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COMPOSITE SAMPLE MOUNT ASSEMBLY (SAMOA): THE ULTIMATE SAMPLE PREPARATION FOR ROTARY SHEAR EXPERIMENTS

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Abstract

Rotary shear machines are becoming a popular tool for rock friction experiments. Such machines are of particular interest to study conditions approaching those of natural earthquakes (slip rates of one meter per second or more, normal stress of several tens of MPa, total slip up to several meters). One key issue for a successful rotary shear experiment is the use of a very carefully and precisely shaped sample. Imperfect samples induce misalignment and spurious vibrations which alter the mechanical data or induce sample failure in the early experimental stages. Traditionally, the cylindrical or annular sample is shaped from a block of the rock which is the object of the test and then introduced in the machine sample holder, either with or without a metal jacket slid around its perimeter. A difficult and lengthy preparation and rectification of the bottom, top and sides of the cylinder is necessary. Here we show that it is possible and advantageous to create a composite sample where one portion only is composed of the rocky material to be studied. A synthetic mortar fills the remaining void between a previously machined metal jacket and the rock portion, insuring cohesion of the assembly. After curing the mortar, the rectification needs only to be done on the top part of the sample (the frictional contact surface for the test). The advantages are that the precision in the sample is improved, the labor time is reduced and it is possible to create a water-tight system for fluid pressurized experiments.

Introduction

The rotary shear configuration for the study of earthquake-like rock sliding was initially proposed by [Shimamoto & Tsutsumi 1994]. Recently several prototypes of similar machines have been installed world-wide. The popularity of this type of apparatus is growing and multiple studies illustrate its use and utility, among others see [Hirose & Shimamoto 2005, Han et al. 2007, Sone & Shimamoto 2009, De Paola et al. 2011, Di Toro et al. 2011]. At the moment the most versatile and powerful specimen SHIVA is in service at INGV Roma, Italy; we do not expand here on the structure and functionality of the machine as this is done elsewhere [Di Toro et al. 2010, Niemeijer et al. 2011].

Earthquake-like rock friction experiments are technically challenging to perform because of the combination of (1) a high relative slip velocity (up to 6 m/s), (2) a large relative cumulative slip (up to several meters) and (3) a rather high normal stress (up to 50 MPa) imposed onto the pair of cylindrical rock samples. The combination of conditions (1) and (3) may be achieved by the use of modified Hopkinson bars [F. Yuan 2008], however the latter attains only small amounts of slip (less than one mm) thus failing to realize conditions (2). Only the rotary configuration allows, so far, to impose slip of the order of meters, as expected in large natural earthquakes, and to verify all three conditions.

During the experiments, one should monitor the evolution of the sample by recording variables such as the dynamic evolution of shear stress, the shortening of the sample and possibly other variables of interest (gas emissions, temperature, etc) using a set of specifics sensors.

The key to a successful rotary experiment is that the pair of samples be perfectly matched, aligned and rectified to a tolerance of a few tens of microns or less, which implies a very careful preparation of the sample.

Here we propose a third-body approach to sample preparation which may appear unorthodox and questionable. Many people, owing to their mechanical, chemical or religious convictions, are at first skeptical in particular about introducing a synthetic mortar (the third body: at this moment, we use epoxy resin) into the sample mount. However, in the lab one learns to accept or reject one approach based on the experimental results. This approach proved to allow good sample alignment and high quality (less noisy) experimental data with a relatively small labor and or cost. Of course, it is subject to improvement as we learn day by day. It has several advantages and few caveats. Altogether we find that the advantages are greater.

First and foremost, it is the only way we found so far to allow water-tight experiments with pressurized fluids. In addition, we started to use the method also for the dry experiments, where it is also advantageous.

The advantages of the described third-body approach are that:

- it allows the use of small or irregular rock samples to some extent;
- it reduces considerably labor time for the sample preparation (lathing, grinding);
- it allows water-tight experiments;

- it prevents sample rotation inside the Aluminum ring;
- it avoids the use of a spacer at the bottom of the sample;
- it allows to achieve a great accuracy in the alignment and the size of the cylindrical sample mount;

while the disadvantages are that:

- the sample mount needs to be cured for ≈48 hours before the use;
- like for cooking, the user needs to acquire a minimum skill through practice;
- it implies the use of a synthetic mortar (e.g. epoxy) with a small extra cost and manipulation;
- it implies the use and the accurate preparation of metal jackets (Al or steel which is best for water-pressurized);
- when the sample mount rotates in the holder by accident, the burnt epoxy stinks.

