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Ceramics International 30 (2004) 75–80

CERAMICS INTERNATIONAL

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TEM observation of dynamic distortion in 2Y-PSZ/steel composites

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Received 15 January 2003; received in revised form 27 January 2003; accepted 25 February 2003

Abstract

2Y-PSZ/steel composites have been sintered by vacuum hot-pressing. The microstructure was studied by TEM after the composites were impacted at the average strain of 1.0×10^3 S^{-1} by split Hopkinson method. The results showed that the phase transformation from γ to α' occurred in the matrix of TRIP steel under dynamic loading. Dynamic mechanical properties of 2Y-PSZ/steel composites were improved because of the transformation of distortion induced Martensite. The morphology of Martensite induced by distortion was mainly twins. The sub-structure of Martensite was mainly twins. But there was no mid-ridge and distortion twins comptetely expanded to the whole Martensite. Moreover, there was dislocation Martensite at the same sample. The inhomogeneous spread of stress wave in 2Y-PSZ/steel composites led to the different dimension of twins Martensite. When dynamic distortion was relatively efficient, Martensitic dimension and twins distance were increased and the second twins would occur. ZrO_2 grains are finely distributed in matrix TRIP steel, which improved the dynamic flow stress of 2Y-PSZ/steel composites. Moreover, ZrO_2 could undergo tetragonal→monoclinic phase transformation, which would improve the dynamic yield strength of the composites. But when the content of ZrO_2 exceeded 20 vol.%, it would restrain the transformation of dynamic distortion induced Martensite in TRIP steel and led to the decrease of the dynamic mechanical properties of 2Y-PSZ/steel composites.

Keywords: B. Microstructure; Matensite transformation; Dynamic strength; 2Y-PSZ/steel composite

1. Introduction

Steel matrix composites strengthened by ceramic particles have the advantages of both ceramics and steel and have low cost. In recent years, much more research interest has been focused on the non-ferrous metal matrix composites as defensive materials [1–3]. The mechanical properties of 2Y-PSZ/steel composites under dynamic loading are better than that for the pure ceramic or for the pure non-ferrous alloy. ZrO_2 has advantages of high strength, high hardness, and high wear resistance as well as good chemical compatibility with steels. Especially, transformation from t to m phase induced by stress is the main mean to improve the toughness of ceramics [4–6]. Martensitic transformation in TRIP steels (TRansformation Induced Plastic steels) can improve not only materials strength, but also distortion ability to a greater degree because of plasticity induced by transformation [7–9]. In the past, there is few report on mechanical properties of ZrO_2 ceramics and TRIP steels. In fact, mechanical properties of the materials result from their microstructure. So it is necessary to thoroughly investigate microstructure of the materials. It has important theoretical significances and engineering application values on understanding its destroying mechanisms under dynamic loading and dynamic mechanical properties and thereby to improve protective properties of the materials.

2. Experimental

ZrO_2+2 mol% Y_2O_3 powder (2Y-PSZ) with the average grain size of about 0.65 μm was purchased from China Institute of Architecture Materials. The spherical powder of TRIP steel with the average grain size of 40 μm was obtained by gas (N_2) sputtering method. The chemical composition is shown in Table 1.

2Y-PSZ and TRIP steel powders were mixed by ball milling for 30 h. Then the mixtures were hot pressed in vacuum. The sintering parameters are 1250 °C/1.3×10^3Torr/20 MPa/30 min with axial loading. The fracture properties were tested by Split Hopkinson

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doi:10.1016/S0272-8842(03)00065-8

Table 1
Chemical compositions of TRIP steel powders

Compositions	C	Cr	Mn	Ni	Mo	Si	Other
Content (wt.%)	<0.18	8.5	1.1	4.5	3.7	1.7	Fe

Pressure Bar method. We cut thin samples along impact surface after dynamic distortion at the average strain rate of 2.5×10^{2} s^{-1} and then ground them. Microstructure of 2Y-PSZ/steel composites was observed in Phillips CMH2 TEM with accelerating voltage of 120 kV. The morphology of fracture section was observed in Hitachi-570 SEM.

3. Results and discussion

3.1. Dynamic mechanical properties

Partial mechanical properties of 2Y-PSZ/steel composites were shown in Table 2. It was obvious that unloading strain and dynamic yield strength improved with the increase of ZrO_2 content. When the content of ZrO_2 exceeded 20 vol.%, they began to drop. The hardness value of 2Y-PSZ/steel composites was significantly increased after dynamic loading seeing from the hardness value before and after dynamic loading.

