Vol. 6 № 4 Trans. Nonferrous Met. Soc. China Dec. 1996

# DETERMINATION OF MECHANICAL PROPERTIES IN MICROZONE OF METAL MATRIX COMPOSTITES BY ULTRAMICROHARDNESS①

Chen Yu, Zhang Guoding
*State Key Lab of MMCs, Shanghai Jiao Tong University, Shanghai 200030*

**ABSTRACT** Ultramicrohardness technique has been used to test the mechanical properties in the microzone of metal matrix composites. It is found that the ultramicrohardness can effectively reflect the variation of mechanical properties at the interface and the mechanical properties distribute unevenly in its microzone. It was also found that the mechanical properties in the microzone, as well as the macroscopic properties, are influenced by the distribution of fibers, the manufacture process and the heat treatment.

**Key words** ultramicrohardness interface metal matrix composites residual stress

## 1 INTRODUCTION

Metal matrix composite (MMCs) is a kind of newly developed high- technological material. As an important branch of advanced composite, the MMCs has outstanding properties in many aspects and it has been paid great attention to and applied in many fields[1]. But the mechanical properties of the matrix metal near the interface change because the properties of the reinforcement differ from those of the matrix. The difference of the thermal expansion coefficient is so great between the reinforcement and matrix that the residual stress distributes unevenly in the interface microzone, which plays a key role in fracture processes and the mechanical properties of the composite. Therefore, the research and measurement of the mechanical properties and their uneven distribution become an important part of the research for the MMCs' interface and fracture.

When the interface bonding is good, there is dislocation at the interface resulting from the difference of thermal expansion coefficients between the reinforcement and matrix. The amount of residual stress is related to the density and twist status of the dislocation[2]. Because the MMCs are opaque, the residual stress is measured by $\sin^2 \Psi$ method of X-ray diffraction. But it is quite difficult to know the exact stress at the interface field because of the complexity of the composite interface. Ultramicrohardness is believed to be an indirect way to measure the mechanical properties in the microzone of MMCs' interface.

Hardness is a comprehensive index of mechanical properties and has an intimate relation with tensile fatigue strength[3] and distributes in the same trend as the stress field does[4]. Hardness can be tested easily and directly. The ultramicrohardness, with extremely low loads and small indentation, can measure the hardness in a microzone effectively. Therefore, the ultramicrohardness is an indirect index of the mechanical properties at the interface of MMCs.

The ultramicrohardness test carried out in this research was on the specimen made of aluminum reinforced graphite fiber composite (Gr/Al). The main purpose was to measure the ultramicrohardness in different microzones of the composite and realized the regulation of the me-

---

① Sponsored by the National Natural Science Foundation of China(Registration No. 59471011)
Received Oct. 29, 1995; accepted Jan. 26, 1996

chanical properties distributed in the Gr/Al. Also, the influence of manufacture process and heat treatment on the relationship between the stress distribution and the macroscopic properties of composite was studied.

## 2 EXPERIMENTAL

### 2.1 Ultramicrohardness tester

UMHT-3 ultramicrohardness tester and PHILIPS-SEM 515 scanning electron microscope was used to measure the ultramicrohardness. UMHT-3, with a four-side diamond pyramid (plane angle 136°) as the indenter, had the testing load ranging from $5\times10^{-5}$ to $2\times10^{-2}$ N. Load resolution was $1\times10^{-5}$ N and the local resolution of the indentation was 1μm when using SEM.

The technical parameter used in this research is shown in Table 1.

**Table 1 Technical parameters of UMHT-3**

| Test load/ mN | Descent speed/ μm·s$^{-1}$ | Indentation speed/ mN·s$^{-1}$ | Time under load/ s |
|---|---|---|---|
| 5 | 25 | 0.25 | 15 |

### 2.2 Composites

The specimens were made of aluminum reinforced by P-55 graphite fiber, which were made by vacuum pressure infiltration[5]. The matrix alloys, manufacture parameter and mechanical properties of the composite are shown in Table 2.