1. Motivation

Regarding the shape of its outer envelop, the ideal annular or cylindrical sample should have top and bottom perfectly flat and parallel. The walls should be perfectly cylindrical, co-axial and perpendicular to top and bottom.

Otherwise the sample could be mis-aligned and the two sliding faces not perfectly matching once in the machine, inducing stress concentrations, oscillations, increasing risk of sample collapse, and all sorts of annoying consequences which tend to multiply in the presence of guests and visitors.

This is why experimentalists take pains to produce the most perfect rock cylinder by going through a complex and lengthy process involving usually three steps of (1) drilling, (2) grinding, (3) lathing.

We consider this : two thirds of the envelope (bottom and sides) go in contact with "the machine" (e.g., the sample holder); one third only (the top) goes against the other rock sample in frictional contact and this should the only portion of the sample where the properties of the material really matter, because that's what we measure.

So, only the top portion needs to be rock; the rest of the sample may be considered as a passive filler, as far as it can be adapted to the shape of the sample holder and be sufficiently stiff and resistant (thermally, mechanically and chemically) to endure the experimental conditions.

Accordingly, the cylinder that goes in the machine can be prepared as a *sample-mount assembly* (SAMOA) instead of a homogeneous, rock-only sample. All that matters is that (1) the outer shape is precise; (2) the top portion is made of the solid rock that we need to study, down to a sufficient thickness to allow all the relevant processes (thermal conduction, phase transitions, plastic strain, cracking, shortening ...) to take place within the rock; (3) the whole SAMOA is rigid, resistant and possibly water-tight.

This generalization can help us improving the sample preparation and data quality.

Figure 1. Metal rings: (left) original tube cuts, one used, one new; (middle) rings with rectified outer diameter for dry experiments; (right) rings rectified with profiling for use with pressure vessel. Toothbrush for your personal hygiene.

2. Step by step example of preparation

NOTE: The dimensions cited here are specific to our current SHIVA sample dimensions, but they may adapted as needed.

2.1 Metal jackets

For each sample pair, you'll need two metal rings of approx 4 cm height. Cut them from a metal tube of 50/55 mm inner/outer diameter. At this moment we have the exterior rectified down to ≈ 54.9 mm.

If you plan use of pressure vessel, have them rectified to obtain a double outer-diameter tube with etched edges as shown (base 54.9, top 53 mm to go in the pressure vessel O-ring). The portion which goes in contact with the O-ring needs to be optically flat (mirror-like surface) to avoid leakage; this can be achieved by polishing with abrasive paste.

For drying experiments, just use the simple tube segments but slightly thinned down to 54.9 mm. It is better to have a minimum stock of metal jackets all manufactured together in a single order. Mr. Massimo Mari does it for us at the INGV metal workshop, otherwise we can order them to RMP (approx 15 € each pair of the sophisticated, pressure-vessel jackets).

Figure 2. Coaxial drill bit. Drilled rock sample. Lighter (for smokers only).

2.2 Rock

From your available sample, produce something close to 2 rock rings, using the coaxial double-drill bit. Our current drill bit produces something a little less than 50 mm outer diameter. The shape is terrible, and it you were to lathe the outer edge into a perfect cylinder, it would take a lot of time and considerably reduce the outer diameter.

Figure 3. A nylon cable tie is wrapped close to the top of the sample. The rock sample is pushed into the ring until the desired height remains exposed at the top. The uglier, irregular side of the sample faces toward bottom. The nylon tie may be used in order to position the height. Note that the final adjustment of the exposed height will be rectified later using the lathe, so leave a little more than the final height.

Figure 4. Seal bottom of ring with latex.

2.3 Mortar filling

Seal the bottom of the metal jacket (you can use a plastic cap, a latex glove like here, or you can use more provocative items).

Prepare a mix of epoxy resin in the needed amount. As far as possible, mix-in rock powder and rock fragments into the epoxy, so as to obtain an amalgam of rock cemented by the epoxy (except on the sides of the sample which fit narrowly against the metal jacket, where epoxy only should be used as a glue). The use of rock fragments/powder prevents excessive volume loss by shrinking and saves epoxy.

