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Sub-micron magnetic patterns and local variations of adhesion force induced in non-ferromagnetic amorphous steel by femtosecond pulsed laser irradiation

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ABSTRACT

Periodic ripple and nanoripple patterns are formed at the surface of amorphous steel after femtosecond pulsed laser irradiation (FSPLI). Formation of such ripples is accompanied with the emergence of a surface ferromagnetic behavior which is not initially present in the non-irradiated amorphous steel. The occurrence of ferromagnetic properties is associated with the laser-induced devitrification of the glassy structure to form ferromagnetic (α-Fe and Fe_3C) and ferrimagnetic [$(Fe,Mn)_3O_4$ and Fe_2CrO_4] phases located in the ripples. The generation of magnetic structures by FSPLI turns out to be one of the fastest ways to induce magnetic patterning without the need of any shadow mask. Furthermore, local variations of the adhesion force, wettability and nanomechanical properties are also observed and compared to those of the as-cast amorphous alloy. These effects are of interest for applications (e.g., biological, magnetic recording, etc.) where both ferromagnetism and tribological/adhesion properties act synergistically to optimize material performance.

1. Introduction

The unprecedented technological progress in diverse areas of nanoscience and nanotechnology is raising an increasing demand for new types of materials, novel lithographic procedures and new techniques to assemble micro-/nanocomponents into complex systems, such as micro-/nanodevices, lab-on-a-chip or miniaturized robotic platforms. To a large extent, coping with the current technological challenges relies on the implementation of innovative methods to fabricate large areas of patterned structures with sub-micrometer scale precision in a rapid, inexpensive and industrially scalable manner.

High-resolution magnetic patterning is crucial in applications like magnetic encoding, magnetic sensors and actuators, wirelessly actuated magnetic microrobots, spin-electronics or high-density magnetic recording media. In all these applications, not only the magnetic properties are important but other aspects, such as surface adhesion, nanomechanical behavior or hydrophobicity need to be precisely controlled in order to attain optimized material performance. The tribological behavior of patterned magnetic materials and the quantification of surface adhesion forces, for example, are of paramount importance in high-density recording media, where the write/read heads fly only a few nm from the surface of the recorded information [1]. Adhesion is a crucial parameter in magnetic systems for biological and mechatronic applications [2,3], in some bioinspired actuator devices [4] or in magnetic wall-climbing devices [5]. Surface roughness plays also a crucial role on the magneto-electrical properties of a variety of thin films [6,7].

In many of these cases it is desirable that the magnetic behavior of the patterned structures is not affected by the presence of magnetic stray fields stemming from neighboring magnetic materials or underlying magnetic layers. For this reason, sophisticated lithographic procedures, that are usually rather time-consuming (i.e., consisting of multiple steps) and rather costly (i.e., requiring

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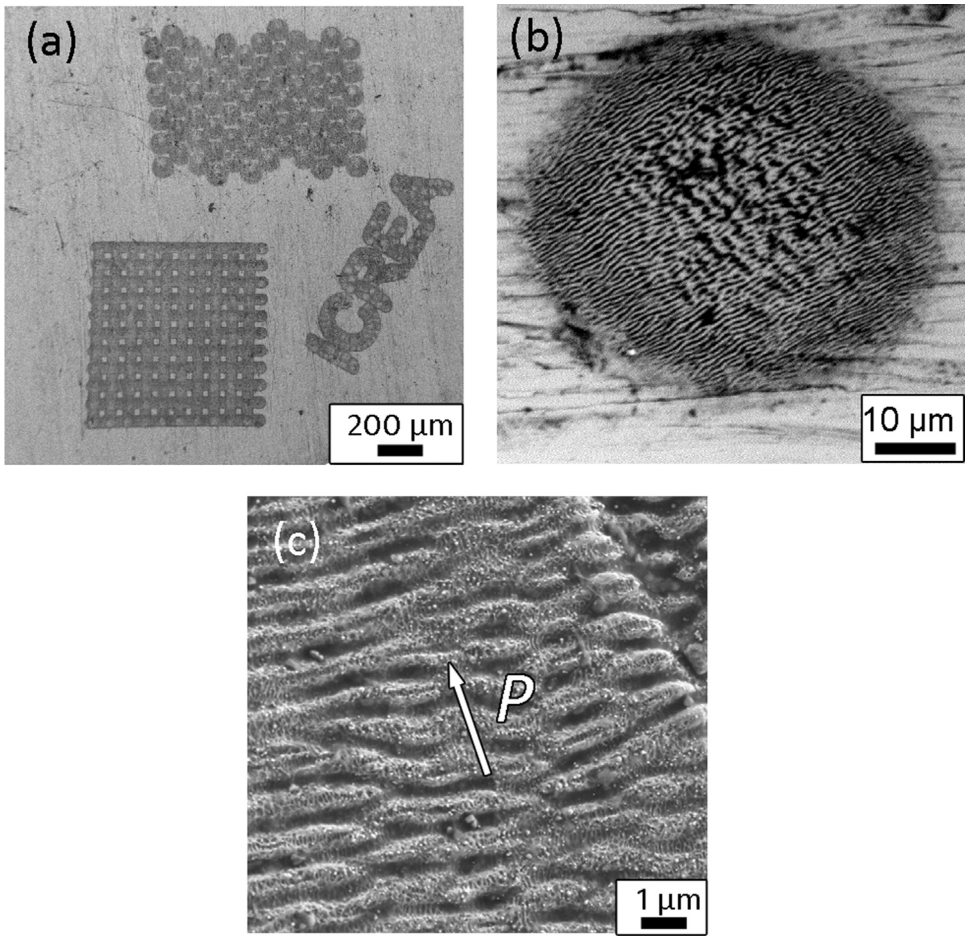

