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Development of Integrated Insulation Joint for Cooling Pipe in Tokamak Reactor

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In a tokamak fusion reactor, an electrically insulated part is needed for an in-vessel piping system in order to break an electric circuit loop. When a closed loop is formed in the piping system, large induced electromagnetic forces during a plasma disruption (rapid plasma current quench) could give damages on the piping system. Ceramic brazing joint is a conventional method for the electric circuit break, but an application to the fusion reactor is not feasible due to its brittleness.

Here, a stainless steel／ceramics／stainless steel functionally gradient material (FGM) has been proposed and developed as an integrated insulation joint of the piping system. Both sides of the joint can be welded to the main pipes, and expected to be reliable even in the fusion reactor environment. When the FGM joint is manufactured by way of a sintering process, a residual thermal stress is the key issue. Through detailed computations of the residual thermal stress and several trial productions, tubular elements of FGM joints have been successfully manufactured.

Keywords: Functionally Gradient Material, Residual Thermal Stress, Hot Isostatic Press Sintering, Tokamak Fusion Reactor, Plasma Disruption, Pipe Joint Element

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核融合炉内配管用機能傾斜型電気絶縁継手の開発

日本原子力研究所那珂研究所核融合工学部
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（1994年6月9日受理）

核融合炉内の配管系に作用する電磁力の軽減対策として配管系の適切な箇所に絶縁部あるいは高抵抗部を設置することが効果的である。高い水圧，高真空，放射線場という厳しい環境で，高い信頼性を有する配管の絶縁継手として，中央部をセラミクス，両端部を溶接可能な金属とし，中間領域には両者の成分を緩やかに傾斜させたパイプ要素を提案し，開発を進めてきた。積層粉体の焼結成形で得られる機能傾斜材（FGM）の最大の技術課題は焼結温度から室温に至る過程で発生する残留熱応力の緩和対策である。詳細な応力解析と幾つかの試作を通して適切な焼結条件を設定することが可能となり，実機に適用し得る機能傾斜型電気絶縁継手の試作に成功した。更に，大型FGMの製造技術に不可欠な焼結バランスの制御についても基本技術が確立され，大型配管への適用の見通しが得られた。

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1. Introduction

In a tokamak fusion reactor like ITER[1], a rapid quench of plasma current, so called "plasma disruption", induces eddy current on conducting structures surrounding the plasma column. The eddy currents produce enormous electromagnetic forces by the interaction with intense magnetic fields generated by a toroidal field (TF) coil system and a poloidal field (PF) coil system. In order to obtain the structural integrity of the lightly built piping system, it is attractive way to put an electrically insulated part into the appropriate location of the piping system to break the circuit loops. However, it seems to be difficult to realize the reliable insulation joint element which should work under the high temperature, vacuum, narrow space and nuclear environments.

Here, a stainless steel/ceramics/stainless steel functionally gradient material (FGM) has been proposed and developed as an integrated insulation joint of the piping system. The word "integrated" means "without any mechanical connection part". Both sides of the joint part can be welded to the main pipes, and expected to be reliable even in the fusion reactor environment. Less residual stress can be expected in the FGM joints than a ceramics/metal bonding joints. Higher leak tightness and more compact system can be expected in the FGM joints than a mechanical joints. However, when the FGM is produced by way of a sintering process, a residual thermal stress is still the key issue.

In Section 2, the concept of the FGM joint element as to break the circuit loops of piping system is briefly described. In Section 3, the FGM producible parameter window is discussed from view point of the residual thermal stress. Based on the residual thermal stress analysis, a successfully produced FGM joint element is also shown in Section 3. Concluding remarks and future issues are given in Section 4.

2. Concept of FGM joint element

The research and development for a conventional FGM[2] has been mainly focused on a high heat flux component, where the FGM is one side graded structure whose one end is heat sink metallic material and the other end is high heat flux facing ceramic material. The required function for that FGM is only the heat removal. A leak tightness is not required for the graded region. When the residual thermal stress is severe, the FGM unit size can be reduced as possible as small. Even when a few units of all the FGM parts are peeled off or broken, the system accident is not necessarily caused. Therefore, a high reliability may not be necessarily required for that FGM. On the other hand, our aiming FGM is quite different from above mentioned FGM.

A schematic drawing of our aiming tubular FGM joint is shown in Fig.1. The material composition is gradually changed along the axis. The electric insulation ceramics are located at the central region and the pure metallic material is located at the both ends regions which are to be welded to the main pipes. Then the closed circuit loop can be eliminated by putting the insulation joint into the appropriate location of the piping system.

The FGM is produced through a sintering process of powder materials. Two kinds of sintering processes are considered. One is a hot press (HP) sintering method and the other is a hot isostatic press (HIP) method. Both processes are briefly shown in Fig.2. The advantages of HP method are

(i) Simple process
(ii) Since the radial deformation is restricted by the thick carbon mold, the axial non-uniformity of the initial powder packing ratio can be acceptable.

and the disadvantages are

(iii) It is difficult to sinter the complicated shaped FGM product because of the axial direction press.
(iv) Since thick and large carbon mold is needed, the size of sintering chamber is necessarily large. Therefore the FGM production cost by the HP method is relatively high.

On the other hand, the major advantage of HIP method is

(i) The complicated shaped and large sized FGM product is easily sintered without sintering defects because of the isostatic press.

and the disadvantages are

(ii) Complicated process

(iii) Since the isostatic press does not restrict the shape deformation in sintering process, the initial powder packing should be delicately carried out so that the final sintered shape becomes uniform along the axial direction. This difficulty comes from that the packing ratio depends on the particle size and the material properties.

In any case, it is a key issue to suppress the residual thermal stress generated in the sintering process. Major parameters of FGM, which have effects on the residual thermal stress, are the thickness of graded layer, the column diameter and the difference of thermal expansivity between the ceramics and the metallic materials. As the candidates of FGM constituent materials, a partially stabilized zirconia with 20wt%Al_2O_3 as the ceramics material, and an austenitic (Type 316) and ferritic (Type 430) stainless steels as the metallic material were offered for a design analysis, trial production and performance test. Because the partially stabilized zirconia with 20wt%Al_2O_3 itself has an excellent mechanical strength, high electric resistance and sintering compatibility with metallic materials, and Types 316 and 430 stainless steels are based on the candidate structural material of the fusion experimental reactor. The chemical composition of the partially stabilized zirconia with 20wt%Al_2O_3 is listed in Table 1.

3. FGM Producible Conditions and Trial Production

Here, as the basic and indispensable data for FGM design and production, the material properties of ceramic/metal homogeneously (not graded) composite sinter are described. Then the FGM design and production are discussed. The preliminary test results of the FGM trial production are briefly described.

