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Tensile and wear properties of TiC reinforced 420 stainless steel fabricated by in situ synthesis

Wang Li Sun Yangshan Fan Quan Xue Feng Duan Zhichao

(Department of Materials Science and Engineering, Southeast University, Nanjing 210096, China)

Abstract: TiC particle reinforced 420 stainless steel matrix composites were fabricated, and the microstructure, tensile properties and wear resistance of the composites were studied. The experimental results indicate that the distribution of TiC particles with size of 5 to 10 μm in diameter is uniform if the volume fraction of TiC is lower than 6%. However, slight agglomeration can be observed when the TiC content exceeds 6%. With the increase of TiC content the tensile and yield strength of the composites prepared increases and reaches the maximum when the volume fraction of TiC increases to 5%. Further increase of TiC content causes reductions of yield and tensile strength. The ductility of the composites shows a monotone decrease with the increase of TiC addition. The introduction of TiC into 420 stainless steel results in significant improvement on wear resistance, which reaches a steady level when the volume fraction of TiC increases to 11% and does not show obvious variation if the TiC content is further increased.

Key words: in situ synthesis; composite; microstructure; tensile properties; TiC; wear resistance

Particle reinforced metal matrix composites (MMCp) are usually produced by powder metallurgy[1,2] or traditional casting technology[3], where ceramic particles are directly incorporated into solid or liquid matrices, respectively. In recent years, however, novel processing techniques[4-8] based on the in situ production of MMCs have emerged. Compared with the conventional MMCp produced by ex situ methods, this technique eliminates the interface incompatibility between matrix and reinforcement by creating more thermodynamically stable reinforcements based on their nucleation and growth from parent matrix phase. In addition, the in situ formed reinforcing particles are finer in size and their distribution in the matrix is more uniform[9]. These composites produced via in situ techniques exhibit high specific strength and modulus, as well as excellent wear resistance[10-12].

In the past decade, investigation has been focused on in situ ceramic particle reinforced aluminum matrix composites due to their potentially low fabrication cost, while less work has been carried out on in situ steel matrix composites[13-16]. In the present work, TiC particle reinforced 420 stainless steel matrix composites have been fabricated by in situ synthesis in the steel melt. The microstructure, tensile properties and wear resistance of the composites with different volume fractions of reinforcements have also been studied.

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Biographies: Wang Li (1981—), female, graduate; Sun Yangshan (corresponding author), male, professor, yssun@seu.edu.cn.

1 Experiment

Five composites with TiC volume fraction of 3%, 5%, 8%, 11% and 14%, respectively, were prepared in a vacuum median frequency induction furnace. The small TiC particles are acquired by in situ reaction of carbon and titanium under high temperature, which are introduced into the melting steel as the form of preformed blocks. To fabricate these performed blocks, titanium, carbon and iron powders with different volume fractions were dry mixed and subsequently compacted in a mold with the size of 30 mm × 30 mm × 10 mm. When the matrix alloy (420 stainless steel) was melted in the median induction furnace, the preformed blocks were introduced into the melt. The reaction of titanium and carbon soon occurred and its products TiC particles dispersed throughout the host metal uniformly due to the electromagnetically induced stirring. The melt with TiC particulate was held at 1 650 ℃ for several minutes then poured into graphite molds. The ingots with different volume fractions of TiC were hot forged at 1 050 ℃ into 15 mm-thick bars, then hot rolled to 2 mm-thick sheets at 1 000 ℃.

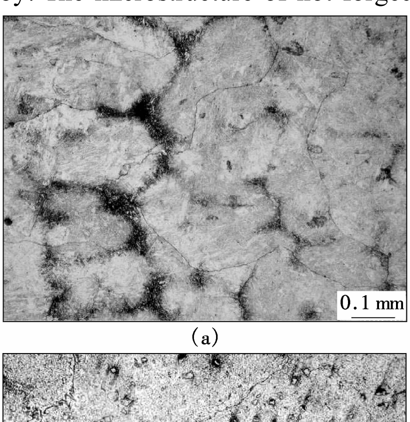
Tensile specimens with a gage section of 18 mm × 2 mm × 1.8 mm were cut by electric spark machining from the hot rolled sheets and tensile tests were performed using a CSS-2202 test machine at the strain rate of 10^{-2} r/s. Microstructures of the alloys were characterized on selected specimens using optical microscope (OM) and scanning electron microscope (SEM), respectively.

