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Carbon nanotube/alumina and graphite/alumina composite coatings on stainless steel for tribological applications

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ABSTRACT

Carbon/alumina coatings on stainless steel are prepared by a sol-gel route, using either carbon nanotubes (8 walls on average) or graphite flakes. The friction coefficient against a steel ball is decreased by a factor of 4–5 compared to pure alumina and wear is reduced by a factor of 2 with graphite flakes. A Raman spectroscopy study of selected specimens outside and inside the worn surface shows that the carbon nanotubes are not dramatically damaged whereas the graphite flakes are broken into graphene layers. The reasons why graphite is more effective than the carbon nanotubes, for the same carbon content, to improve the tribological behavior are discussed.

1. Introduction

Austenitic stainless steels are widely used in the aerospace, energy, medical and food industries because of their resistance to corrosion but they are highly susceptible to adhesive wear (seizure), therefore leading to a significant loss of profitability and possibly to some environmental impact. Carbon-containing composites are of particular interest as self-lubricating materials showing a high resistance to friction and wear, preventing the need for liquid lubricants. Reports on the tribological behavior of metal- [1–11] and ceramic-matrix [12–17] bulk composites containing carbon nanotubes (CNTs) are increasingly abundant. However, the comparison of the results reported by different groups is hampered notably because different CNTs are used, the preparation routes markedly differ and the tribological testing conditions (counter-face, load, sliding distance, relative humidity, temperature) vary widely. Moreover, it is either undesirable or impossible to use bulk composites for applications such as the protection of austenitic steels. Therefore, composite coatings are to be preferred, such as CNT-metal electroless coatings [3] and plasma-sprayed CNT/Al_2O_3 coatings [18,19]. Balani et al. [18] reported that the sliding wear volume loss of a 8 wt.% CNT/Al_2O_3 coating against a ZrO_2 pin (dry conditions, normal load 48 N) was 49 times lower than for an Al_2O_3 coating. Keshri et al. [19] reported a 72% increase in wear resistance against a WC ball (298 K, ball-on-disk tribometer) for a 8 wt.% CNT/Al_2O_3 coating compared to Al_2O_3. Note that these results are partly attributed to indirect effects of the presence of CNTs, such as a locally enhanced densification of the wear surface and a higher toughness of the coating through CNTs bridging between the splats and/or Al_2O_3 grains. Graphite/Al_2O_3 bulk composites were shown [20] to have a friction coefficient half of that of pure Al_2O_3. A low shear strength in the sliding direction and high compression strength in the direction of the load (i.e. perpendicular to the sliding direction) are beneficial to lower the friction coefficient. Laminated graphite/Al_2O_3 composites were reported [21] to show significantly better friction and wear behaviors than monolithic graphite/Al_2O_3 composites (against an Al_2O_3 ball, dry conditions room temperature) because graphite particles can be easily dragged on to the friction surface from the graphite layers. Changes in the layer spacing and in the graphite volume fraction affect the formation of lubricating and transferring films, load-bearing capacities and wear mechanisms of the materials. The aims of the present work are to shape CNT/Al_2O_3 coatings onto an austenitic 304-L stainless steel substrate, to compare their tribological behavior to that of pure Al_2O_3 and graphite/Al_2O_3 coatings