Figure 5. Sit sample, ring and latex on a flat surface. Mix epoxy resin. Pour in resin. Move sample up and down into ring to make sure that epoxy covers effectively the walls between rock and metal. Normally epoxy rises also by capillarity, if the spacing between ring and rock is tight.

Pour the mortar thus obtained inside the ring. Slip the rock ring inside the jacket, until a few millimeters come out the top. Use a nylon cable tie to prevent the rock from sinking too low into the jacket.

Once the rock ring is in place, you can rectify the level of mortar by pouring adding some or inserting rock fragments into the center of the annulus until the desired level is reached.

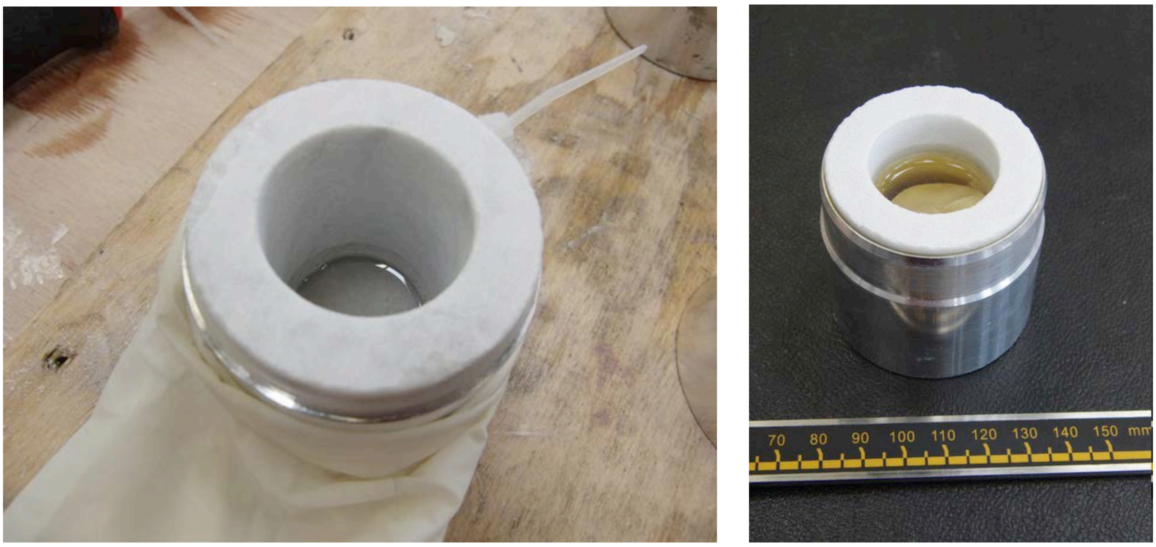

Figure 6. A minimum level of epoxy is sufficient (left), however some like to have a higher level of epoxy (right). If the level is high, insert rock plugs or fragments, in particular in the center hole, in order to use less epoxy. This will also reduce contraction of the mortar during curing.

2.4 Cure

For experiments where fluid-tightness is desired, cure at least for 48 hours. Producers of epoxy say that it cures in less than 24 hours: it's not exact: while it becomes hard to the touch, it is not fully cured to its top resistance and hardness. When using pressure vessel, in particular, not fully cured samples will crack and water will leak. They also say that epoxy does not shrink while curing: false, most of them loose about 10% in volume! Be aware of that for the preparation.

