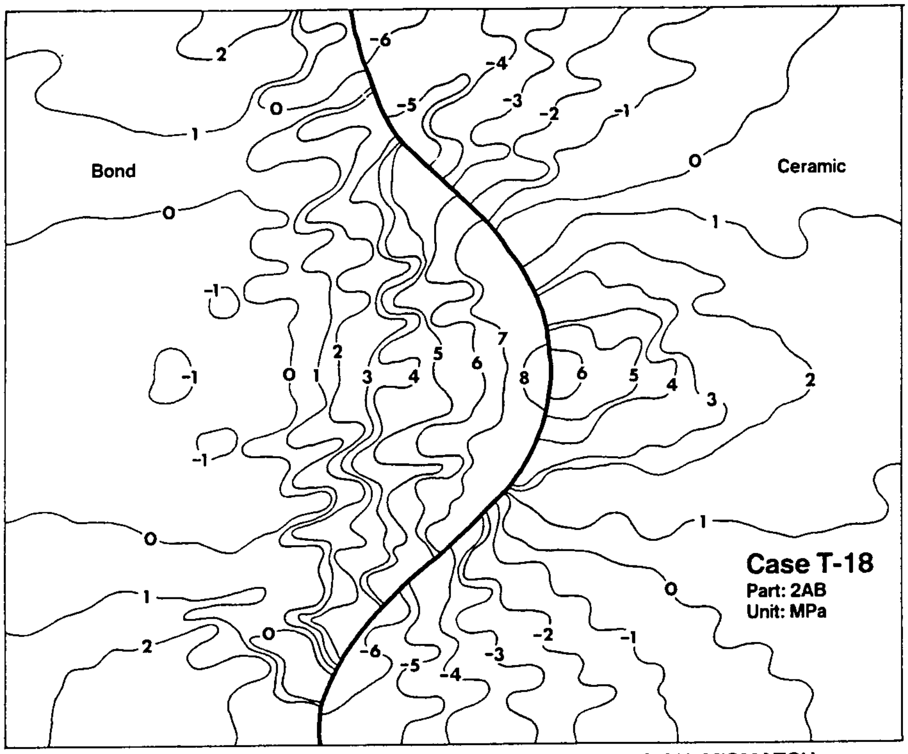

Figure 6. STRESS IN X-DIRECTION DUE TO THERMAL EXPANSION MISMATCH AND PLASTICITY

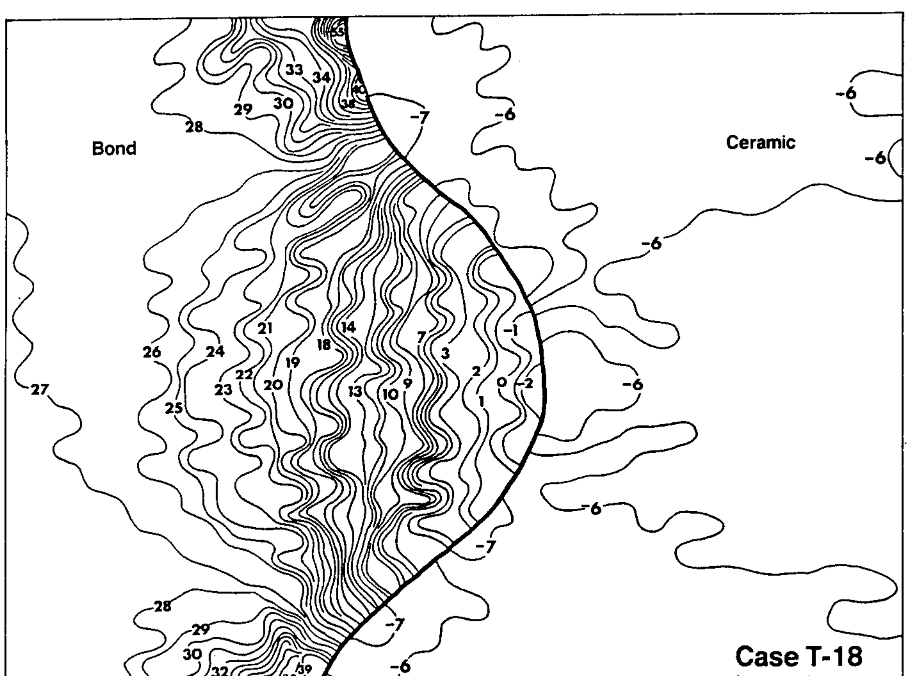

Figure 7. STRESS IN Y-DIRECTION