Wear properties of the composites were investigated using an MM-200 wear-testing machine, which employed a bearing steel ring with the diameter of 45 mm rotating against the test block. The test blocks of the size 15 mm × 15 mm × 20 mm were sectioned from hot-forging bars and the loss of volume of the test block was determined at definite time intervals. Before testing all the test blocks were heated at 1 000 ℃ for 1 h and quenched in oil. Tempering of the test blocks was carried out at temperatures between 300 and 700 ℃; afterwards, the surface of blocks was polished with emery papers up to 4/0 grade and cleaned. The ring and the test block were mounted on the testing machine and the selected load was applied before the ring shaft started to circumrotate at a given speed (300 r/min). After conducting the wear tests, the wear scars of the samples were examined by SEM and OM.

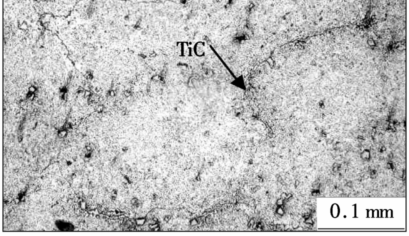
2 Results and Discussions

2.1 Microstructure

Fig.1(a) shows the as-cast microstructure of the matrix alloy which is composed of ferrite and fine particles distributed along grain boundaries. These dispersed fine particles are chromium carbides such as $(Cr, Fe)_{23}C_6$ and $(Cr, Fe)_7C_3$ according to the Fe-Cr-C ternary phase diagram[17]. As can be seen in Fig.2(b), TiC particles are embedded around the grain boundary in the composite formed by in situ reaction in the matrix alloy. The microstructure of hot forged and oil quenched samples of the matrix alloy are similar. They are composed of martensite and chromium carbides which appeared to be finer and distributed more uniformly than those in the as-cast microstructure. Fig.2 is light micrographs showing the microstructure of the samples tempered at 660 ℃. It can be seen that the tempered matrix alloy shows typical sorbite microstructure (mixture of ferrite and cementite particle) with randomly dispersed particles of chromium carbide, as shown in Fig.2(a). Compared with the matrix alloy, the sorbite structure in the composite with 5% TiC addition tempered at the same temperature is finer (Fig.2(b)), and the distribution of TiC particles in tempered composite is more uniform than that in the as-cast microstructure.

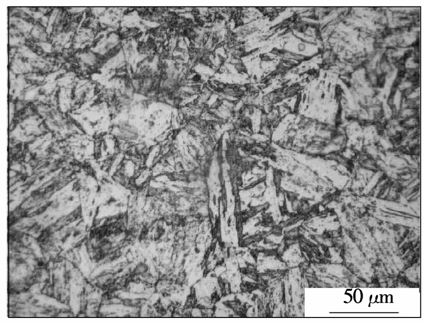


(a)

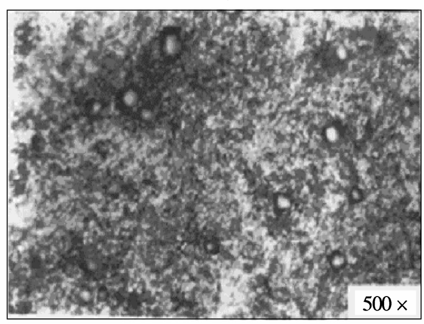


(b)

Fig.1 Light micrographs of as-cast materials. (a) Matrix alloy; (b) Stainless steel + 5% TiC



(a)



(b)

Fig.2 Light micrographs of the materials held at 1 000 ℃ for oil quenching and 660 ℃ for tempering. (a) Unreinforced alloy; (b) Stainless steel + 5% TiC

The morphology and the size of TiC particles in composites prepared can be observed more clearly from the unetched samples of composites. Figs.3(a), (b) and (c) are optical micrographs taken from unetched samples of as-forged, oil quenched and tempered (at 660 ℃) composite with 5% TiC addition, respectively. In all these samples, TiC particles exhibit a faceted morphology and are on an average 5 to 10 μm in diameter. In addition, the morphology and the size of TiC particles do not seem to have obvious changes after hot processing and heat treatment, indicating that these TiC particles in composites have high thermal stability. The distribution of TiC in the composites with TiC addition up to 6% is basically uniform (Figs. 3 (a), (b) and (c)); however, slight agglomeration appears in the composite with 8% TiC addition, as shown in Fig.3(d).

