Applied Surface Science 258 (2012) 9656–9663

Contents lists available at SciVerse ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Effects of the AFM tip trace on nanobundles formation on the polymer surface

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ARTICLE INFO

Article history:
Received 22 March 2012
Received in revised form 2 June 2012
Accepted 2 June 2012
Available online 15 June 2012

Keywords:
AFM
Scratch
Bundles
Polycarbonate (PC)

ABSTRACT

Atomic Force Microscope (AFM) has become a popular experimental tool for the nanotribological studies. Nanobundles formation perpendicular to the scanning direction has been reported as a typical wear mode for the thermoplastics, and such bundle structures are also considered as sinusoidal wave micro-/nanostructures now. In the present study, the AFM tip based nanomechanical machining method is employed to scratch a polymer Polycarbonate (PC) surface for only once with the normal load of several micro-Newtons in order to achieve the perfect regular nanobundle structures. Based on a modified AFM system, effects of different tip traces in the tip scanning mode and in the sample scanning mode on nanobundles formation on the PC surface are studied. The experimental results show that the controlled reciprocal movement of the stage in the sample scanning mode is feasible for perfect nanobundle structures formation. Moreover, effects of the normal load and the feed on bundles formation in the sample scanning mode are analyzed. Experimental results reveal that the feed value directly affects the formed patterns including the bundles and grooves structures. The reciprocal effect of the tip trace is the decisive factor of forming ideal nanobundles. The repeating times on the same area acted by the tip which are larger than twice are necessary to form a perfect nanobundle structure.

1. Introduction

Micro-/nanostructures on the polymer surface have significant applications, such as for directed cell growth, stamps in nanoimprint lithography, complex surface nanostructures of binary optics, micro-/nanogratings of sensors, and so on [1–4]. At present, the manufacture technologies used to achieve nanostructures mainly include nanoimprint lithography (NIL) [5], focused ion beam (FIB) [6], scanning probe microscope (SPM) based nanofabrication methods [7–9], electron beam lithography (EBL) [10], self-assembly (SA) [11], etc. Among them, the SPM-based nanofabrication technique is a relatively convenient method with good repeatability and high resolution. Especially, the AFM tip based nanomechanical method, which belongs to one of the SPM-based nanofabrication methods, is looked on as a novel way of forming complex nanostructures which attracts more and more scholars' attentions.

Since its invention, besides imaging, AFM has become a popular experimental tool for the nanotribological studies because it can deal with the nano-Newton force, low wear rates and smooth surfaces [12]. A number of wear modes have been observed where an AFM tip is used as a single nanoabrasive sliding over a polymer surface. Among the wear modes, bundle-type structures perpendicular to the scanning direction has been reported as a typical wear mode for most thermoplastics polymers, such as polystyrene (PS), polyesters (PE), polyacetylene, polycarbonate (PC), and poly(tert-butyl acrylate) (PtBuA) [13–17]. The formation mechanisms of these bundles are generally attributed to Schallamach waves [18], stick-slip dynamics, fracture mechanisms [15] and erosion–diffusion process [19]. Among them, the Schallamach waves appear to be rather weak to interpret the mechanism of the formed bundles patterns [20,21]. Such bundle structures are actually the quasi-sinusoidal nanostructures which are looked on as typical three-dimensional nanostructures by some scholars. It is agreed that the AFM-based nanomechanical wear technique may become a novel way for processing 3D polymer nanostructures [4].

Nowadays, most studies on bundles formation are carried out from the view of the wear process. It has been reported that bundle formation during scanning by the AFM tip depends on the normal load, the feed, the tip radius, scan times and so on. Kassavetis [22] scratched the polymeric (polyethylene terephthalate, PET) film, and observed that the larger normal force (F_a) resulted in the increase of the materials piled-up and the decrease of the aspect ratio of the created pits for $F_a < 760$ nN. Kaneko [23] studied the morphologies of the polymer polycarbonate, polymethyl methacrylate and epoxy at different feeds with the tip radius of 100 nm and the normal load of 500 nN. They observed that the wear modes of polycarbonate included grooves, ridges and upheavals. Khurshudov [24] reported

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http://dx.doi.org/10.1016/j.apsusc.2012.06.005