3.1 Ceramic/metal Homogeneous Composite

The electrical resistance and mechanical strength were measured for several kinds of metal content of the ceramic/metal homogeneous composite.

Figure 3 shows the electrical resistivity of the homogeneous composite, where the ceramic material is the partially stabilized zirconia with 20wt%Al_2O_3 and the metallic material is the austenitic (Type 316) stainless steel. The measurement method is a quadrupole-terminal direct current method. The difference of the electrical resistivity between Types 316 and 430 is negligibly small. When the FGM is assumed to be 21-laminas structure with the thickness of 38 mm, its equivalent resistivity is evaluated to be $2.2 \times 10^2\ \Omega\,m$. This value is approximately 10^6 times as large as that of the stainless steel. From view point of the design requirement, it is sufficient that the FGM equivalent resistivity is $10^3 \sim 10^4$ times as large as the stainless steel. Therefore, it is possible to locate the metal content layer even in the FGM central region in order to increase the mechanical strength.

The residual thermal stress generated in the cool-down process from the FGM sintering temperature is a critical issue and has to be mitigated as low as possible. Prior to the residual thermal stress analysis, the flexural strength of the homogeneous composite was measured, as shown in Fig.4, by utilizing 3-points bending test at several kinds of temperature conditions, where the ceramic material is also the partially stabilized zirconia with 20wt%Al_2O_3 and the metallic material is also the austenitic (Type 316) stainless steel. Since test samples are made of the homogeneous composite material, the difference of thermal expansivity between Types 316 and 430 stainless steels does not have an effect on the flexural strength.

3.2 FGM Producible Conditions

Prior to the trial production, the residual thermal stress analysis was numerically carried out by using an axi-symmetrical shape model. The computer code named ABAQUS was offered for these calculations. The effects of differences in the thermal expansivity and in the thickness of graded layer were examined. The geometrical information is shown in Fig.5. As the FGM constituent materials, the partially stabilized zirconia with 20wt%Al_2O_3 as the ceramics material, and the austenitic (Type 316) and ferritic (Type 430) stainless steels as the metallic material were offered for the residual thermal stress analysis. The material properties, i.e. the thermal expansivity and elastic modulus, used for the calculation were measured for the ceramic/metal homogeneous composite.

Figure 6 shows the calculation results of the residual thermal stress distribution for Type 316 stainless steel and the graded layer thickness of 9.5 mm. The fracture stress marked by the open circles in this figure means the fracture strength of the homogeneous composite by utilizing the 3-points bending test at a room temperature condition. These open circles directly come from above mentioned Fig.4, because the axial position of Fig. 6 corresponds to a certain value of the stainless steel content for the homogeneous composite. Since the generated stress exceeds the fracture strength over the FGM central region of 6 mm, these parameters set might not be a producible condition.

Figure 7 shows the calculation results of the residual thermal stress distribution for Type 430 stainless steel and the graded layer thickness of 9.5 mm. It is obvious that the producibility is remarkably improved by using the lower thermal expansivity material, where the thermal expansivity of Type 430 is approximately half of that of Type 316. Since the generated stress is less than the fracture strength over the FGM region except 2 mm far location from the center, these parameters set might be marginal condition.

When a further improvement is required for mitigating the residual thermal stress, it is practical way to increase the thickness of the FGM graded region. Figures 8 and 9 show the calculation results of the residual thermal stress distribution for Type 430 stainless steel and the graded layer thickness of 19 mm and 38 mm, respectively. In comparison between Figs. 7, 8 and 9, the obtained residual strength increases from the marginal value, i. e. almost zero to 173 MPa further to 241 MPa by increasing the graded thickness from 9.5 mm to 19 mm and to 38 mm, respectively. Therefore, it can be indicated for later two cases to be sufficiently producible conditions.

3.3 Trial Production

First of all, the production method is the hot press (HP) sintering method as shown on the left side in Fig. 2, because of its simple process and easy sintering balance. The major aim of this trial production was to verify the producible condition mentioned above. Therefore, the production conditions were based on the above mentioned producible parameter study. The columnar FGM sample comprising the austenitic (Type 316), ferritic (Type 430) stainless steels and the partially stabilized zirconia with 20wt%Al_2O_3, whose diameter of 30 mm with 9.5 mm and 38 mm graded layer thickness, were tried. The result of producibility dependence on the thermal expansivity difference of metallic material and on the graded layer thickness, is summarized in Table 2. This result is explained well by the above mentioned producible parameter study. A successfully produced tubular FGM is exemplified in Fig. 10. A micro photograph of the graded region is shown in Fig.11, where no pore can be observed.

Secondary, the hot isostatic press (HIP) sintering method was tried as a clue to the large sized columnar FGM production which is addressed as a near future R&D activity. As mentioned in Section 2, the major technical issue of the HIP sintering method is how to obtain the uniform powder packing ratio along the axial direction in order to obtain the uniform radial shrinking. Since the radial deformation is not restricted in the sintering process and the shrinking ratio is different between the ceramics and metal, the diameter of the sintered columnar FGM does not become uniform. Figure 12 shows the HIP sintered FGM sample by using the same particle sizes as the HP method. Because of the larger shrinking ratio of the ceramics than the metal, the sample is broken near the mid plane. The initial packing ratio in the cold isostatic press (CIP) of 200 MPa was measured for the former particle sizes and summarized in Fig. 13 as a dependence of the stainless steel content. The average particle sizes of the ceramics and stainless steel are 3 μm and 5 μm, respectively. Figure 13 is, however, explained from that an amount of scatter in the particle shape and size is much larger for the stainless steel than for the ceramics. Regardless of the initial packing ratio, the final value of the sintered FGM is almost unity. Here, an improvement for the uniform packing ratio was realized by intermixing the larger sized ceramics particles into the former ceramics. The average size of larger one is approximately 13 μm. The initial packing ratios with the larger ceramics content of 40 % and 80 % into the former ceramics were measured as the dependence of the stainless steel content. The results are shown in Fig. 14. In case of 40 %, it is found that the difference of packing ratio in the axial direction can be suppressed less than 5 %. The columnar sintered FGM before and after a tubular machining are shown in Fig. 15.

4. Concluding Remarks

The integrated insulation pipe joint made of the functionally gradient material (FGM) has been successfully produced. The FGM composed of metal and ceramics is produced by a sintering process from the powder stainless steel and powder ZrO_2-Al_2O_3. It is a key issue to suppress the residual thermal stress generated in the sintering process. Major parameters of FGM, which have effects on the residual thermal stress, are the thickness of graded layer, the column diameter and the difference of thermal expansivity between the ceramics and the metallic materials. They have been quantitatively assessed by numerical calculations and several trial productions. Two kinds of sintering processes have been optimized. One is a hot press (HP) sintering method for small sized (at most 30 mm diameter) and high productivity, and the other is a hot isostatic press (HIP) method for large sized (50~100 mm diameter).