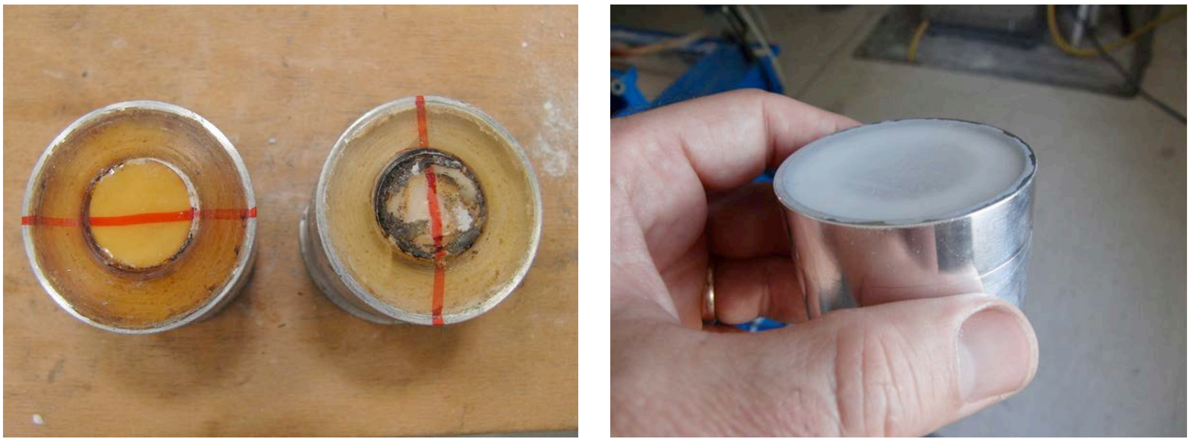

Figure 7. Examples of SAMOAs' bottoms after curing, with or without rock plugs.

2.5 Rectify

Put the sample-mount in the lathe. You have nice and accurate cylindrical walls of the metal jacket as a reference! Lathe only the top of the rock sample coming out of the jacket: Spin the sample-mount in the lathe and spin the drill in the opposite direction, using the flat part of the cylindrical drill bit against the sample top. Fix the drill at an angle of a few degrees to the axis of the lathe, not completely coaxial! This should take only about ten minutes to get a flat, rectified sample top.

Although it's not absolutely necessary, you may want to lathe also the outer and the inner cylindrical walls of the topmost part of the rock, the part close to the frictional contact surface. In this case make sure to scratch off all residue of epoxy on the rock walls beforehand: the spin-bit of the drill does extremely poorly on epoxy and gets spoiled.

Figure 8. Fix the SAMOA in the lathe. BE CAREFUL! Make sure you removed all mobile parts (keys,...) from the mandrel before starting the machine. Do not put hands or objects too close to the claws. Check smoothness of rotation and centering: an object on the metal surface should not vibrate or jump (right).

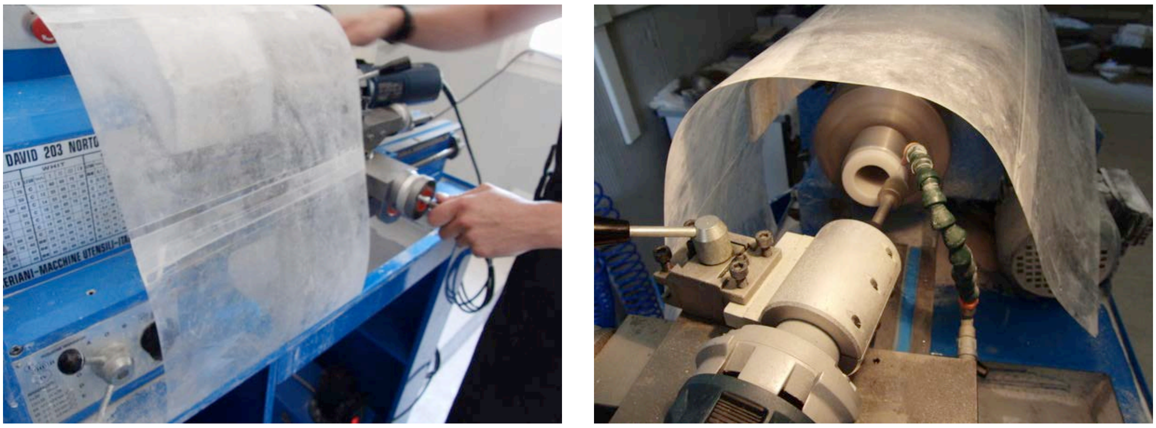

Figure 9. Cover with screens, plastic sheets, protections to avoid excessive water outflow.