3.2. TEM observation

Fig. 1 shows a TEM photograph of ZrO_2 in 2Y-PSZ/steel composites. It can be seen that most ZrO_2 grains, which distributed in the matrix TRIP steel and was sintered at 1250 °C, did not grow up. So dynamic flow stress and dynamic yield strength of 2Y-PSZ/steel composites improved. However, when the content of ZrO_2 exceeded 20 vol.%, not only distortion ability decreased, but also combination strength between ZrO_2 grains dropped. Microcracks were easily produced under dynamic loading (referring to Fig. 2). Moreover, ZrO_2 grain with the size above the critical value was also observed in local area, which produced transformation from tetragonal phase to monoclinic phase under dynamic loading as shown in Fig. 3. There is no doubt that the t–m phase transformation of ZrO_2 had great contribution to improve the dynamic strength of 2Y-PSZ/steel composites. Fig. 4 showed the XRD profiles of 20 vol.% 2Y-PSZ/steel composites before and after dynamic loading. The TRIP steel matrix consisted almost of Austenite before dynamic loading as indicated by $(111)_{\gamma}$ peak of γ phase in Fig. 4a. $(110)_{abm5}$ Peak of Martensite and $(111)_{\gamma}$ peak of Austenite were evidently separated in Fig. 4b. It was obvious that the TRIP steel matrix had undergo transformation from γ to α' phase under dynamic loading. The relative content of Martensite was deduced as

$$M\% = \frac{I_{(110)_{\alpha'}}}{I_{(111)\gamma} + I_{(110)\alpha'}} \times 100\% = \frac{132}{132+93} \times 100\% = 58.67\%$$

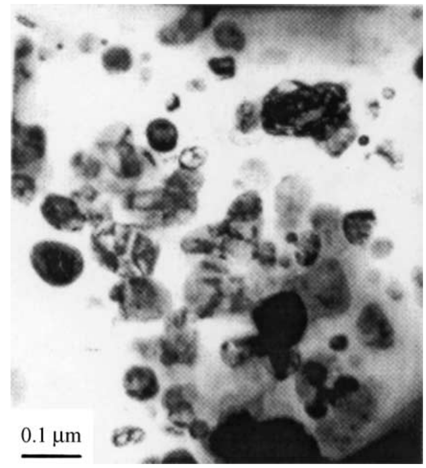

Fig. 1. TEM photograph of ZrO_2 distributed in 2Y-PSZ/steel composites.

Table 2
Mechanical properties of 2Y-PSZ/steel composites under dynamic loading

Sample	Unloading strain[a] (%)	Dynamic Strength (MPa)	Vickers hardness (MPa)	
			Before impact	After impact
TRIP steel + 10 vol.% ZrO_2	0.08	900	374.92	657.52
TRIP steel + 15 vol.% ZrO_2	0.12	1100	524.55	732.67
TRIP steel + 20 vol.% ZrO_2	0.13	1400	579.48	760.68
TRIP steel + 25 vol.% ZrO_2	0.11	1000	591.23	765.13
TRIP steel + 30 vol.% ZrO_2	0.10	800	610.11	769.41
TRIP steel + 35 vol.% ZrO_2	0.09	600	622.74	775.63

[a] Unloading strain referred to the strain after dynamic loading being loaded in this table.

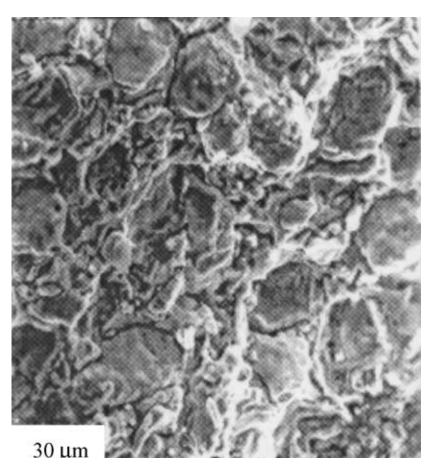

Fig. 2. Photograph of ZrO_2 2Y-PSZ/steel composites' fracture.