As a result, a FGM joint capable of providing high leak tightness without mechanical joint interface is available for electrical insulation of cooling pipes for vacuum use.

Acknowledgment

The authors would like to express their gratitude to E. Tada, Y. Matsuzaki and J. Fujioka for their valuable comments and stimulating discussions.

References

[1] ITER CONCEPTUAL DESIGN REPORT, IAEA, ITER DOCUMENT SERIES No.18 (1991)

[2] Proc. of 1st Int. Symp. on Functionally Gradient Material, at Sendai (1991)

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Table 1 Chemical composition of the partially stabilized zirconia with 20wt%Al_2O_3

chemical composition (wt-%)						
ZrO_2	Y_2O_3	Al_2O_3	SiO_2	Fe_2O_3	Na_2O	Ig·Loss
val.	3.91	20.30	0.004	0.004	0.019	0.97
crystallite size (Å)				250		
Specific surface area (m^2/g)				17.3		

Table 2 Producibility dependence on thermal expansivity difference of metallic material and on graded layer thickness

metal	graded layer thickness	result
SUS316	9.8 mm	severe crack nearby ceramics layer
SUS430	9.8 mm	slight crack nearby ceramics layer
SUS430	38.0 mm	no cracks

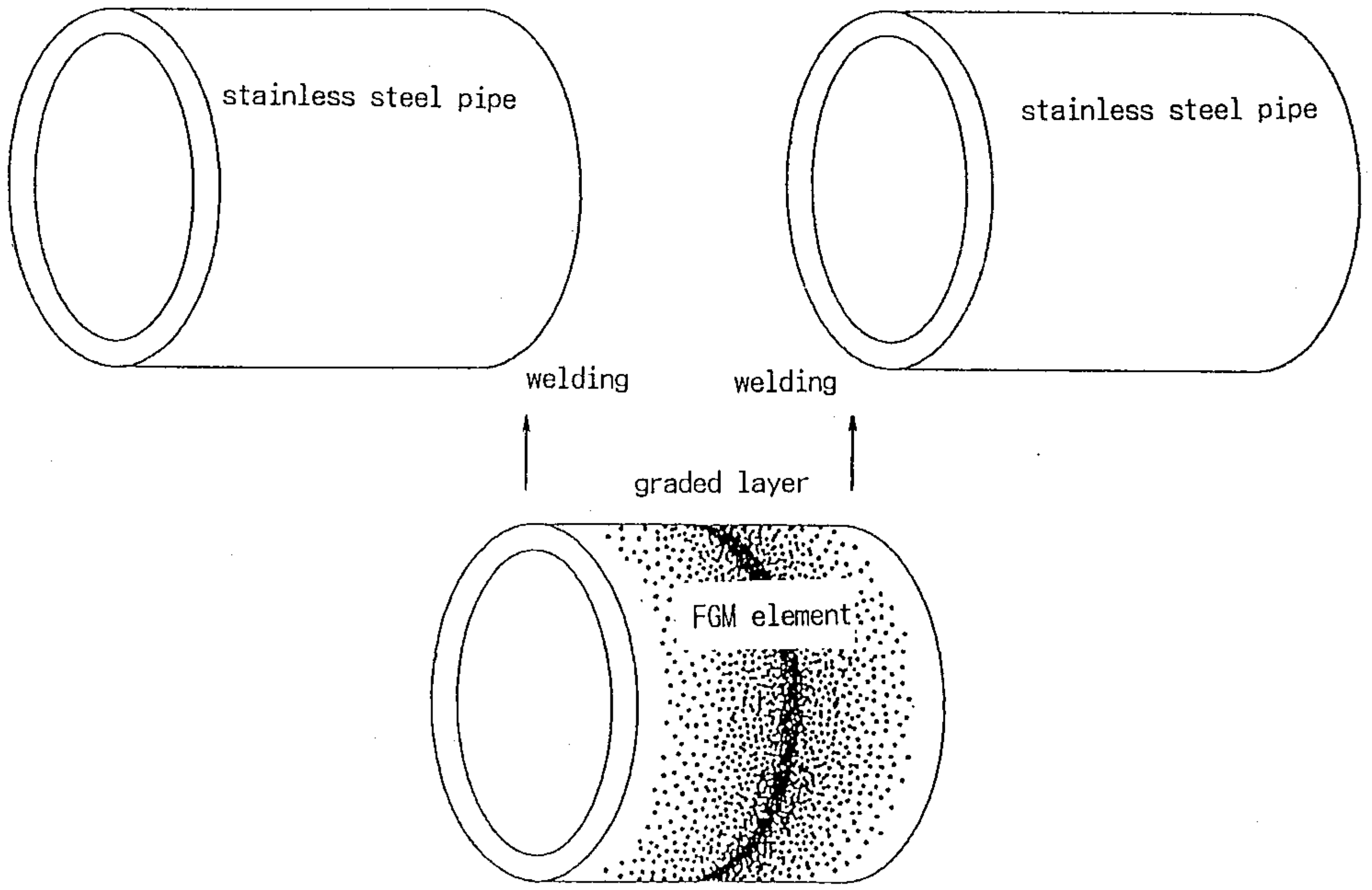


Fig. 1 Schematic view of FGM pipe joint

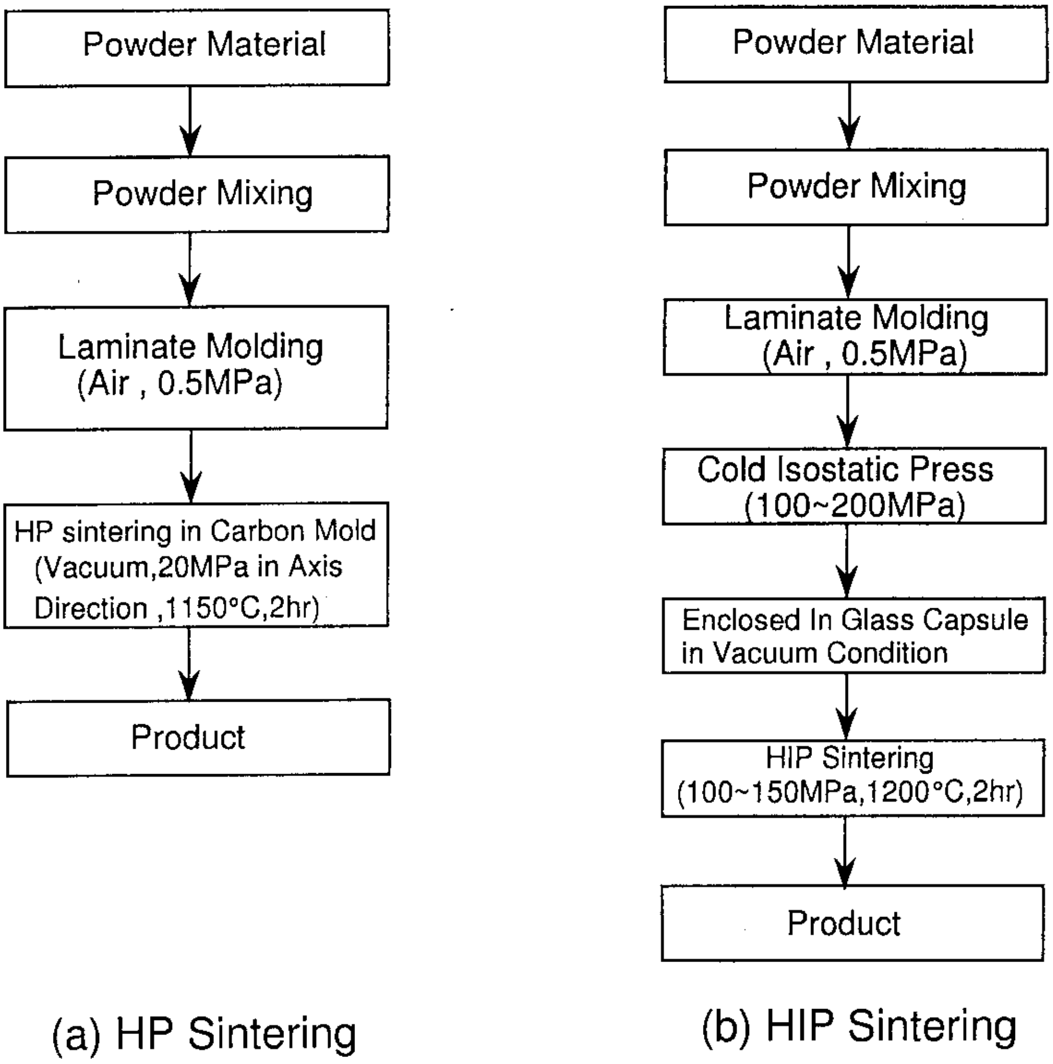


Fig. 2 Sequences of hot press (HP) and hot isostatic press (HIP) sintering methods

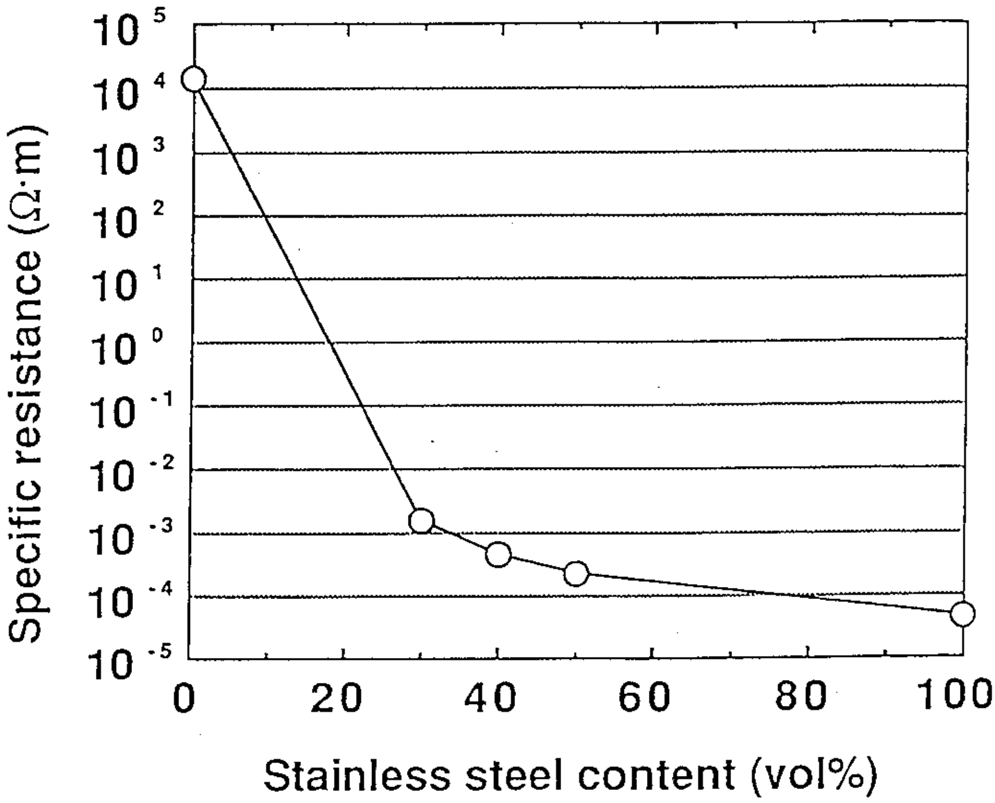


Fig. 3 Resistance dependence of ceramic／metal homogeneous composite on metal volumetric content

