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Gripping by controllable wet adhesion using a magnetorheological fluid

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ABSTRACT

The magnetorheological properties of ferrofluids (or smart, or active fluids) are well known, and are currently exploited in shear in advanced damping systems in the automotive industry, robotics (prosthesis), and machine tools (chatter reduction, positioning). This paper proposes an end effector for gripping by a novel form of controllable wet adhesion inspired by gastropod pedal mucus. The design of a gripper has been proposed, along with performance analysis based on experiments on various parameters, materials and surfaces, exhibiting robustness in unknown and dirty environment, typical of disassembly. Benefits over competing handling technologies and future research directions in this new area have been addressed.

1. Introduction

The reduction of lot sizes and increase in product variety [1,2] for global competition and manufacturing efficiency makes automated assembly and disassembly [3] more demanding and challenging. Flexible automation to face decreasing manpower cost and more complex assembly tasks require the development of performing handling methods and devices.

Various principles have been inspired by nature to allow for gripping and adhesion [4]. Advances are recorded in *dry* adhesion inspired by certain lizards (geckos) and spiders [5] and in grasping by spines as in insects [6]. A novel form of controllable *wet* adhesion has been recently observed, although not completely understood, on gastropod (snails and slugs) pedal mucus [7].

As opposed to dry adhesion, where Van der Waals forces require large areas of intimate contact between the gripper's compliant structures and the surfaces to which they attach in order to achieve sufficient force, in wet adhesion, stronger forces can be achieved by interposing a glue, such as in pressure-sensitive adhesives (PSA) like tape.

Among the main criticalities in wet adhesion are

- the relatively high forces for attachment and detachment,
- residue can remain on the handled part, and
- they are subject to rapid fouling by dust and dirt, decreasing performance over time.

In this paper the use a magnetorheological fluid as the medium in order to achieve *controllable* adhesion by a magnetic field and overcome the mentioned drawbacks of wet adhesion is proposed. By changing the magnetic field, not only attachment and detachment can be controlled, but also the adhesion strength.

It will be experimentally shown that this novel form of controllable wet adhesion can be applied to a wide range of surface conditions, i.e. substrate types and roughnesses (as opposed to suction), it can yield large clamping pressures without needing a ferrous substrate (as opposed to magnetic gripping) and potentially overcome problems with dust and other surface contaminants, e.g. oil from manufacturing operations, which are common in other types of dry and wet adhesion and suction. One potential drawback to consider when selecting the application is that the fluid deposited may stain the substrate with oil, although it has been observed that most of the fluid can be recovered.

2. MR fluid (MRF) properties

Magnetorheological fluids (MRFs) typically consist of a suspension of non-colloidal ferromagnetic particles in an inert oil. The selected MRF [8] is composed of iron particles between 1 and 20 μm, 80% by weight, in synthetic hydrocarbon base oil. (Non-Newtonian) fluids that change their viscosity by an electrical or magnetic field or similar are called active or smart fluids.

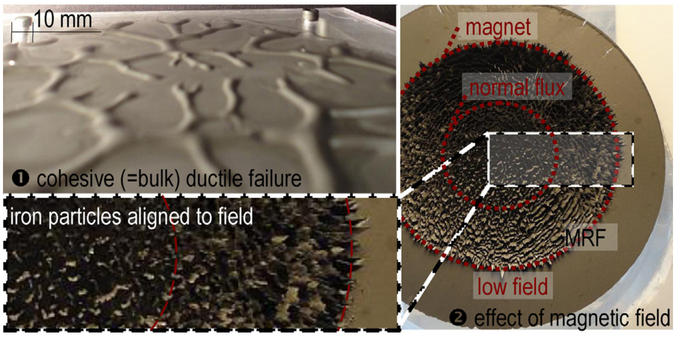

Fig. 1. Effect of the magnetic field on the MR fluid.

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The magnetorheological properties of ferrofluids are well known. In engineering most literature on ferrofluids is on advanced damping systems and brakes in the automotive industry, in addition to machine tools (chatter reduction [9], positioning by controlled buoyancy [10] and polishing [11]) and robotics [12] (prostheses [13]).

An external magnetic field induces magnetic dipoles in the particles, causing them to form chains along field lines. Fig. 1.❷ shows the alignment of particles, more and more inclined toward the edge (zone of influence) of the cylindrical magnet and flat outside, where the field is negligible.

This field-aligned anisotropic configuration strongly resists shear deformation to the viscosity increase with displacements perpendicular to the field lines. Most studies and applications subject MR fluids to shear loading (e.g. dampers). The proposed use of such fluids in this paper is as adhesives with the mechanism described in the next section.

MR fluid adhesive strength can be varied and controlled by varying the external magnetic field over several orders of magnitude. The yield stress on the MR fluid increases with the square of the applied magnetic flux $|B|$ [7] and the maximum, which is material-specific, can be achieved at 0.6–0.9 T [8].

3. Adhesion model

Adhesion forces represented in Fig. 2 are generated as a reaction to the pull-off force applied to the two plates. During separation, in order to keep its volume constant, the incompressible fluid is driven toward the center by the atmospheric pressure and the internal molecular cohesion forces. The negative pressure gradient produces adhesion between the fluid and the two solid surfaces.