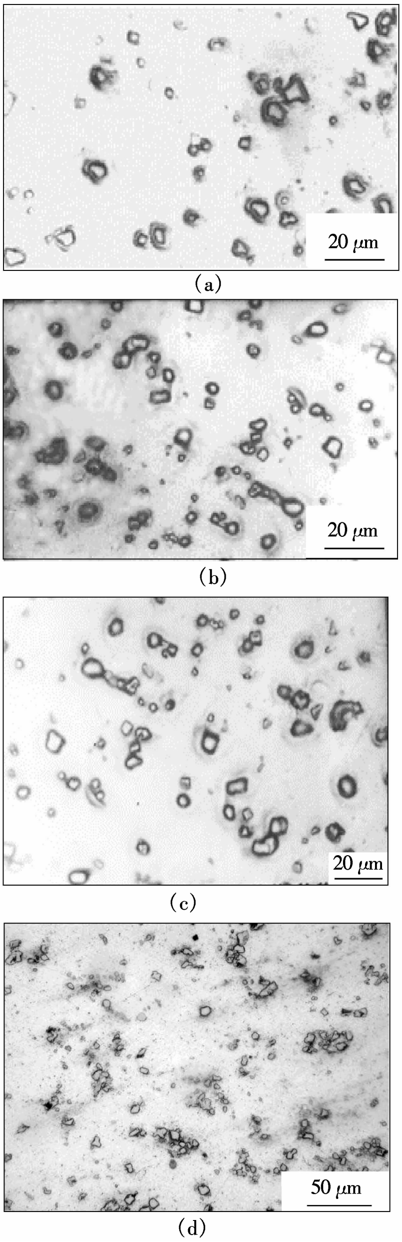


Fig.3 Light micrographs of the composites (unetched). (a) As-forged 420 stainless steel + 5% TiC composite; (b) Oil quenched 420 stainless steel + 5% TiC composite; (c) 420 stainless steel + 5% TiC composite held at 1 000 ℃ for oil quenching and 660 ℃ for tempering; (d) 420 stainless steel + 8% TiC composite

2.2 Tensile properties

Room temperature tensile tests are performed on samples tempered at 660 ℃ and the results are shown in Fig.4. It can be seen that tensile and yield strength increase with the increase of TiC addition and reach the maximum when the volume fraction of TiC increases to 5%. Further increase of TiC addition causes decreases of both tensile and yield strength. The room temperature ductility monotonously decreases with the increase of TiC addition and the elongation of the composite with 14% TiC addition is only 2.0%, one fifth of that of the matrix alloy.

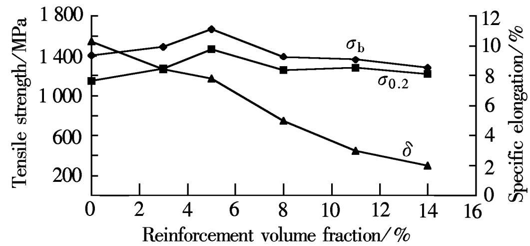


Fig.4 Influence of reinforcement volume fraction on the tensile properties of the matrix alloy and composites studied at room temperature

During the past decades plenty of investigations have been carried out to reveal the strengthening mechanisms of metal matrix composites, and both continuum and micromechanical models have been developed[18]. All the preceding strengthening mechanisms, from a theoretical point of view, seem suitable to take place in steel matrix composites. However, when the volume fraction of TiC is over 8%, the agglomeration of TiC particles in the microstructure of composites can be observed, which can be one of the possible reasons for the decrease of the strength of the composites. The stresses on the reinforcement become large enough to lead the fracture of the reinforcement to occur as composites with higher strength matrix are strained, particularly in the presence of a pre-existing flaw in the reinforcement formed probably during earlier processing. Once the reinforcement fractures, the net load-carrying capacity of the composite decreases, therefore, strength may decrease. In addition, the thermal mismatch between reinforcement and matrix leads to a large stress concentration near the reinforcement. Apparently, the higher TiC content produces larger stress. Provided no sufficient plastic relaxation takes place, the matrix in that region fails prematurely during straining. For the steel matrix composites large temperature differences are encountered during processing or heat treatment[19].

2.3 Wear resistance

Both dry and lubricated wear tests have been performed on the matrix alloy as well as the composites prepared. For the dry test, the loading weight on the block sample against the rotating ring is 5 kg. The rotation speed of the ring is 300 r/min and the test lasts 1 min. Fig.5 shows the variation of wear volume loss of as-forged samples after the dry test with the increase of TiC content in composites. It can be seen that the volume loss of the sample reduces with the increase of TiC addition when the volume fraction of TiC is lower than 11%. However, further increase of TiC content does not result in significant change of the volume loss, which appears to reach a steady value when TiC content is higher than 11%. For the lubricated wear test, the volume loss of as-forged samples is plotted as a function of TiC content in Fig.5. The load applied on the sample is 15 kg and the test lasts 20 min. From Fig.5 it can be seen that the variation tendency of volume loss with increase of TiC content is similar to that of the dry test. In both cases the volume loss of the composite with 11% TiC addition is one order of magnitude lower than that of the matrix alloy.