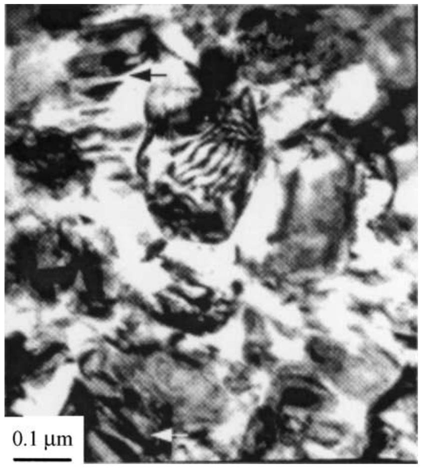

Fig. 3. TEM Photograph of m-ZrO_2.

Martensitic transformation improved not only dynamic yield strength, but also strain of transformation induced plasticity and hardness of 2Y-PSZ/steel composites. So dynamic mechanical properties of 2Y-PSZ/steel composites depended on the transformation of distortion induced Martensite in TRIP steel matrix. Wave resistance ρC (ρ is density and C is wave velocity) between ZrO_2 and TRIP was different. Spread speed of strain wave in ZrO_2 and TRIP steel was different. The spread speed of elastic strain wave is $C_e = \sqrt{\frac{E}{\rho_0}}$ and the plastic one $C_p = \sqrt{\frac{1}{\rho_0}\frac{d\sigma}{d\varepsilon}}$. All these led to the inhomogeneous distortion in 2Y-PSZ/steel composites, which started in softer TRIP steel matrix under dynamic loading. TEM photographs in Fig. 5 showed the distribution of distortion induced Martensite in TRIP steel matrix. Fig. 5a was an acicular twins. Martensite surrounded by Austenite, which stopped growing up because of the resistance of frontal dislocations. Fig. 5b showed the $[\bar{1}11]$ electron diffraction pattern of the Martensite in Fig. 5a. The following conclusion could be deduced from Fig. 5. The interface was straight between Martensite and Austenite with no mid-ridge and small quantities of dislocations. The interior sub-structure was mainly distortion twins due to Martensitic distortion. The distortion in twins was superfine. Twins produced high-tension dislocations with former Austenite and mechanical stability and then restrained the growth of Martensite. So the Martensite only grew up in the direction of length. Fig. 6 showed Martensite produced in the interface between ZrO_2 and TRIP steel matrix, which hadn't grown up enough because of the restriction of ZrO_2 in the process of distortion. The size of Martensite was very small and the interior sub-structure could not be distinguished. So the increase of ZrO_2 content would prevent the distortion of 2Y-PSZ/steel composites, restrain the formation of distortion induced Martensite and then lead to the decrease of dynamic mechanical properties. This could be explained in Table 2 by the decrease of both dynamic yield strength and unloading strain when the content of ZrO_2 exceeded 20 vol.%. Fig. 7 was twins Martensite in TRIP steel matrix. Because distribution was relatively more efficient, Martensite dimension was also bigger compared with Fig. 6.

3.3. Second twins

Fig. 8a showed the Martensite induced by distortion, which nucleated and grew up in Austenite interface. Fig. 8b gave the electron diffraction pattern of zone axis

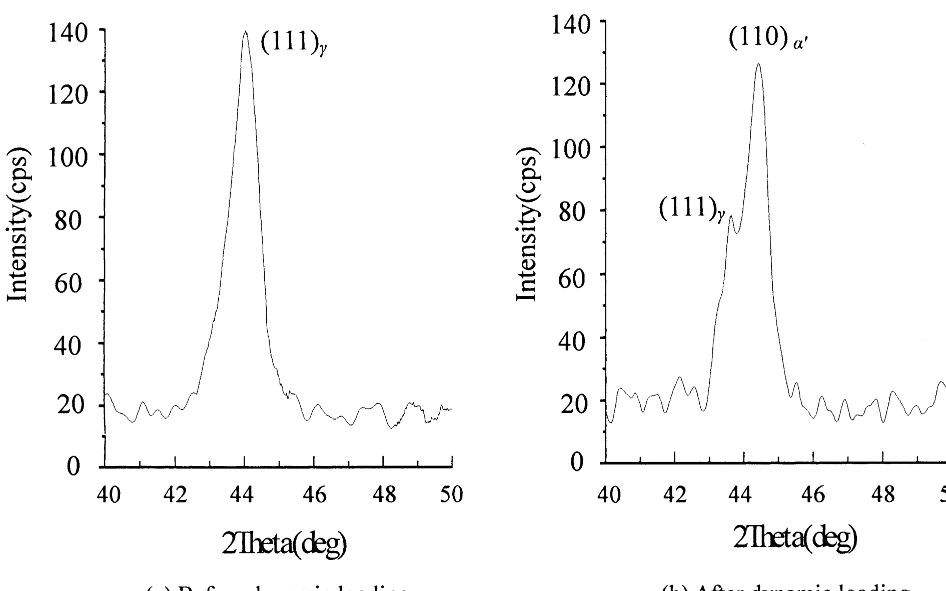

Fig. 4. XRD patterns of 2Y-PSZ/steel composites before and after dynamic loading (20 vol.% ZrO_2).

