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THERMAL STRESS ANALYSIS IN ZrO_2 INSULATION COATINGS ON Cr-Ni SUBSTRATES DURING COOLING PROCESS

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Abstract- In this study, thermal stresses analysis of ZrO_2 insulation coatings on Cr-Ni substrate during the cooling process was investigated. A transient thermal analysis was performed using finite element method (FEM) via ANSYS software. The temperature versus the time curve obtained from FEM solution was controlled with the temperature-time diagram measured by a thermocouple. The results obtained from the numerical calculations were improved by the experimental measurement. Additionally, residual stresses were calculated by FEM solutions and they were compared in different points. The compressive and tensile stresses occurred in ZrO_2 coating and Cr-Ni substrate owing to the different thermal expansion coefficients in each material, respectively.

Key words- Sol-gel preparation, Thermal properties, FEM

1. INTRODUCTION

The reel-to-reel, continuous sol–gel technique is a popular and simple method for the insulation coatings. Nonetheless, ceramic insulation coatings usually suffer failure because of flaking and cracking during cooling, due to excessive residual stresses generated near the interface and poor bonding strength between the ZrO_2 coating and the Ag substrate. In coatings, the strength of the bonded system is governed by a number of variables: the thermal and elastic mismatch effect; the plastic flow stress of the metal; the relative substrate coating thickness; the thickness of interlayer and the fracture resistance of the interface; and the flaw distributions in the ceramic and at the interface. Most failures in sol-gel coatings also depend on the processing parameters [1-4].

Islamoglu et al. [5] analyzed the thermal stresses of sol-gel ZrO_2 insulation ceramic coatings on Ag tapes sheathing Bi-2212 superconducting materials under several annealing conditions using ANSYS program. In addition, the fracture properties of 8-mm thick coatings were investigated at the optimum annealing temperature. Perin et al. [6] investigated aluminium alloys coated by magnesium zirconate used as thermal barriers Thermal shocks were conducted to evaluate the resistance of various types of coatings: cylindrical specimens were submitted to an oxyacetylene torch. Different geometries and various shock intensities were tested and special attention was paid to the influence of the thickness of the coating on the crazing phenomenon. Numerical calculations have also been performed using the finite element code. Crack initiations were then predicted. The numerical and experimental results are in good accordance. Celik et. al [7] studied the synthesis, characterization and application of high temperature compatible ZrO_2 insulation on Ag and AgMg sheathed Bi-2212 superconducting wires and tapes from Zr based precursor materials using the reel-to-reel, continuous sol-gel technique. In addition, the growth mechanism of ZrO_2 coatings was evaluated.

The effect of residual stresses of CeO_2 buffer layers on Ni substrate for YBCO coated conductors was studied [8]. CeO_2 films were fabricated on Ni tape substrate from the solutions prepared from alkoxide precursors, solvent, chelating agent and modifying liquid material by using a reel-to-reel sol-gel technique. SEM observation showed that CeO_2 buffer layers had crack-free, pinhole-free and continuous structures and the characteristic feature of the films was grain boundary grooves owing to Ni substrate. FEM was used to calculate the temperature and stress fields of the sample with CeO_2/Ni configuration. Taymaz et. al. [9] employed thermal and structural finite element analysis to analyse the level of stresses developed in Al_2O_3-spherical cast iron (SG), ZrO_2-(12□□Si+Al) and ZrO_2-SG coatings subjected to thermal loading. Coatings with a coating-to-substrate thickness ratio of 1/10 were modeled. ZrO_2–SG coatings with NiAl, NiCrAlY or NiCoCrAlY interlayer, and with different combinations of these interlayer materials, were also modeled. Nominal and shear stresses at the critical interface regions (film/interlayer/substrate) were obtained and compared. The results showed that the ZrO_2–SG coatings have a higher thermal shock resistance than the Al_2O_3–SG and ZrO_2–(12□□Si +Al) coating systems. Furthermore, the interlayer thickness and material combinations have a significant influence on the level of thermal stresses developed. It is also concluded that the finite element technique can be used to optimize the design and processing of ceramic coatings. Sen et al. [10] investigated residual stresses occurred during cooling procedure of ZrO_2 insulation coating on Ag substrate for magnet technologies. ZrO_2 coatings were produced on Ag tape substrate by using a reel-to-reel sol-gel technique. SEM inspection showed that ZrO_2 coatings had mosaic structures. ANSYS finite element software was used to calculate the temperature and stress distribution of the ZrO_2/Ag structure. The effect of coating thickness on residual stresses was also examined. The results showed that thermal stresses in ZrO_2 coating and Ag substrate were considerably affected by the cooling time and coating thickness. It is concluded the thermal stresses increase with increase of film thickness. Toparli et al. [11] reported an investigation on the thermal stress analysis of WC–Co bonded NiAl coating on 316 L substrate using finite elements methods as used for hot copper rolling process. Thermal cycling tests were performed at the temperature range of 373 and 873 ^oK without external load. In FEM, thermal residual stresses, developed during and after thermal cycling, were determined by using ANSYS.