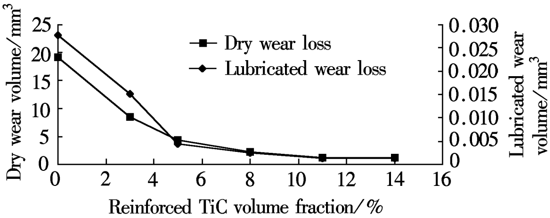


Fig.5 Wear loss vs. TiC volume fraction after dry and lubricated wear tests

In order to study the influence of heat treatment on the wear resistance of the composites prepared, quenched samples with 5% TiC addition are tempered at different temperatures between 300 and 700 ℃ for 1 h. Hardness and lubricated wear tests have been performed on these tempered samples under the same condition as that applied to as-forged samples. Fig.6 illustrates the hardness and wear volume loss of the samples tempered at different temperatures. It can be seen that the hardness decreases with the increase of tempering temperature and drops rapidly when the temperature is raised from 500 to 600 ℃. However, the wear resistance of the composites does not appear obvious variation with the increase of tempering temperature.

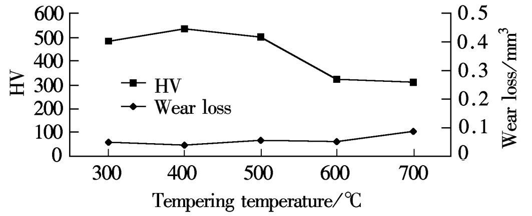


Fig.6 Variation of hardness and volume loss after wear tests of the composites tempered at different temperatures

In comparison with traditional metallic materials, high wear resistance is an attribute ascribed to metal matrix composites. In the present investigation the wear resistance of 420 stainless steel is remarkably improved by introducing TiC reinforcement through in situ reaction in the melt. The benefits in increased wear resistance result from the incorporation of the hard ceramic phase TiC into the stainless steel matrix. The microhardness of TiC is as high as 3 200 HV, much higher than that of the matrix. Although many investigations have been made up to now, the fundamentals of wear processes are incompletely understood. One of possible modes of interaction between a GCr15 ring (759 HV) and the composite surface is presumed in Fig.7.

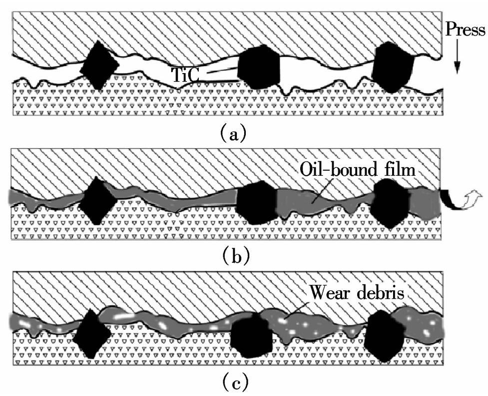


Fig.7 Schematic representation of the wear mechanism in the present investigation. (a) TiC particles were pressed into the ductile matrix; (b) The gap between the surfaces of the wheel and the composite was imbued with lubricant; (c) The abrasive grits tumble between the surfaces

For the composites prepared in the present investigation, the mechanism of wear can be described by a schematic representation shown in Fig. 7. For solid materials, the topography of their surface always consists of an irregular series of crests and troughs, as illustrated in a rather exaggerated way in Fig. 7 (a). Under the loading force applied on the block sample through the hard steel ring, TiC particles are indented into the surface of the matrix more deeply than that in the wheel because of the more ductile matrix facilitating to accept hard particles. If the loading is not large enough, there must be a gap between the surfaces of the samples of composite and wheel (see Fig. 7 (a)). Therefore, TiC particles distributing uniformly on the sample surface bear most of the weight given by the ring. As the wear test in the present investigation is under lubricated condition, an oil-bound film is generated in the gap (see Fig.7(b)), which results in great improvement of wear condition. As soon as the wheel starts to rotate, sliding between the sample and wheel forces the edges and corners of TiC particles to plough the surface of the ring removing some fragments from the rotating wheel. These fragments as tumbling grits cause abrasive wear on the sample surface as illustrated in Fig.7(c). Some samples after wear tests have been placed in the scanning electron microscope for detailed characterization of the abrasion regions. Fig.8 makes a comparison of the appearance of TiC in non-abrasion regions with that in abrasion regions. It can be seen that TiC particles are embossed on the surface of non-abrasion regions (Fig. 8 (a)), while they seem to be embedded more deeply in abrasion regions (Fig.8(b)). No crack can be observed around the particle, and the traces of wear are fleet and shallow. In comparison with composite, deep and bold scratches can be observed on the surface of the matrix alloy after wear test, as shown in Fig. 8 (c), reflecting that the mechanism of wear between the matrix alloy and hard steel ring is different from that between the composite and the same ring. The former is a typical kind of wear caused by metal to metal contact. As the hardness of the wheel is much higher than that of the matrix alloy, deformation as well as surface fracture easily occurs to the matrix alloy when the loading force is applied . The rotation of the wheel removes fragments from the fracture surface and forms wear scratches. The results of wear tests in the present study indicate that the technique of in situ synthesis introducing TiC particles to steel is very efficient in improving wear resistance.