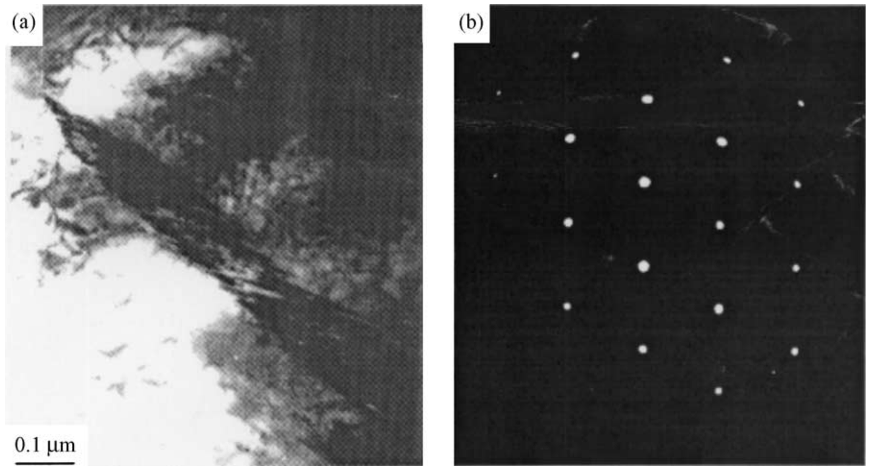

Fig. 5. TEM photographs of dynamic distortion induced Martensite in TRIP steel.

[$\bar{1}$13] of the Martensite in Fig. 8a. Distortion twins expanded to the whole Martensite completely, every twin sub-structure arranged parallell and twins distance was evident bigger than that in Fig. 5a. Second twins could be observed in twins, which could be seen from the obvious difference of twins contrast indicated by arrow in Fig. 5a and second twins distance obviously became narrow. All these showed that shear growth of distortion induced Martensite had a close relationship with the action of stress wave. Every stress wave induced action made Martensite grow up to some extent and the corresponding twins distance was different. Second twins led to the change of Martensitic twins orientation, which was further in favor of the growth of Martensite and the plastic distortion. So the distortion in Fig. 8a was more efficient and the contribution to the plastic distortion of 2Y-PSZ/steel composites was greater. Furthermore, there were a lot of dislocations in the region of non-twins and the interface between α' and γ phases. We deduced that the procedure of Martensitic growth might be divided into two stages. Firstly, inhomogeneous shear derived from twins. Transformation produced heat and made the temperature raised to a high lever in small local areas. In the second stage, slip occurred and formed dislocations [10]. As for dislocations produced at the interface between α' and γ phases, twins distortion led to the generation of a larger cutting strain in its surrounding matrix and to the plastic distortion in the neighboring TRIP steel Austenite matrix. The parallel strip Martensite could be observed in TRIP steel matrix, shown in Fig. 9. The characteristic of the sub-structure was high dislocation density. Dislocations might be produced by Austenitic plasticity in TRIP steel matrix under the action of stress wave and transmitted to Martensite or from α' to γ phase. In any condition, the TRIP steel matrix could produce plastic distortion and gave much contribution to the plastic distortion of 2Y-PSZ/steel composites under dynamic loading. Therefore, dynamic plasticity of 2Y-PSZ/steel composites was mainly due to the contribution of Martensitic transformation induced plasticity in TRIP steel matrix. The distortion was mainly in twins style and there was

Fig. 6. TEM photograph of distortion induced Martensite in the interface.