**Table 2 Manufacture parameters and mechanical properties of Gr/Al**

| Specimen No. | Matrix Alloy | Temperature of Molten Metal/ ℃ | Temperature of Preform / ℃ | Tensile Strength / MPa |
|---|---|---|---|---|
| 1 | 1100-Al | 700 | 610 | 262 |
| 2 | Al-0.34%Ti | 725 | 611 | 529 |
| 3 | Al-0.34%Ti | 717 | 642 | 390 |

Some of specimens were treated with thermal cycling three times. The temperature was 150 ℃ to -196 ℃, cooling rate was 20 ℃/s.

Metallographical samples were polished and the fiber axes of the samples were orientated vertical to the section. After that the ultramicrohardness was tested and analyzed. The indentations are shown in Fig. 1.

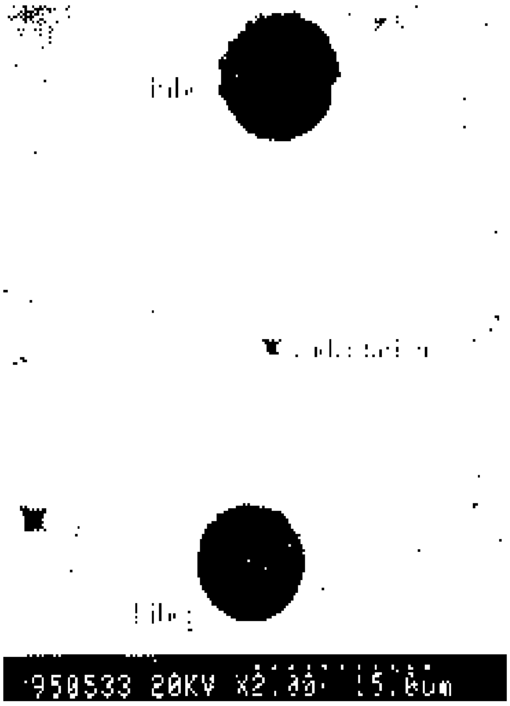


**Fig. 1 Indentations of ultramicrohardness**

## 3 RESULTS AND DISCUSSION

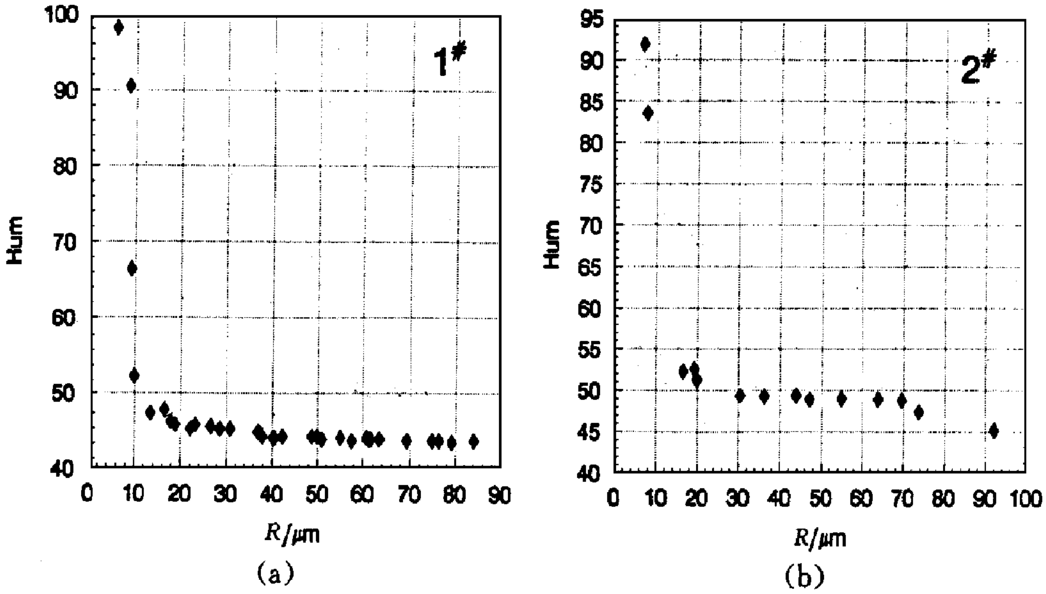
### 3.1 Mechanical properties in microzone of MMCs

#### 3.1.1 Hardness distribution around one single fiber

The hardness distributon around one single fiber of sample 1 and 2 is presented in Fig. 2 (a) and (b) respectively. It is found that the hardness of matrix close to fiber is maximum. When the distance $R$ between the test point and the center of the fiber increases, the hardness decreases. When $R$ is coming to 2 or 3 times of the fiber diameter, i. e. 20~30μm, the change of the hardness slows down. The hardness becomes stationary when the testing points are far away from the fiber. The values are equal to the hardness of alloys which is without stress application. Thus, the distribution of mechanical properties in the interface microzone of MMCs is uneven and the effective distance is about 2 or 3 times of the fiber diameter.