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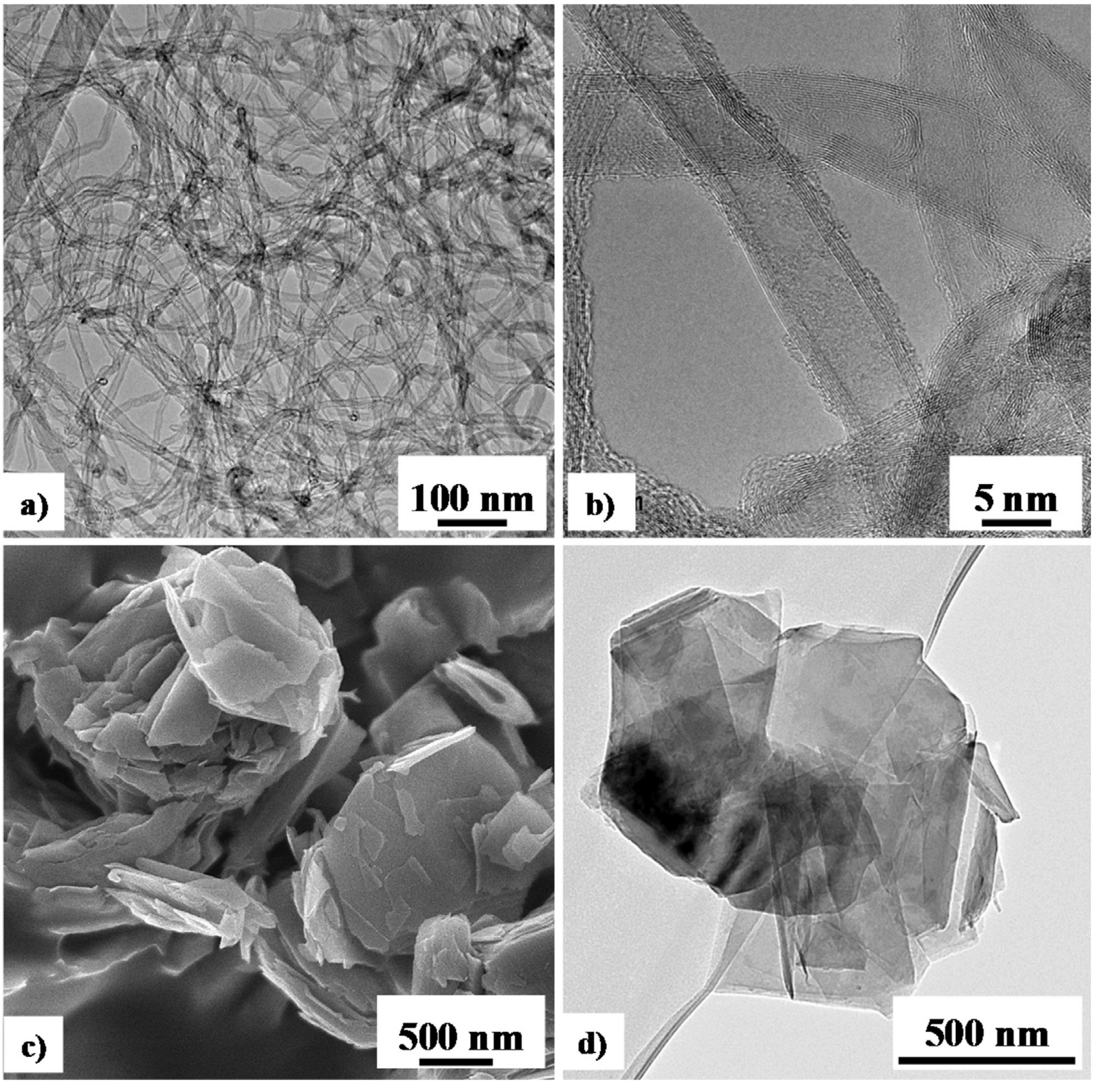

Fig. 1. TEM images of the CNTs (a and b) and FESEM image (c) and TEM image (d) of graphite flakes.

and to explain why graphite is more effective than CNTs to improve the tribological behavior.

2. Experimental methods

2.1. Raw materials

A CNT sample described in detail elsewhere [10] was purchased from Nanocyl (Belgium). TEM images (Fig. 1a and b) show that the CNTs are mostly not bundled and contain a fair number of defects along their lengths. CNTs with 3–22 walls are observed. CNTs with 8 walls are dominant (30%) with CNTs with 7 and 9 walls (both 16%) the second most abundant populations.

The average number of walls is equal to 8.5 (rounded to 8). The average CNT outer diameter is 10.2 nm and length is below 1.5 μm. The specific surface area of the sample is 242 $m^2 g^{-1}$, in agreement with calculations from geometrical data [22]. The CNTs were carboxyl-functionalized with a nitric acid solution (3 mol L^{-1}) as described elsewhere [23]. Graphite platelets (Fig. 1c and d) were purchased from Abcr (Germany). Flakes about 15 nm thick are agglomerated into platelets about 1.5 μm in size. The specific surface area of the sample is 20 $m^2 g^{-1}$.

An aqueous aluminum chloride hexahydrate ($AlCl_3 \cdot 6H_2O$) solution (0.13 mol L^{-1}) was poured into an excess of ammonia solution (5 mol L^{-1}) under magnetic stirring at room temperature. The so-obtained boehmite (AlOOH) precipitate was filtered, washed with deionized water and oven-dried overnight, producing a boehmite

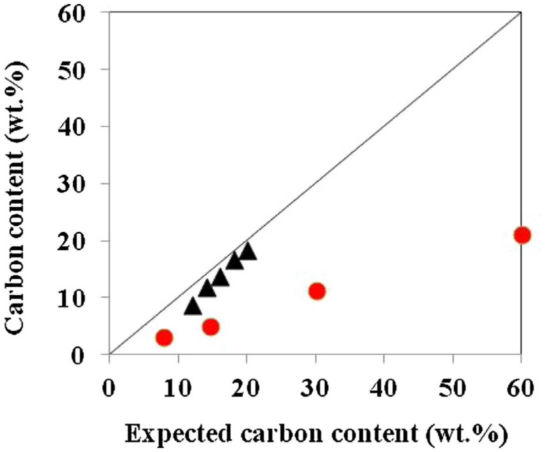

Fig. 2. Measured carbon content versus the expected carbon content for the CNT/Al_2O_3 (▲) and graphite/Al_2O_3 coatings (●). The solid line shows the expected carbon content (i.e. 1 for 1).