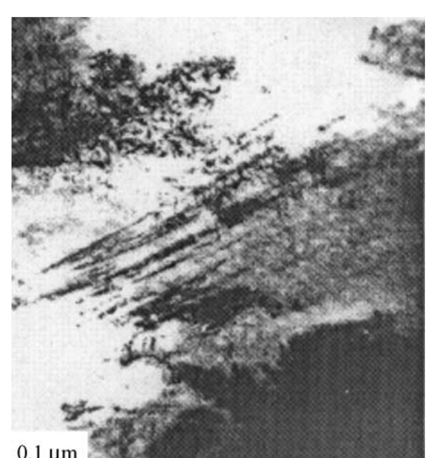

Fig. 7. TEM photograph of twin Martensite in TRIP steel.

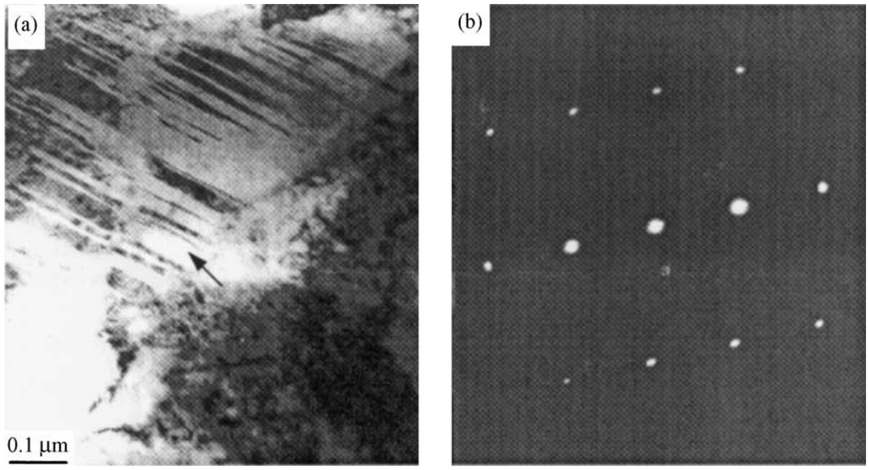

Fig. 8. TEM photographs of second twin Martensite in TRIP steel.

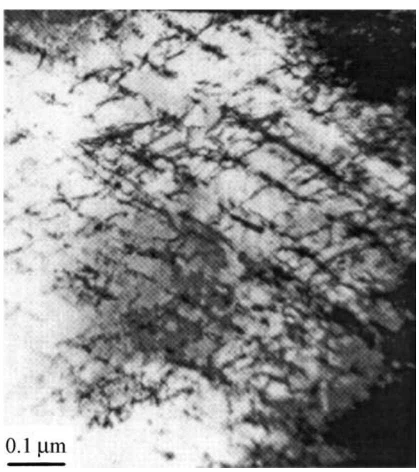

Fig. 9. TEM photograph of strip Martensites.

no explosion transformation style from γ to α' phase. In a word, the morphology of the Martensite in TRIP steel matrix under dynamic loading consisted of both lathy dislocation Martensite and lamellate twins Martensite, which contrasted clearly from the transformation Martensite under the condition of common cooling. This showed that the mechanisms of transformation had a great distinction under these two conditions. This might be derived from the different contents of Cr and Ni in local Austenites, which changed the M_s point, or from the difference of local slippage or twins' critical cutting stress because of inhomogeneous transmission of the stress wave. This resulted in the special morphology of Martensite induced by dynamic distortion. Further detailed study is underway.

4. Conclusions

1. Dynamic mechanical properties of 2Y-PSZ/steel composites depended on Martensitic transformation in TRIP steel matrix. The dynamic yield strength, transformation induced plastic distortion as well as Vickers hardness was improved with Martensitic transformation.
2. There are two kinds of morphology of Martensite induced by distortion under dynamic loading in TRIP steel matrix. One was lathy Martensite with the sub-structure of dislocation, the other was acicular or lamellate Martensite with no mid-ridge and the sub-structure mainly of deformation twins. When dynamic distortion was relatively efficient, both the dimension of Martensite and twins distance increased.
3. Cutting growth of Martensite induced by dynamic distortion had a close relationship with stress wave. Each induced effect of stress wave generated growth to a different extent and the corresponding second twins distance was different too. Second twins resulted in twins orientation of Martensitic growth to cause changes and this was in favor of the progress of plastic distortion.
4. The inhomogeneous transmission of dynamic stress wave resulted in the inhomogeneous distortion in 2Y-PSZ/steel composites. The main distortion style was twins. There were no dislocation in the region of non-twins and the interface between α' and γ phases.

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