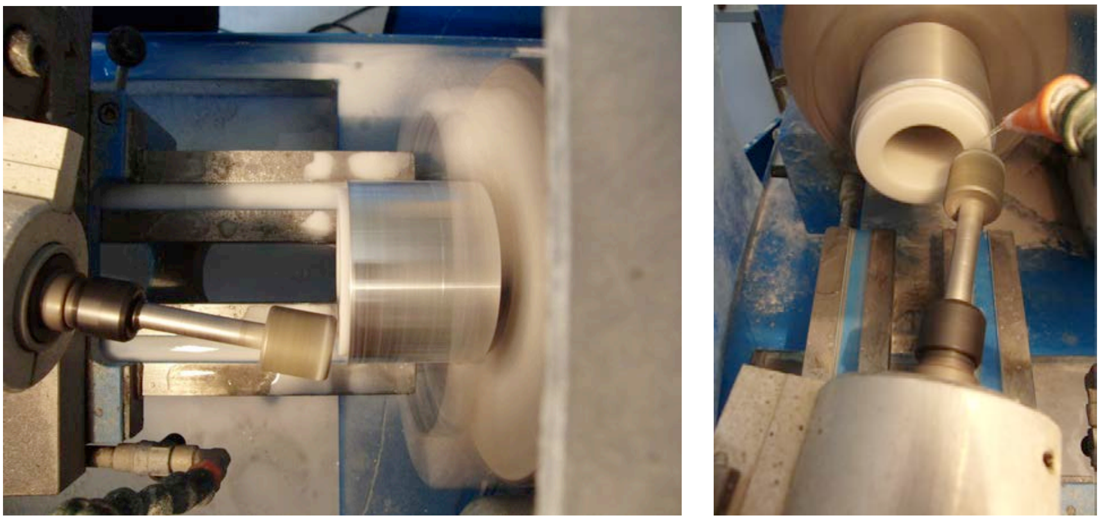

Figure 10. Approximate drill cylindrical bit to the sample top, the drill axis should make an angle of a few degrees with the late rotation axis (left). Turn on water and adjust the water gasket so that water is dripping on the sample. Spin direction: there are several possibilities depending on whether you set the drill at the far or close end of the SAMOA, and whether you make the angle in one direction or the other. Just always think that at the contact point between rock and drill bit, the tangential motions should be opposite in order to maximize mutual speed.

Figure 11. Move the drill into contact and then slide the drill back and forth from inner to outer edge. After each sweep advance slightly the drill in order to remove more fresh rock. Repeat until desired sample height is reached. Slower motion produces smoother results. Sweeping from inside out prevents chipping at the inner edge.

3. Conclusion

We have illustrated the use of mortar for improved rotary sample preparation. A minimum practice of this method is necessary to obtain satisfying results. Users will find that it is easy to adapt this idea to many different situations (full cylindrical samples, different sample sizes, etc) or to improve it with time by implementing slight modifications.

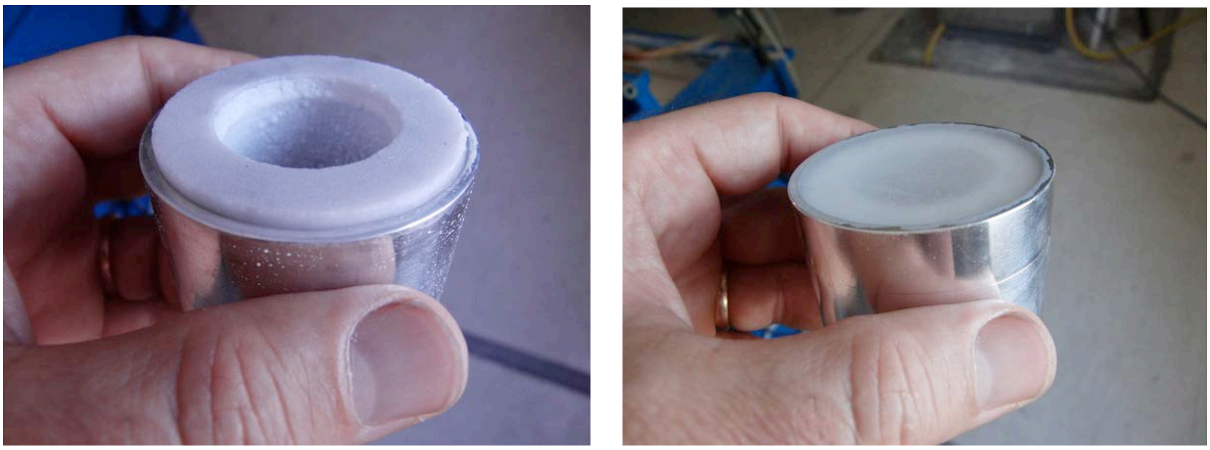

Figure 12. Finalized SAMOA, top and bottom.

Acknowledgements

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