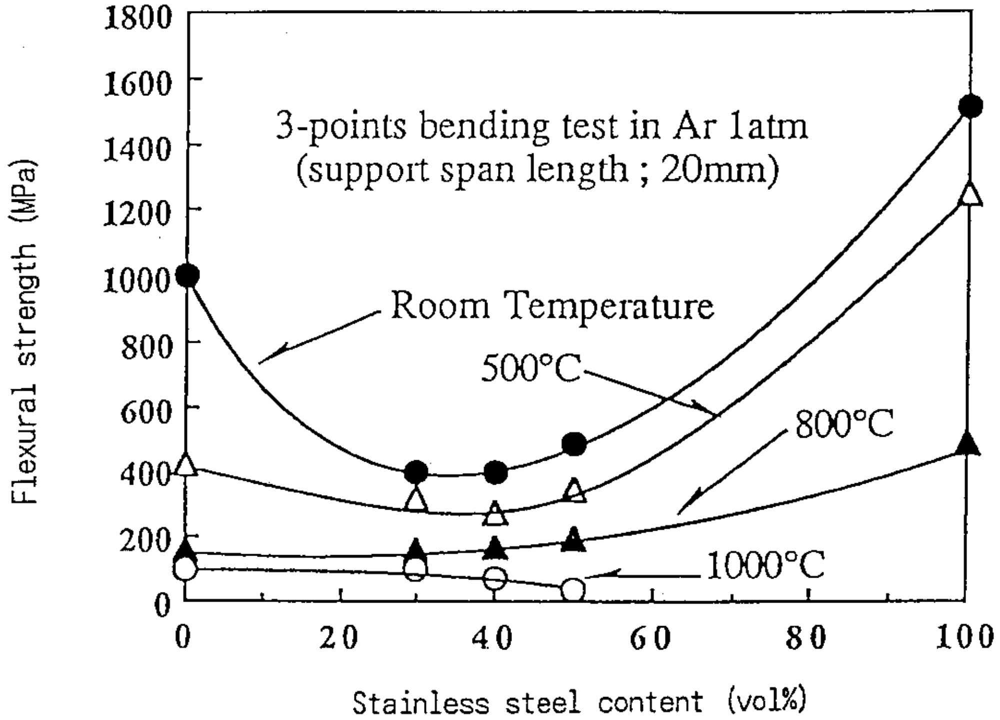
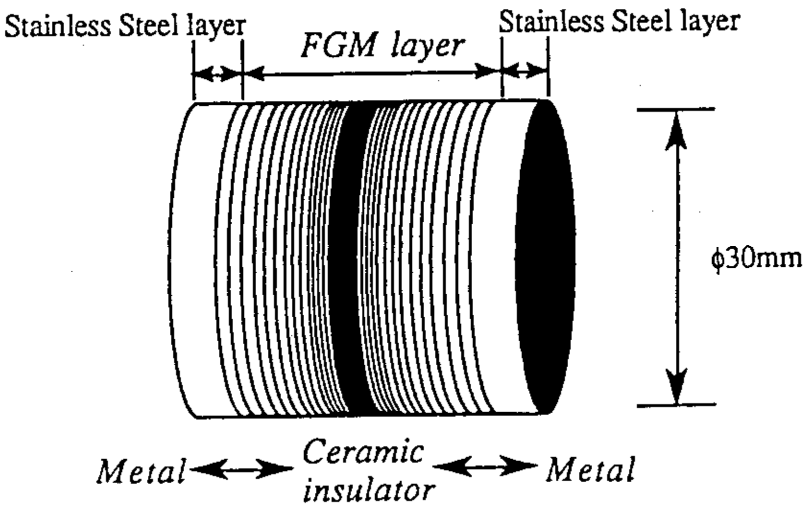


Fig. 4 Flexural strength dependence of ceramic／metal homogeneous composite on metal volumetric content and on test temperature



Analysis model

	Thickness	
	Stainless Steel	FGM layer
case 1	3mm	9.5mm
case 2	3mm	19.0mm
case 3	3mm	38.0mm

Fig. 5 Geometrical information for elastic stress analysis of FGM

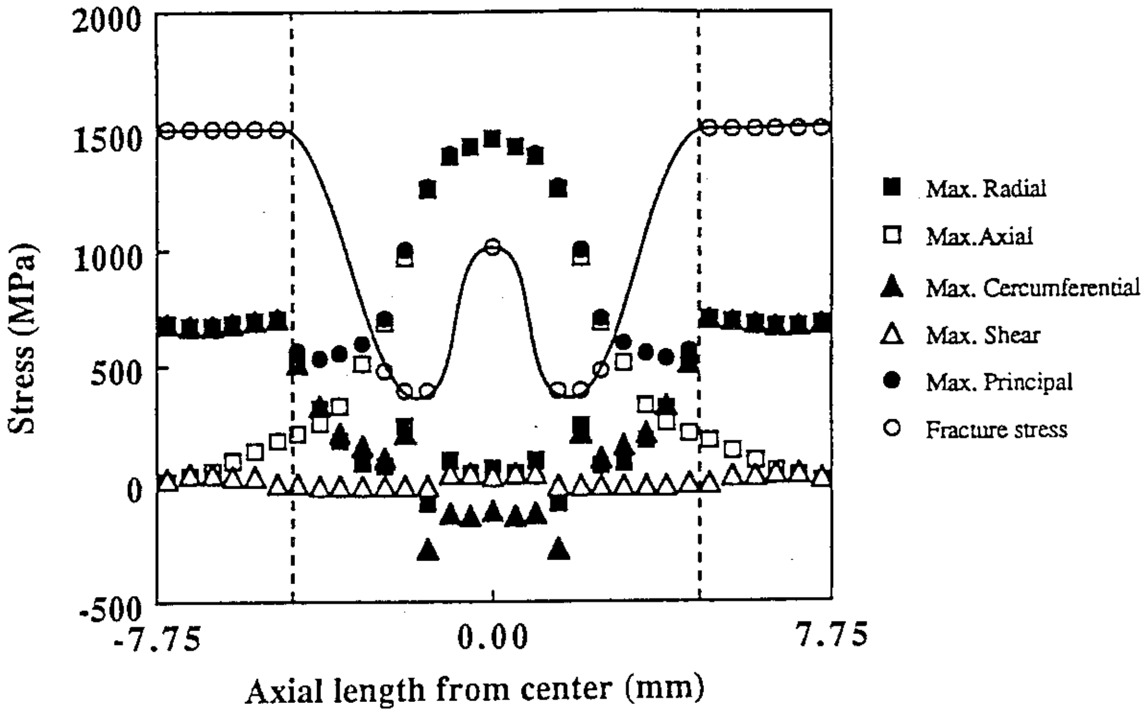


Fig.6 Profiles of thermal residual stresses in FGM after sintering with metal of Type 316 stainless steel, ceramics of partially stabilized zirconia with 20wt%Al_2O_3 and graded layer thickness of 9.5 mm