In the present study, a high temperature ZrO_2 based insulation ceramic coatings on Cr-Ni tapes was cooled in air from 1300 to 298 ^oK as an alternative system for magnet technologies. In the transient analysis temperature versus time obtained from FEM was checked and modified by experimental measurements of temperature during the cooling. It is seen that experimental results are in a good agreement with numerical results.

2. MATERIALS AND METHODS

ZrO_2 insulation coating is deposited on Cr-Ni tapes from solutions derived from Zr based organometallic compounds by using the reel-to-reel continuous sol-gel process. Mechanical and thermal properties of ZrO_2 and Cr-Ni materials are given at different temperatures in Tables 1 and 2, respectively [12]. It is seen that the mechanical properties of ZrO_2 very slowly at different temperatures. However, the mechanical properties of Cr-Ni change rapidly at the given temperatures. The thickness of base material was kept as 5 mm. The thickness of coating was selected as 0.5, 1, 2, 3, 4, 6, 8 and 10 µm. The stress and temperature distributions as a function of the time were obtained in the FEM solutions by a transient analysis. The convection and radiation coefficients were calculated by theoretical formulations in a chosen coating time

Table 1. Thermal and mechanical properties of ZrO_2

Temperature, T (ºK)	300	500	700	900	1100	1300
Elasticity modulus, E (GPa)	206	193	182	175	171	167
Poisson ratio, υ	0.29	0.29	0.29	0.29	0.29	0.29
Thermal expansion coefficient, α [10^{-6}/ º K]	10	10	10	10.1	10.4	10.5
Density, ρ [kg/m^3]	5900	5900	5900	5900	5900	5900
Thermal conductivity, K [W/m º K]	2.2	2.2	2.2	2.2	2.2	2.2
Specific heat, C_p [J/kg º K]	460	460	460	460	460	460

Table 2. Thermal and mechanical properties of Cr-Ni

Temperature (ºK)	300	500	700	900	1100	1300
Elasticity modulus, E (GPa)	214	209	198	182	162	144
Poisson ratio, υ	0.29	0.29	0.29	0.29	0.29	0.29
Thermal expansion coefficient, α [10^{-6}/ º K]	11.45	13.00	14.06	14.85	16.04	17.6
Density, ρ [kg/m^3]	8050	8050	8050	8050	8050	8050
Thermal conductivity, K [W/m º K]	11.40	12.8	18.4	23.9	29.7	34.00
Specific heat, C_p [J/kg º K]	0.45	0.493	0.538	0.611	0.705	0.742
Yield strength [MPa]	252	228	203	190	85	25
Plasticity Constant, K [MPa]	1980	1920	1870	1500	550	150

These values were compared with experimental measuring. After that, theoretical calculations were modified using the experimental results. After four or five iterations, the close results were obtained between the FEM and experimental measuring. σ_x was the greatest stress component. The failure analysis was performed by the von Mises criterion. The materials were cooled from 1300 ºK to the infinity temperature as 298 ºK. The stress components were found by FEM solutions by using a nonlinear solution due to the plastic deformations.

3. RESULTS AND DISCUSSION

Schematic mesh generation and boundary conditions are shown in Fig. 1. The ZrO_2 coating was closely divided for finding the sensitive results due to thin thickness. It was divided into two parts because of the symmetry of the structures. The PLANE 13 2-D coupled-field solid element was used in the solution, since this type of element can perform the both thermal and stress analysis. This element carries out the transient thermal analysis. Five nodes were considered in the solution of ANSYS as shown in Fig. 1. The node A was placed at the upper surface of ZrO_2 coatings. Node B was set at the lower surface of ZrO_2 and, the node C was set at the upper surface of Cr-Ni. The node D and E were introduced at the mid point and lower surface of Cr-Ni substrate materials, respectively.