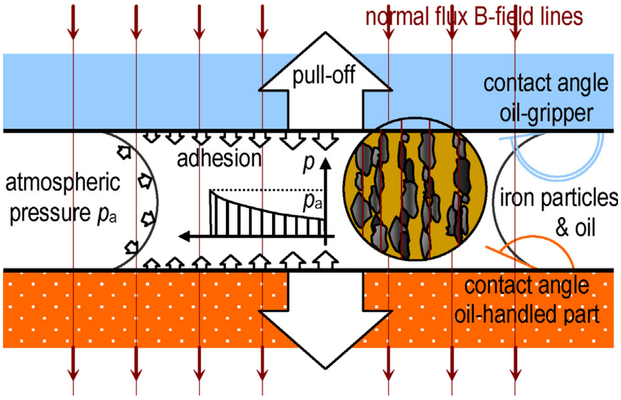

Fig. 2. The proposed adhesion model.

This component of the adhesion force is additional to (molecular or Van der Waals) wetting or capillary forces, due to the difference in surface energy between oil and respectively the gripper and the part materials. In general the MRF shape after spreading is a truncated cone because of different wetting surfaces.

The MRF can be seen as a single use, easily removable temporary glue. The glue itself in turn can be considered like a specialized material, where the iron particles are an elastic metal structure supporting a compliant gripping material, the high viscosity (plastic) oil.

The grasping force is spread over the entire surface of the handled part thus reducing likelihood of damage.

In cohesive failure, the MR fluid yields and deforms in the bulk to relieve the applied strain. In a preliminary set of experiments it has been shown that cohesive failure occurs only at low magnetic fields, below approximately 0.1 T or when link chains (shown in the magnified circular inset of Fig. 2 in actual colors) are degraded by repeated adhesion, as demonstrated in Fig. 1.❶, where the handled part with ripples of fluid is shown after separation from the gripper.

Activated MR fluid exhibits much higher adhesion than the ambient MR fluid ($|B| = 0$ T), making adhesion controllable as desired. At magnetic fields above 0.1 T, the primary observed failure mechanism is interfacial; the MR fluid slowly detaches from the surface until failing in a single brittle event. This critical yield stress is of paramount engineering importance; it sets the boundary between adhesive and cohesive failure defining the maximum stress that can be obtained from a given sample of MR fluid.

In Fig. 3 the two failure mechanisms are visually compared with a cylindrical ∅ 24 mm magnetic field. In cohesive failure, cracks propagate in the bulk and become barely visible at the interface as minute fragmentation. With lower fluid thickness, increased fragmentation has been observed; probably for the contribution of interfacial failure with less available volume of fluid. First cracks appear when the proportional limit in Fig. 5 is reached.

4. Gripper design

This section describes the gripper design aspects involved with the innovative adhesion principle investigated. A scheme of the

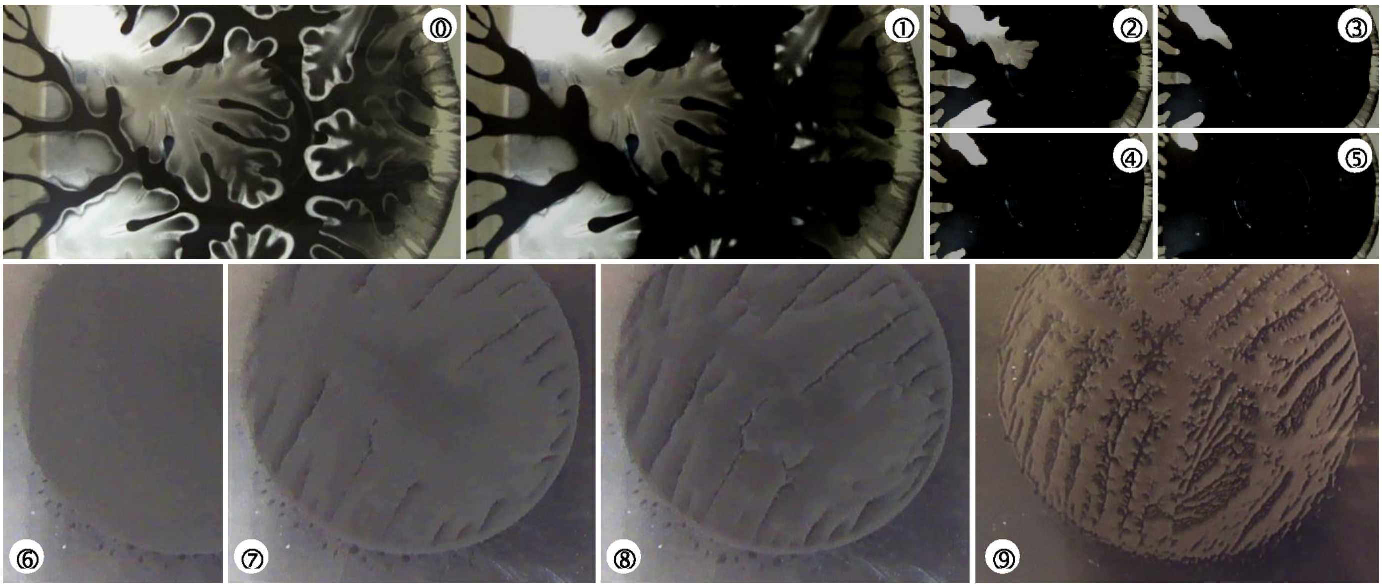

Fig. 3. ⓪: Video frame taken through a PMMA plate immediately after interfacial failure, showing the typical fjord shape with capillary adhesion. ① to ⑤: reversible attachment sequence – similar to detachment – showing that fluid is reusable. ⑥ to ⑧: cohesive failure sequence, maximum strength 675 g, fluid thickness 0.51 mm. ⑨: mixed case, interfacial failure (fjords) triggered from cracks, strength 780 g, thickness 0.24 mm.