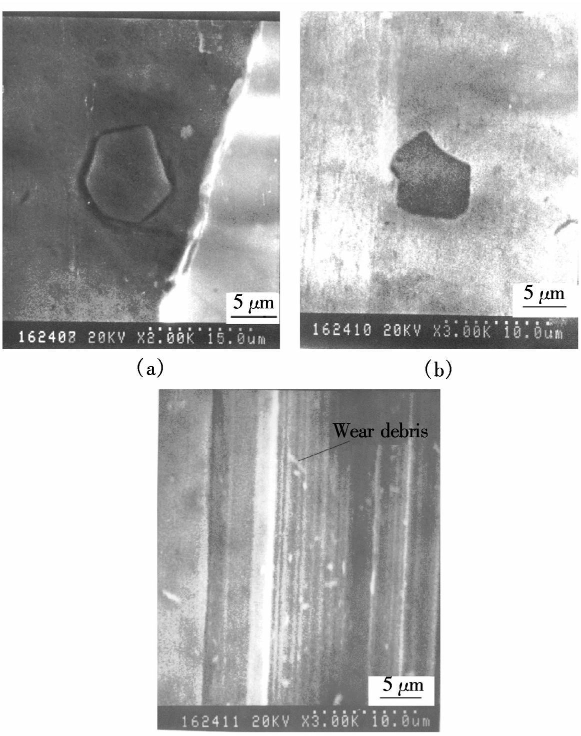


Fig.8 Composite with 5% TiC and unreinforced alloy observed by SEM. (a) Non-abrasion regions of the composite; (b) Abrasion regions of the composite; (c) Wear surface of the unreinforced alloy

3 Conclusions

The current study on in situ 420/TiC composites leads to the following conclusions.

1) Tensile and yield strength increase with the increase of TiC addition and reach the maximum when the volume fraction of TiC reaches 5%. Further increase of TiC addition causes decreases of both tensile and yield strength.

2) The volume loss of the sample after wear test reduces with the increase of TiC addition when the volume fraction of TiC is lower than 11 %. However, further increase of TiC content does not result in significant change of the volume loss, which appears to reach a steady value when TiC content is higher than 11%.

3) The hardness decreases with the increase of tempering temperature and drops rapidly when the temperature is raised from 500 to 600 ℃. However, the wear resistance of the composites does not appear obvious variation with the increase of temperature.

4) TiC particles in composite have high thermal stability. The distribution of TiC in the composites with TiC addition up to 6% is basically uniform; however, slight agglomeration appears in the composite with 8% TiC addition.

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原位合成 TiC 增强 420 不锈钢的力学性能和抗磨损性能

汪 黎 孙扬善 樊 泉 薛 烽 段志超

(东南大学材料科学与工程系, 南京 210096)

摘要: 用原位合成方法制备了 TiC 增强 420 不锈钢基复合材料, 并研究了复合材料的显微组织、力学性能和抗磨损性能. 实验结果表明, 当复合材料中 TiC 颗粒体积分数低于 6% 时, 材料中 TiC 颗粒分布均匀, 颗粒的尺寸在 5 ~ 10 μm 左右; 但颗粒体积分数大于 6% 后, 显微组织中出现 TiC 颗粒的轻微偏聚. 随着 TiC 体积分数的增加, 材料的抗拉强度和屈服强度先是增高, 当 TiC 体积分数达到 5% 时, 强度达最大值. 此后增加 TiC 体积分数会导致强度的下降. 复合材料的塑性随 TiC 体积分数的增加呈单调下降的趋势. TiC 颗粒的引入使材料的抗磨损性能得到显著改善, 但当 TiC 体积分数达到 11% 时, 抗磨损性能接近一个稳定的水平. 继续增加 TiC 含量, 材料的抗磨损性能不再发生明显变化.

关键词: 原位合成; 复合材料; 显微组织; 力学性能; TiC; 抗磨损性能

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