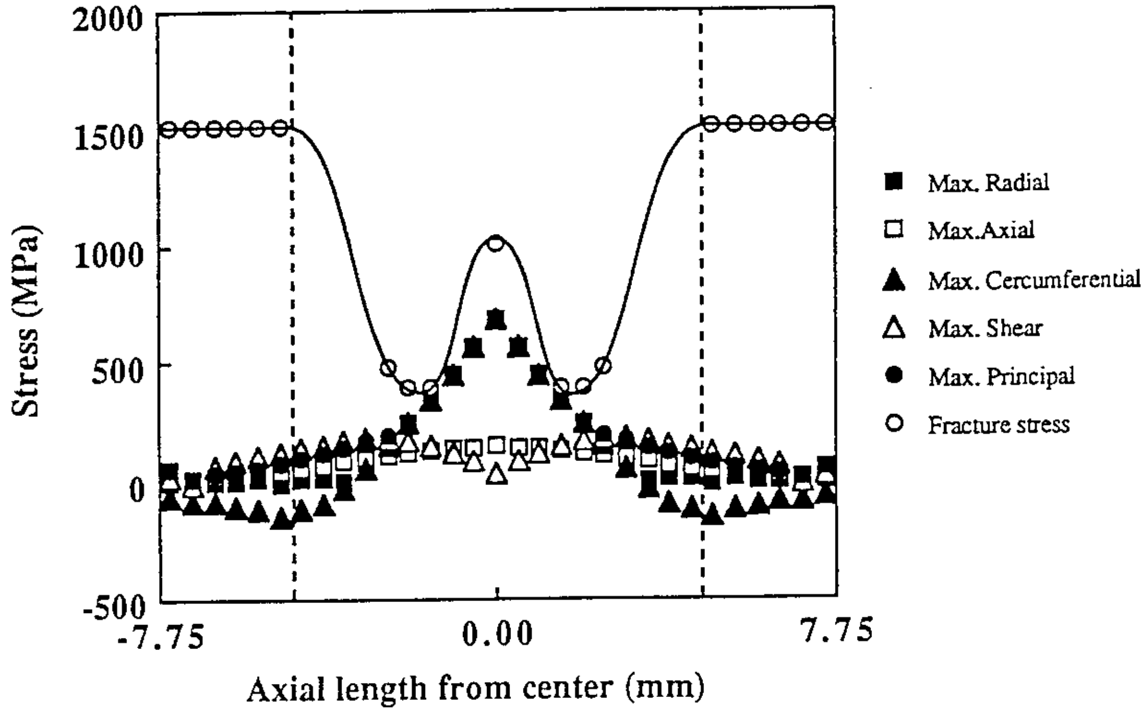


Fig.7 Profiles of thermal residual stresses in FGM after sintering with metal of Type 430 stainless steel, ceramics of partially stabilized zirconia with 20wt%Al_2O_3 and graded layer thickness of 9.5 mm

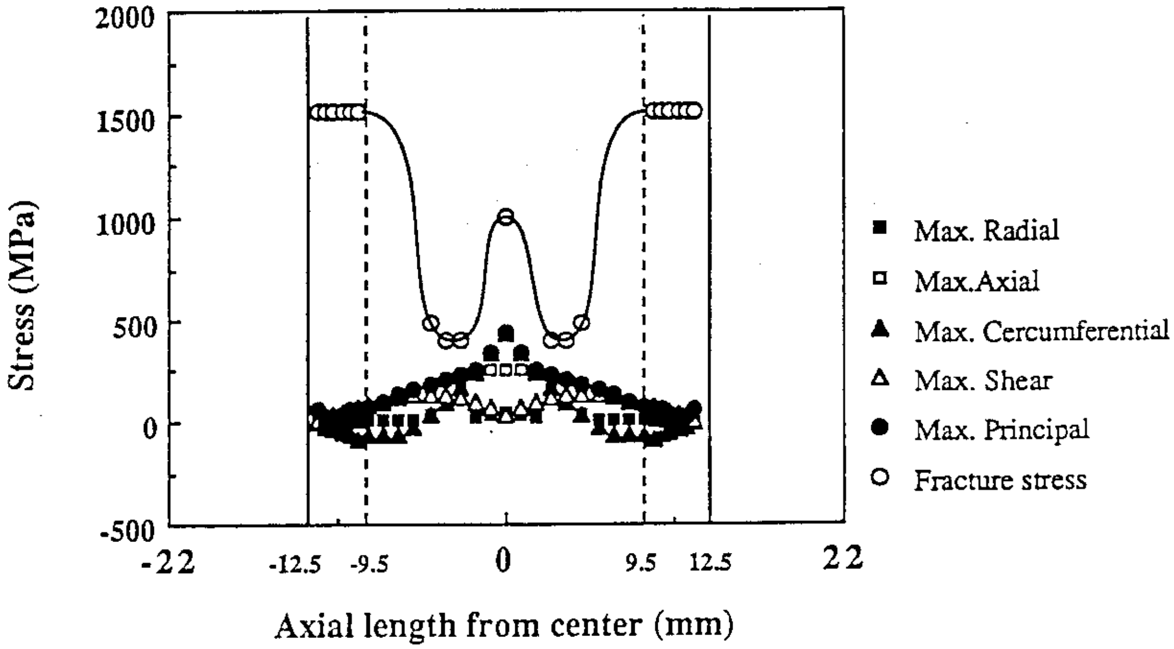


Fig.8 Profiles of thermal residual stresses in FGM after sintering with metal of Type 430 stainless steel, ceramics of partially stabilized zirconia with 20wt%Al_2O_3 and graded layer thickness of 19 mm

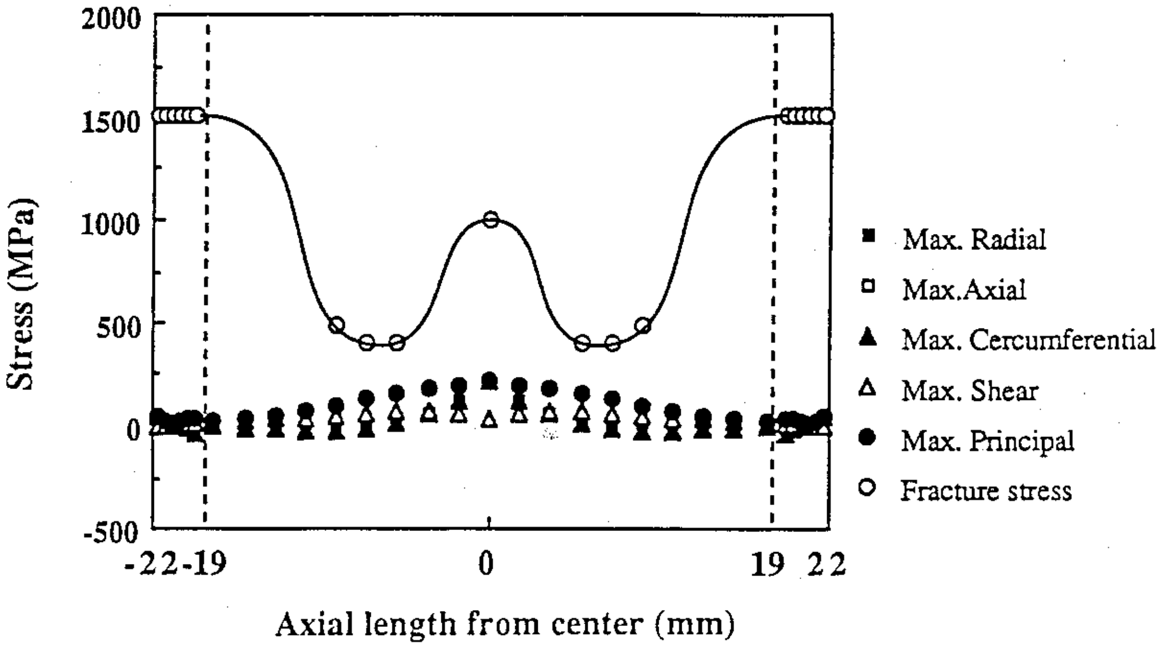


Fig.9 Profiles of thermal residual stresses in FGM after sintering with metal of Type 430 stainless steel, ceramics of partially stabilized zirconia with 20wt%Al_2O_3 and graded layer thickness of 38 mm