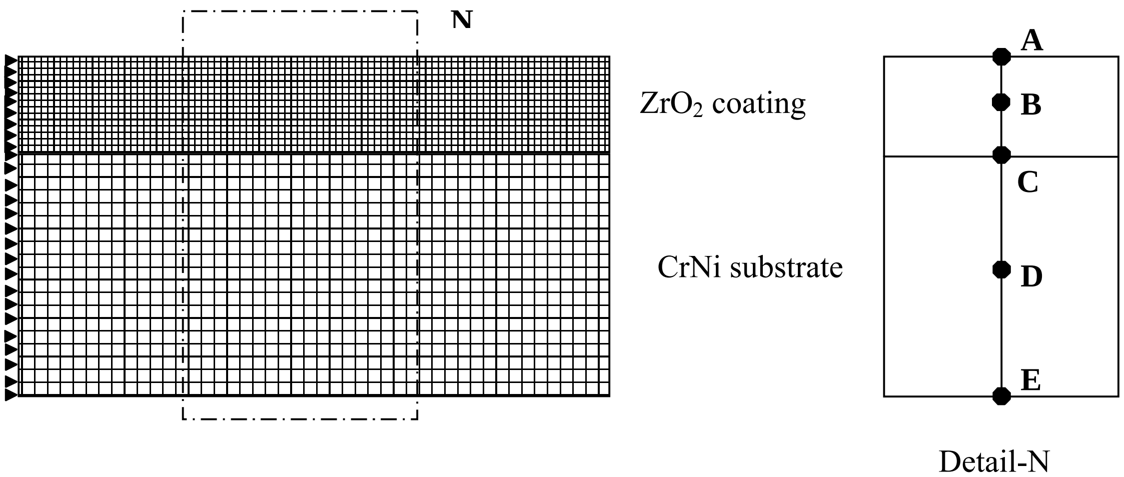

Figure 1. Schematic finite element models and boundary conditions

The substrate material Cr-Ni is a ductile material and ZrO_2 coating represents the brittle material properties. The mechanical properties of ZrO_2 coating and Cr-Ni substrate are given in Table 1, 2 respectively. All the mechanical properties were given from 298 ºK to 1300 ºK, [12]. As shown in these tables the mechanical properties of ZrO_2 change slowly, inasmuch as it reaches these properties at high temperatures. The mechanical properties of Cr-Ni vary rapidly in comparison with the coating material of ZrO_2.
The thickness of substrate material Cr-Ni was chosen as 5 mm. The thickness of the coating material, ZrO_2 was selected as 0.5, 1, 2, 3, 4, 5, 6, 7, 8 and 10 μm. The convection with radiation constants were found numerically. They were illustrated in Table 3. The radiation constant reaches the great values at the high temperatures. They were given in a time step, as a form of table in the ANSYS solution, during the cooling of the coating and the substrate from 1300 ºK to 298 ºK.

Table 3. Combined radiation with convection constants

Temperature, T [K]	500	700	900	1100	1300
Heat transfer coefficient, h, [W/m^2K]	23	35	64	101	154

ZrO_2 coating on Cr-Ni substrate was placed into an oven. It was heated and cooled from 1300 ºK to the room temperature as 298 ºK in the air. The temperature values were measured by an thermocouple during cooling and then temperature versus time diagram was drawn as shown in Fig. 2. As seen in this figure, the solution in ANSYS was closed to the experimental measurements by using 4 or 5 iterations. Thermal residual stresses occur in ZrO_2 coating and Cr-Ni substrate during cooling, because of having different thermal expansion coefficient.