DUE TO THERMAL EXPANSION MISMATCH AND PLASTICITY

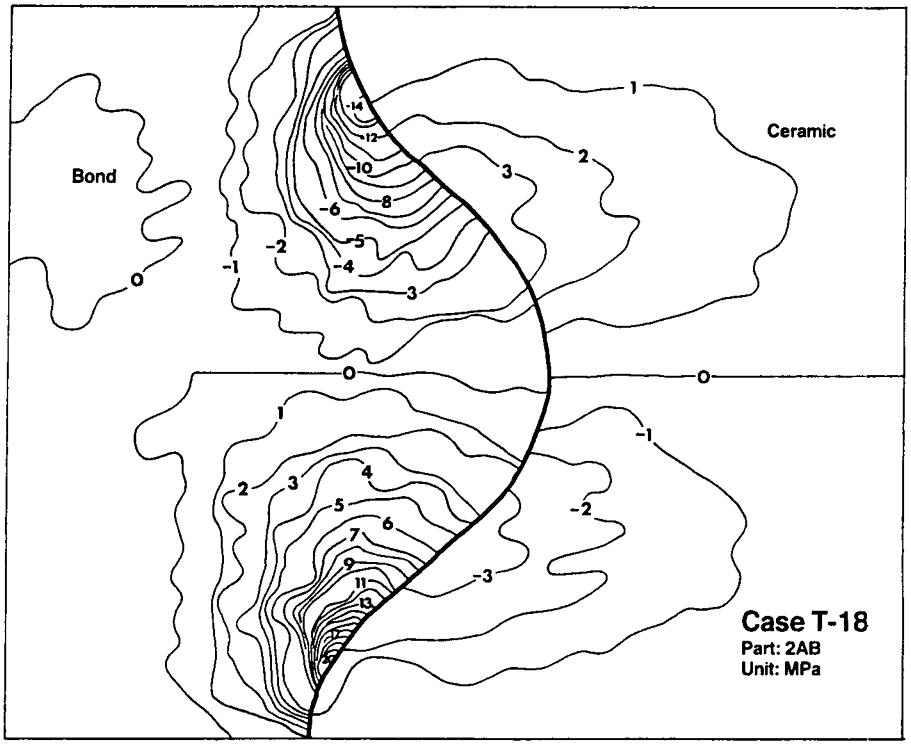

Figure 8. SHEARING STRESS DUE TO THERMAL EXPANSION MISMATCH AND PLASTICITY

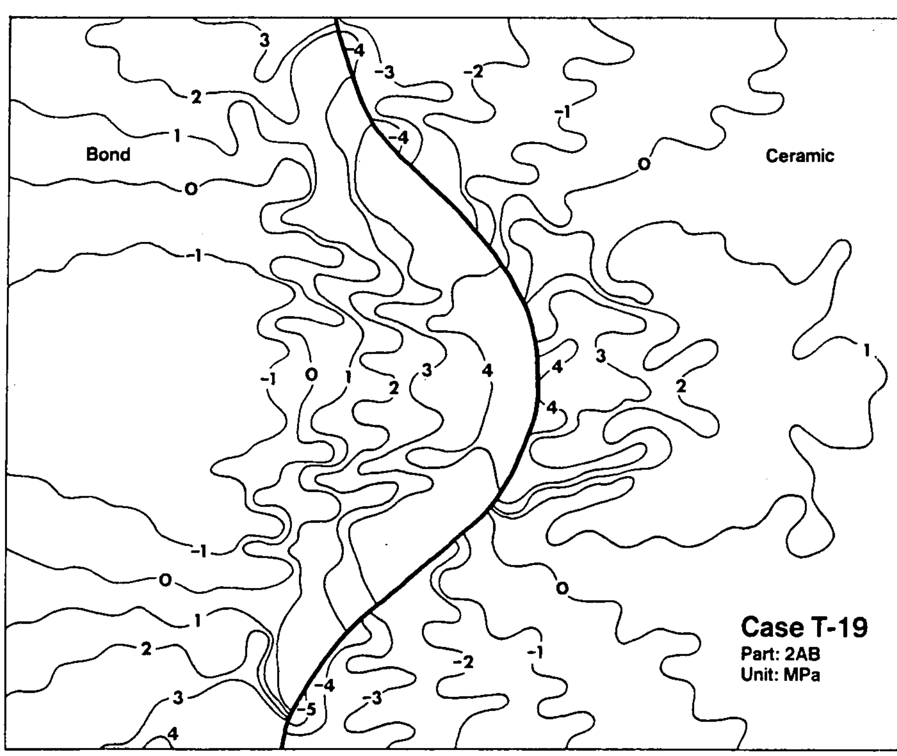