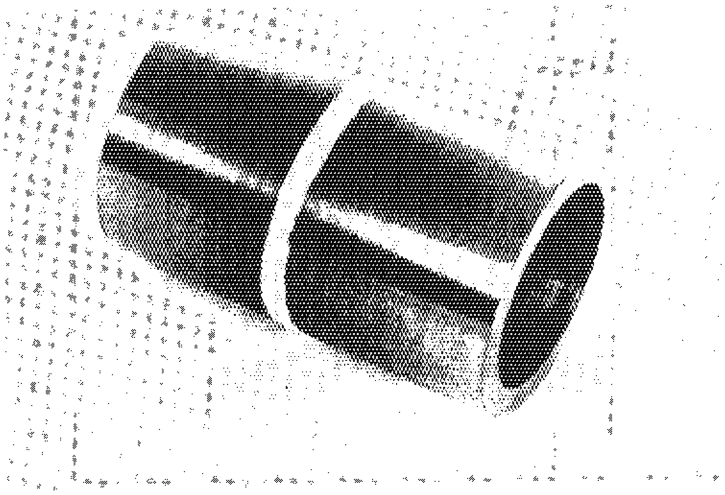


Fig. 10 Successfully produced tubular FGM with diameter of 30 mm

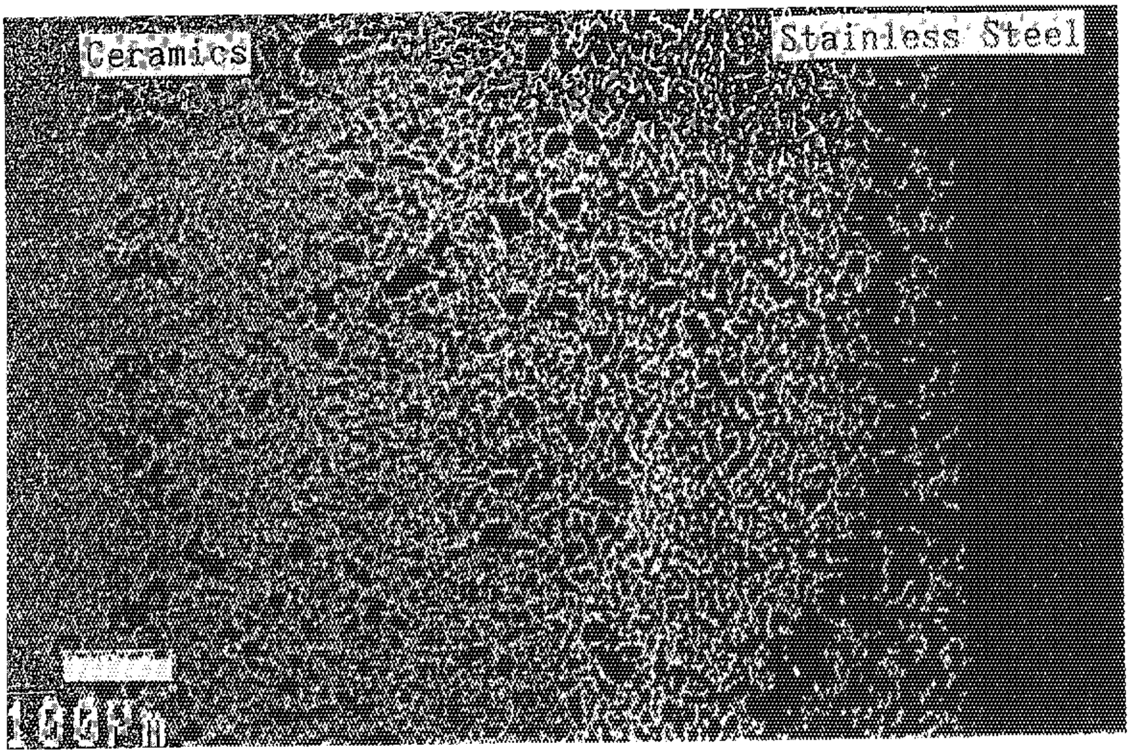


Fig. 11 Micro photograph of ceramic／metal graded region

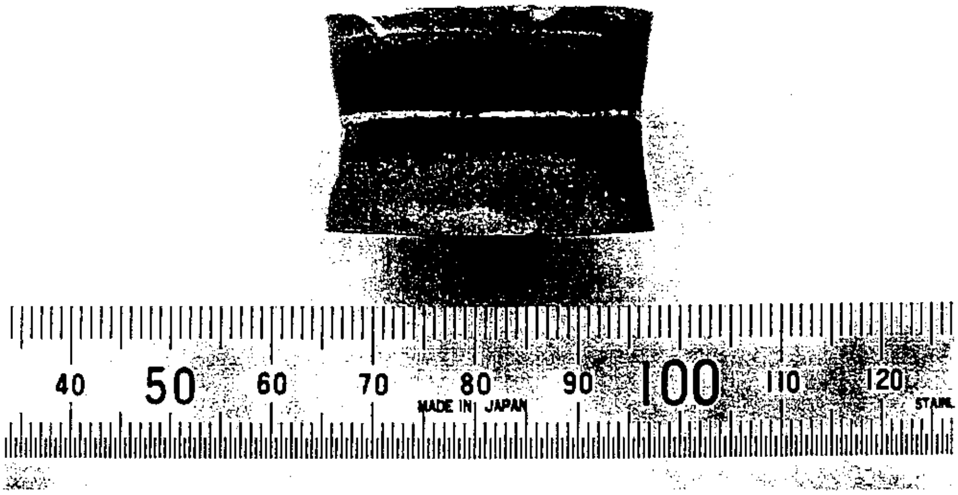


Fig. 12 Hot isostatic press (HIP) sintered FGM without any control of material particle size