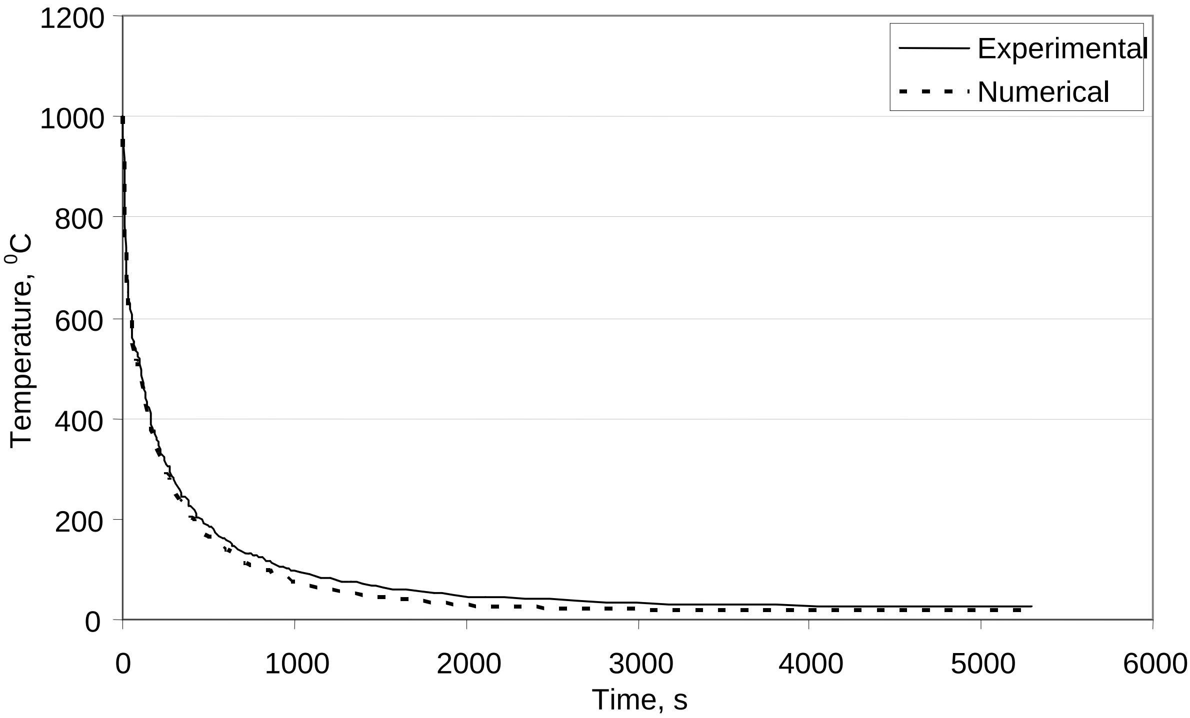

Figure 2. Time-temperature curves in cooling process

As shown in Table 4, while the thickness of ZrO_2 coating decreases, the residual compressive stresses in nodes A and B increase for satisfying equilibrium. Also, it can be noticed from the table that while the thickness of ZrO_2 coating decreases, the residual stresses in node C, D, and E reduce, due to the fact that the curvature radius occurred in model at the end of cooling increases with decreasing the thickness.

The compressive stresses occur in the ZrO_2 coating, since the thermal expansion coefficient of Cr-Ni is larger than that of ZrO_2. The Cr-Ni substrate applies compressive stresses to the ZrO_2 and ZrO_2 applies tensile stresses to the Cr-Ni substrate while they are cooling for satisfying the static equilibrium. The intensity of σ_x is the highest at the boundary of ZrO_2 and Cr-Ni due to the most different mechanical and thermal properties at this section. The compressive stress occurs at the lower surface of Cr-Ni substrate for satisfying the static equilibrium in this structure.

Table 4. Thermal stresses on the selected nodes

The thickness t (μm)	σ_x [MPa]				
	A	B	C	D	E
1.0	-128.0	-168.0	93.1	50.7	-76.3
0.8	-154.0	-183.0	83.0	45.6	-66.4
0.7	-168.0	-192.0	76.8	42.4	-60.9
0.6	-184.0	-199.0	69.7	38.7	-54.5
0.5	-203.0	-212.0	61.5	34.3	-47.5
0.4	-217.0	-226.0	52.2	29.2	-39.7
0.3	-236.0	-241.0	41.6	23.4	-31.2
0.2	-256.0	-258.0	29.5	16.7	-21.8
0.1	-276.0	-277.0	16.7	8.92	-11.4
0.05	-287.0	-288.0	9.8	5.1	-6.79

4. CONCLUSIONS

In this study, ZrO_2 insulation coating is deposited on Cr-Ni tapes from solutions derived from Zr based organometallic compounds by using the reel-to-reel continuous sol-gel process. It was concluded that as transient cooling analysis can be conducted by some experiments. In addition large stresses occur in the thin coatings and the compressive stresses form in the coating.

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