Figure 9. STRESS IN X-DIRECTION DUE TO THERMAL EXPANSION MISMATCH AND INCREASED PLASTICITY

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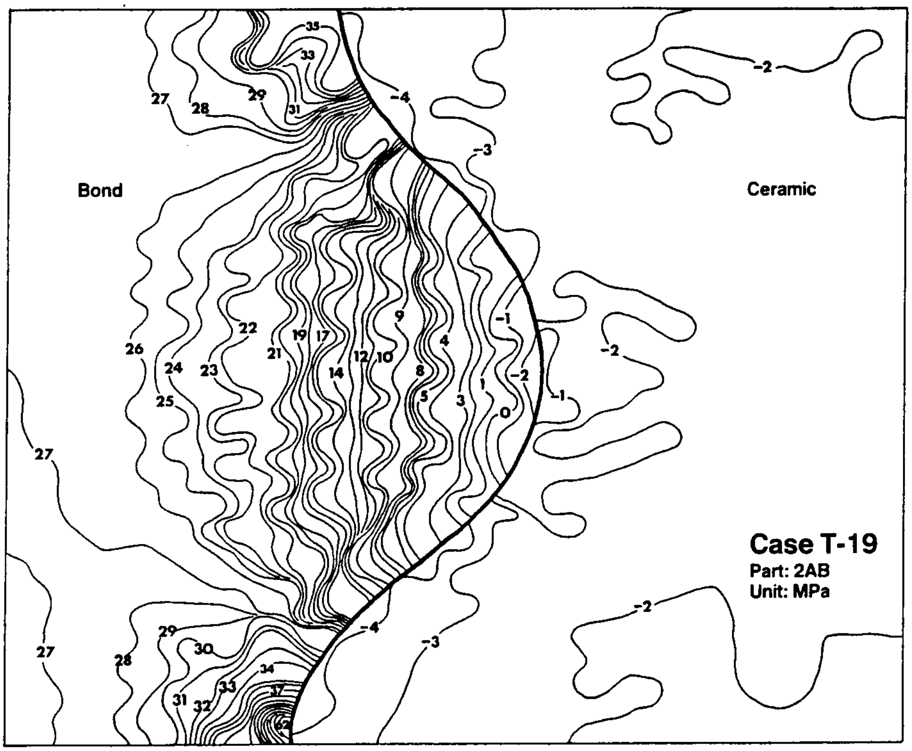