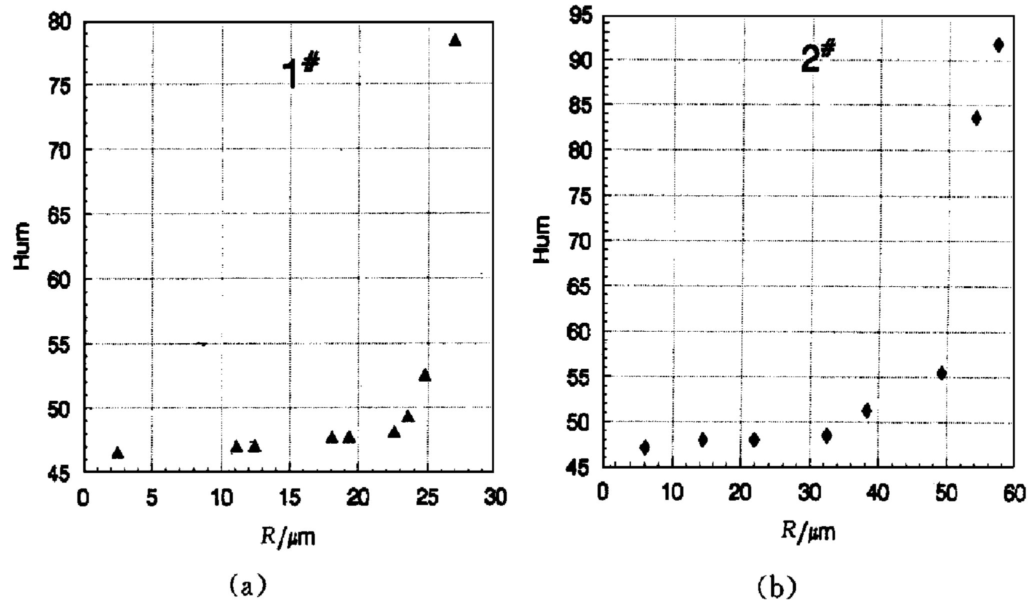
#### 3.1.2 Hardness distributed between two fibers

The results in Fig. 3 indicate the hardness



(a) (b)

**Fig. 2** Hardness distributed around one single fiber



(a) (b)

**Fig. 3** Hardness distributed between two fibers
( *R* represents the distance from the medium point of two fiber)

of the matrix between two fibers. The distance between fibers in Fig. 3(a) is 70 μm and in Fig. 3 (b) is 117 μm. It is found that at the medium point of the line connecting the center of two fibers, the hardness is the lowest. When the distance between the test point and the fiber decreases, the hardness incereases. The hardness changes more violently when the test points move nearer to the interface.

Also when the distance between two fibers changes, the hardness at the medium point is different. In Fig. 4 it is found that the smaller the distance becomes, the larger the hardness is. It is resulted from the interacton of the uneven distribution of the mechanical properties around two fibers.

The distribution of the fibers in the matrix has a great influence on the mechanical performance of the interface microzone. It is not possible to make the distribution of fibers in MMCs thoroughly even. The unevenly distributed mechanical properties in the microzone will affect the macroscopic properties of the composite. As the distance between fibers decreases, the residual stresses in the matrix increase continuously. When the residual stresses are large enough in some areas, the fracture happens first at these areas after applying external loads. At this time the load is much lower than the composite strength and the whole material breaks under low stresses. Hybridization technique is used to make the distance of fibers larger, the uneven distribution in the microzone can be lessened and the probability of low-stress-fracture becomes smaller.