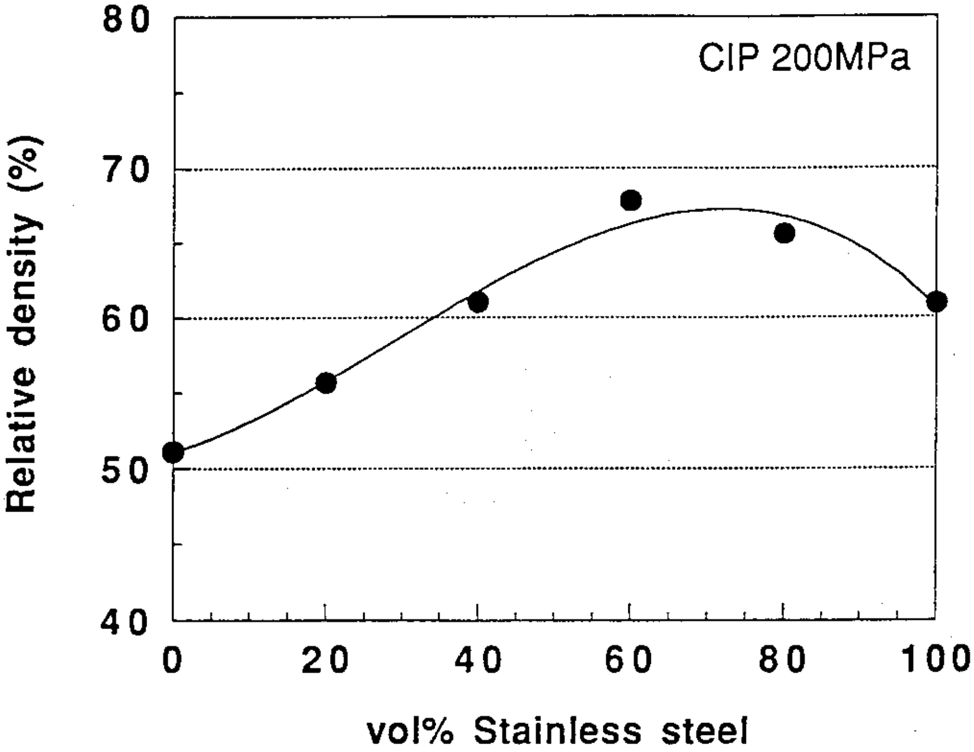


Fig. 13 Dependence of initial packing ratio (relative density) without particle size control on stainless steel volumetric content under cold isostatic press of 200 MPa

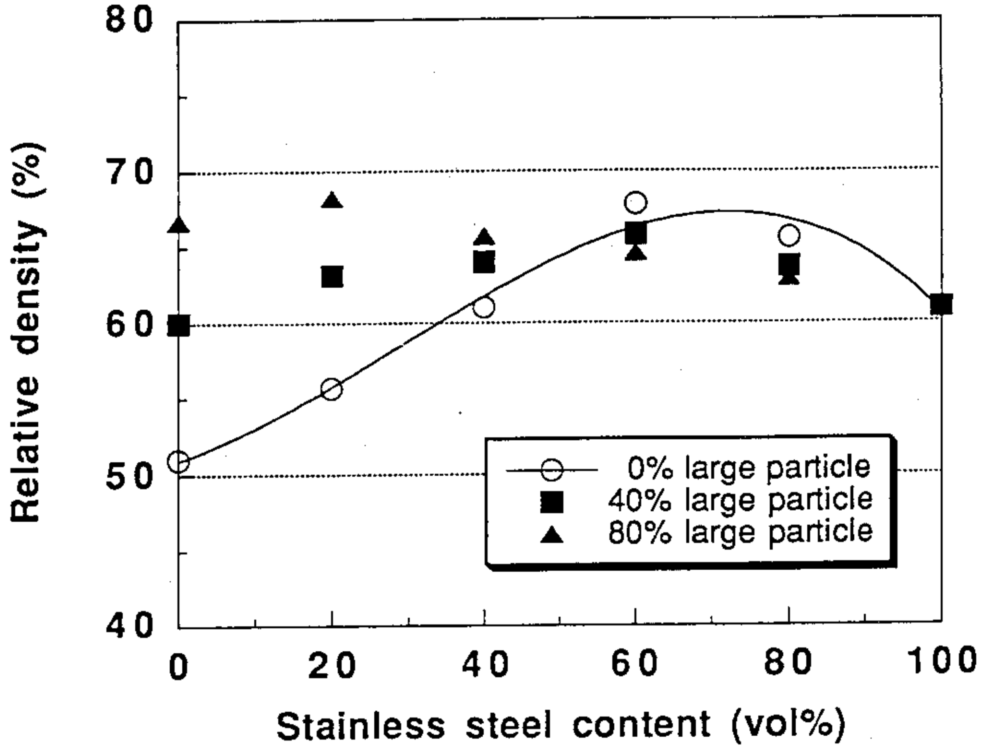


Fig. 14 Dependence of initial packing ratio (relative density) with larger ceramics content of 40 % and 80 % on stainless steel volumetric content under cold isostatic press of 200 MPa

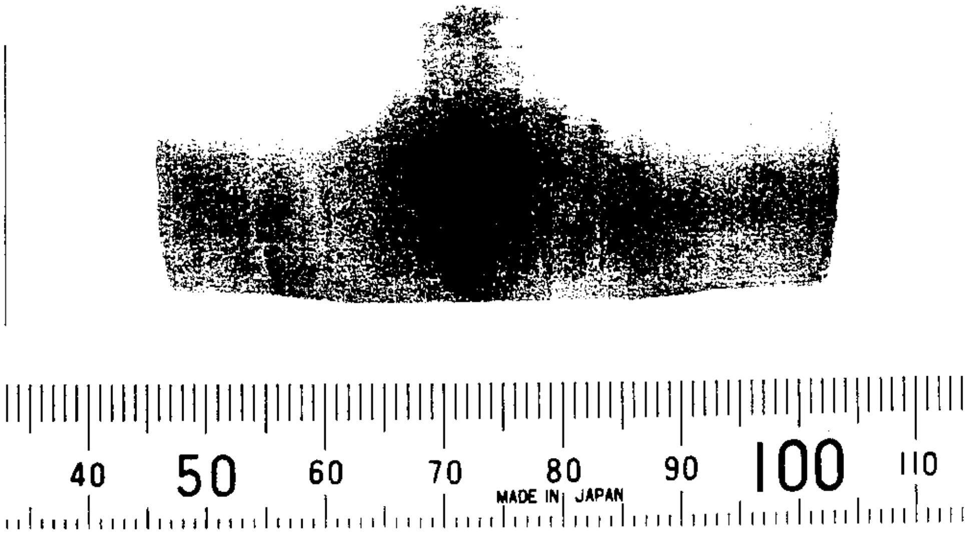


Fig. 15 Columnar HIP sintered FGM before and after tubular machining with optimization of particle size control