Figure 10. STRESS IN Y-DIRECTION DUE TO THERMAL EXPANSION MISMATCH AND INCREASED PLASTICITY

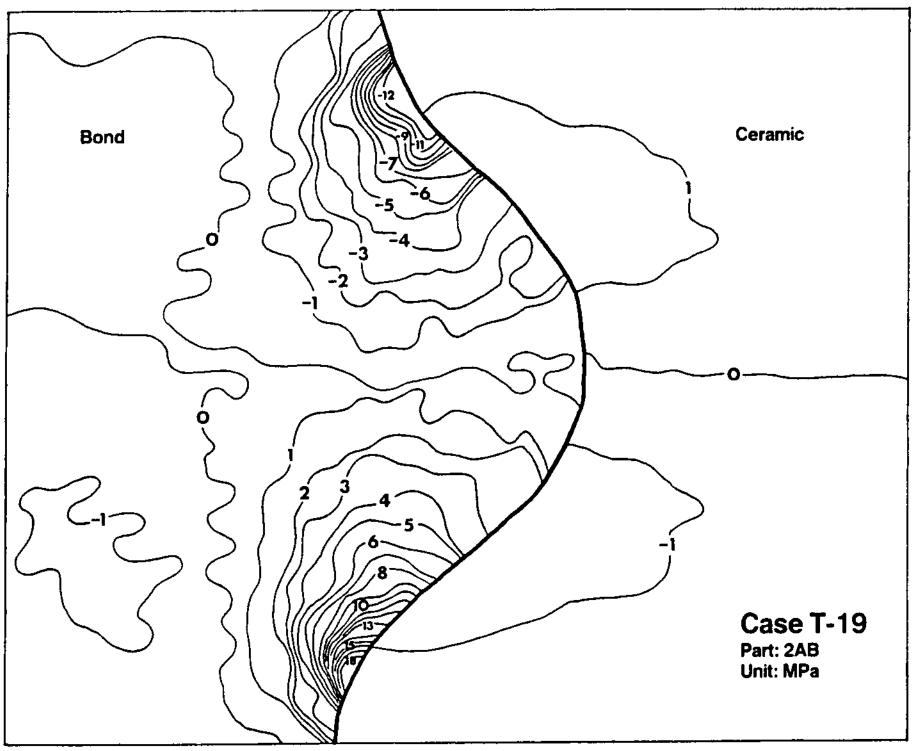

Figure 11. SHEARING STRESS DUE TO THERMAL EXPANSION MISMATCH AND INCREASED PLASTICITY

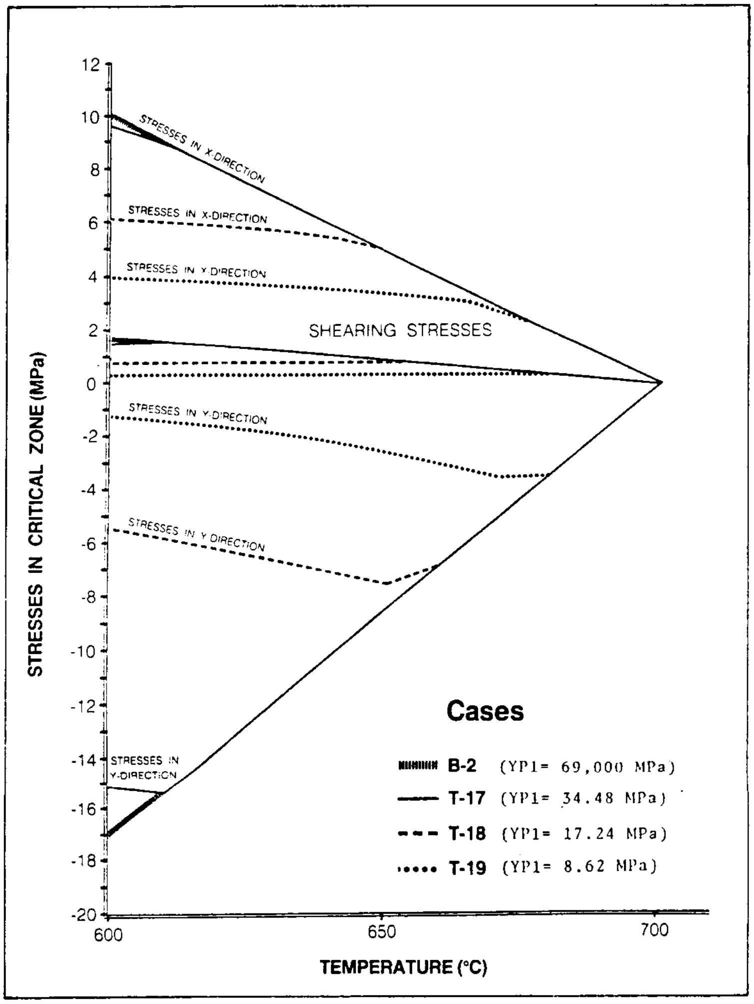

Figure 12. VARIATION OF STRESSES WITH TEMPERATURE

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