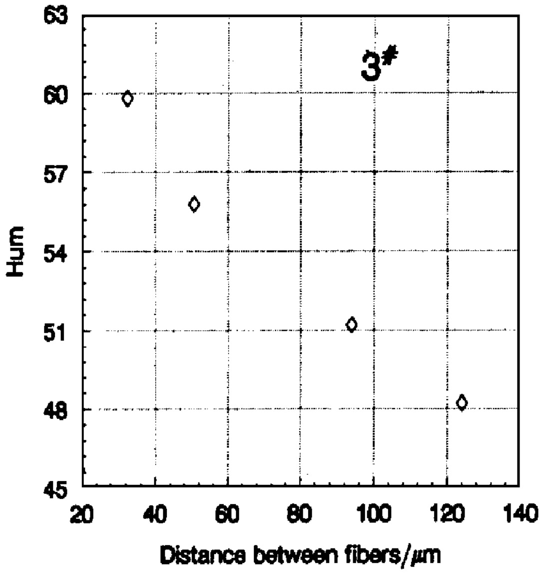


**Fig. 4 Hardness on the medium point of two fibers**

### 3.2 Influence of manufacture process and heat treatment on mechanical properties in microzone

3.2.1 Mehanical properties in microzone under different manufacture processes

The hardness in the microzone of sample 2 and 3 are compared in Fig. 5. where *R* stands for the distance from the medium point of two fibers. In two samples the distance between two fibers was 117 μm and 124 μm respectively. At the medium point the hardness of the two samples are just the same, but at the interface the hardness of sample 3 is higher than that of sample 2. It is because during the manufacture of sample 3 there was a much higher preform temperature than sample 2. Therefore, in sample 3 there is more Al$_4$C$_3$ at the interface[5]. Interfacial bonding strength becomes stronger and so does residual stress. At the meantime, the macroscopic properties of sample 3 are much lower than those of sample 2.

Fig. 6 suggests the hardness comparison of sample 1 and 2. Far from the interface, the hardness in sample 2 is higher than that in sample 1, but at the interface it is vice versa. It is due to the Ti adding to the matrix of sample 2 and during manufacture Ti prevents the formation of Al$_4$C$_3$[5], the interfacial bonding strength becomes weaker and the residual stress, as well as the hardness, are also smaller, but the macroscopic properties of sample 2 are higher.

From the comparison above it is shown that the manufacture process greatly influences on the mechanical properties in the interface microzone.