Fig. 1. (a) SEM images (secondary electrons) of different patterns written at the surface of the $Fe_{51}Mn_{10}Cr_4Mo_{12}C_{15}B_6Er_2$ alloy by femtosecond pulsed laser irradiation (FSPLI) with 95% overlapped 500 fs laser pulses and applied fluence 0.33 J/cm^2; (b) detail of a circular dot obtained by FSPLI imaged by SEM; (c) magnified SEM view of the so-called "classical ripples" formed during the FSPLI process, whose direction is perpendicular to the polarization of the incident laser (*P*).

clean room facilities), are utilized to fabricate arrays of ferromagnetic dots at the surface of non-ferromagnetic substrates [8].

In the last few years, some non-conventional approaches for the direct magnetic patterning of initially non-magnetic materials have been developed. These include, for example, nanoindentation and ion irradiation of atomically-ordered alloys, stainless steels or metallic glasses [9–13]. The large compressive stresses generated during nanoindentation are sufficient to induce atomic order-disorder transitions in Fe-Al alloys, local nanocrystallization in metallic glasses or martensitic transformations in austenitic steels. In all these cases, the induced structural changes result in localized magnetic patterning at specific regions of the sample surface [9–11]. Ion irradiation through shadow masks is an alternative procedure to fabricate arrays of ferromagnetic structures (sometimes without any topological damage) in some of the aforementioned materials [12,13].

Femtosecond pulsed laser irradiation (FSPLI) is a powerful technique to induce periodic topological patterning and concomitant ablation damage at the surface of certain metallic alloys, semiconductors, dielectrics and polymers [14–24]. Depending on the laser processing conditions (fluence and nominal number of pulses) the imprinted structures can change from low-spatial-frequency ripples or "classical ripples" with periodicity close to the laser light (perpendicular to the polarization of the incident laser beam) [16,17] to high-spatial-frequency nanoripples with periodicity smaller than laser wavelength (either perpendicular or parallel to the polarization direction [17–19]. Even spikes [20], regular arrays of nanopores [21] or concentric rings [22] can be induced under certain circumstances. Several models have been put forward in the literature to account for the various types of ripple topologies. Examples include the interference between the laser beam and the surface scattered wave, the excitation of surface plasmon polaritons, and self-organization. Regarding interference, it is proposed that when a laser beam interacts with a material, surface defects cause the incoming incident laser beam to become partially scattered into a tangential wave, which propagates across the material surface. Laser-induced periodic surface structures are thought to appear because of interference of the laser beam scattered by multiple surface defects [23]. Separately, it has been reported that when the incident electromagnetic laser radiation couples with a plasmon charge oscillation, a modified electromagnetic field propagates in the area which has specific polarization dependence, regardless of whether a material is metallic or dielectric in nature [24–26]. For metals, a specific dependence of the plasmon coupling has been reported depending on the grating period [27]. Furthermore, ripple formation has been compared to the formation of sand dunes present in a desert and to other structures spontaneously created following ion beam sputtering on a microscale [28]. These spontaneous processes include the melting and resolidification processes occurring at the surface due to the induced temperature gradients [29–31]. Additionally, second harmonic generation has been shown to play a role in the formation of nanoripples [32]. In spite of the very short duration of the pulses, phase transformations and other microstructural changes are sometimes observed