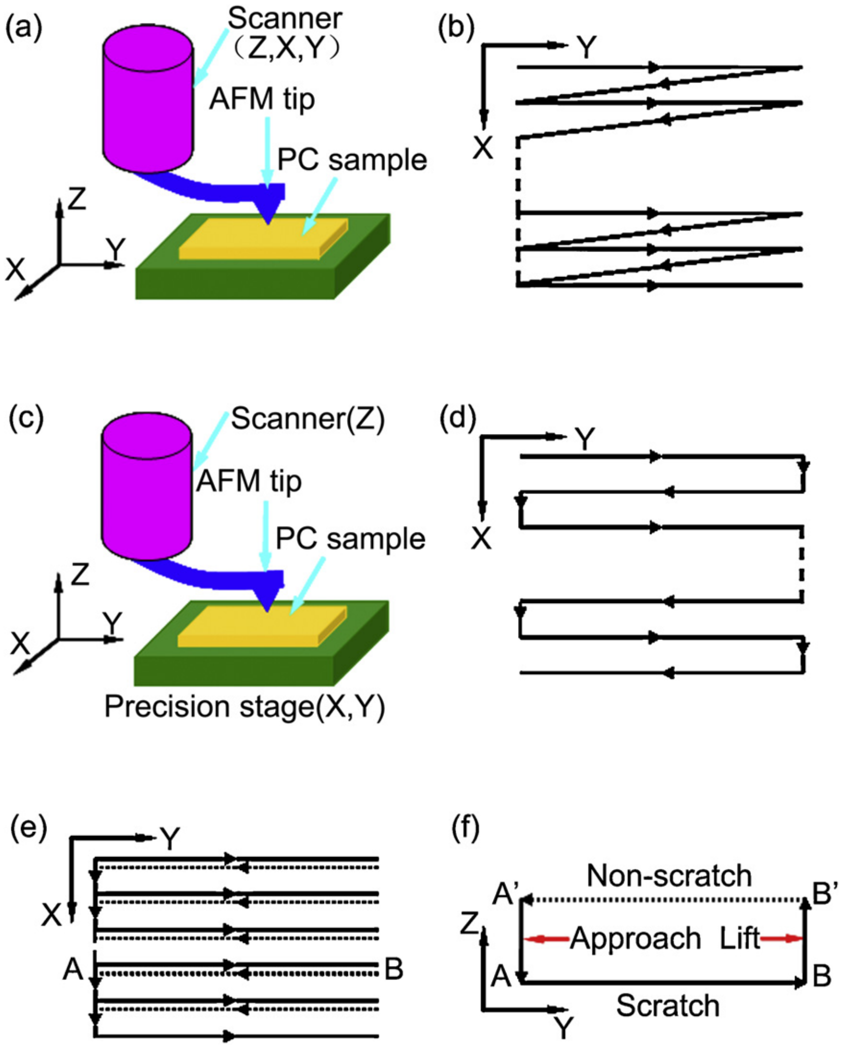

Fig. 1. Schematic illustration of the machining systems and the corresponding tip traces. (a) The AFM system, (b) the tip trace of the AFM system, (c) the modified AFM system, (d) the tip trace named "scan-scratch", (e) the tip trace named "line-scratch" of the modified AFM system and (f) the tip's motion in each line of (e).

that the presence of the AFM tip's lateral feed resulted in relatively fast wear particles separation in repeated scratching of the polycarbonate surface. They also obtained that the surface morphologies are decided by the normal load and the feed. Dinelli [21] studied the effect of the tip shape on nanowear of polystyrene surfaces. They pointed that the penetration depth and the number of bundles formed for the blunt tip were reduced compared to sharper tips. Surtchev [25] investigated the wearing process of the polystyrene films and reported that an overlap between successive scan lines was necessary to obtain a periodic pattern.

From the previous works, it can be found that the nanobundle structures are formed in reciprocity between the AFM tip and the polymer surface. However, up to now, no perfect nanobundle structures which can be employed as the templates have been achieved by this way. This might be due to effects of the tip trace of the AFM system itself. When the tip contacts with the sample, the traditional AFM scans the tip in three axes through controlling the piezo scanner. The tip swings on the sample surface. The corresponding torsion of the tip increases with the scan size which will affect the periodicity of nanobundle structures. This leads to failure of perfect regular bundle structures formation. Meanwhile, most researchers carried out the repeated scanning at a very small normal load of about several nano-Newtons. However, from the view of manufacturing, a single scratching forming the perfect periodical patterns is needed to improve the machining efficiency. Thus, using a larger normal load has been verified to achieve the nanobundles [26]. Up to now, to our knowledge, there are no relevant studies on the effect of the tip paths on the periods of the bundles with a larger normal load of several micro-Newtons for only once scratching test.

Therefore, in order to form controllable, repeated and high accurate nanobundle structures by AFM, a novel scratching tip trace is provided based on the modified AFM. With a micro-Newtons normal load, the Polycarbonate (PC) surface is scratched for only once. Effects of the different tip traces along with the tip feed on the bundles formation are studied in detail.

2. Experimental details

The injection-molded PC sample purchased from Yanqiao Engineering Plastics Co. Ltd. (Shanghai, China) is used in the present study. PC is known as a typical thermoplastic and an important material for future micro-/nanodevices due to its low production cost, low density and easily molding characteristics.

The AFM system (Dimension 3100, Veeco Company, USA) is integrated with a three dimensional precision stage (PI Company, German) forming a modified AFM in the present study. Based on this modified system, different tip traces can be achieved, as shown in Fig. 1(a) and (c).