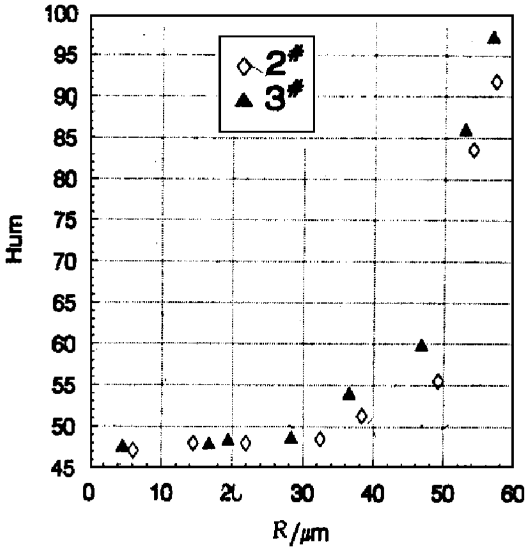


**Fig. 5 Hardness comparison of sample 2 and sample 3**

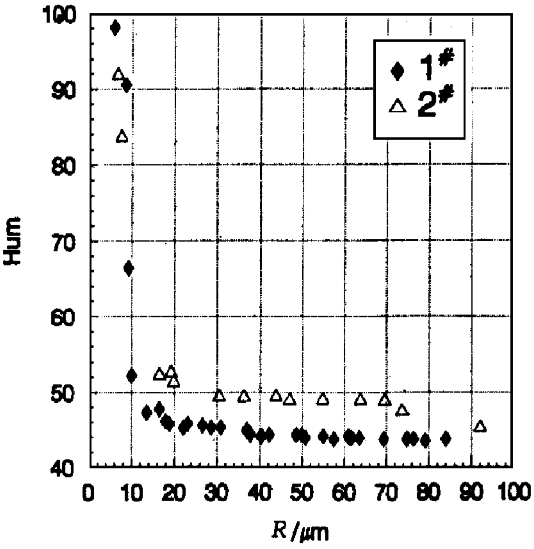
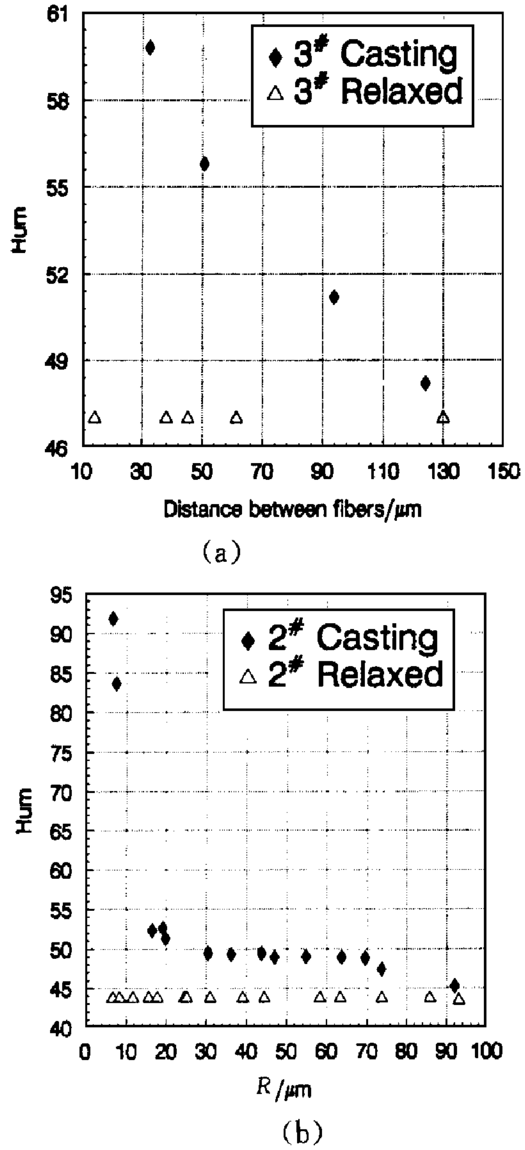


**Fig. 6 Hardness comparison of sample 1 and sample 2**

In Gr/Al, during manufacture when the interfacial bonding strength is stronger, the residual stress is larger and the distribution of the mechanical properties is more uneven. Hence, the macroscopic properties are lower. After selecting suitable manufacture process and the interfacial bonding strength, the uneven distribution of mechanical properties can be lessened and high-quality Gr/Al composite can be produced.

### 3.2.2 Influence of heat treatment on mechanical properties in microzone

Fig. 7 shows the comparison of the hardness before and after thermal cycling treatment. After the treatment, the interface is relaxed, the bonding strength lowered and the residual stress is released to zero. The uneven distribution of hardness disappears and the value of the hardness is equal to the hardness of the alloy without stress application. Thus, the treatment can change the interfacial bonding status and affect the mechanical properties in the microzone. The thermal cycling treatment sometimes can raise the macroscopic properties of the composite.



(a)

(b)

**Fig. 7 Hardness in microzone before and after treatment**

(a) —Sample 3; (b) —Sample 2

## 4 CONCLUSIONS

(1) Mechanical properties distribute unevenly in the interface microzone. The hardness is the highest when the test point is near the fiber. As the distance between the fiber and the test point increases, the hardness decreases. The effective distance is 2 to 3 times of the fiber diameter. It is shown that the ultramicrohardness is an attractive method for evaluating the regulation of the mechanical properties in the microzone.

(2) When the distance between the fiber decreases, the hardness at the medium point increases. Thus, the distribution of fibers in the matrix will affect the mechanical properties in the interface microzone.

(3) The status of the interfacial bonding can be changed by different manufacture process and heat treatment and the mechanical properties in the interface microzone, as well as the macroscopic properties, can also be influenced by them.

## REFERENCES

1 Su B. Materials Science and Engineering, (in Chinese), 1993, 11(2): 1.

2 Rawal S *et al*. In: The Annual Meeting of the Metallurgical Society, USA, The Metallurgical Society, 1986: 211.

3 Su D L. Mechanical Properties of Metal, (in Chinese). Beijing: Mechanical Industry Press, 1987: 67.

4 Westbrook J H *et al*. The Science of Hardness Testing and its Research Applications, (in Chinese). Beijing: Chinese Metrology Press, 1987: 51.

5 Cornie J A *et al*. Adv Compos Mater, 1991, 1(4): 851.

**(Edited by Li Kedi)**