A SERIOUS KINEMATIC COUPLING

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What are the design parameters for a kinematic coupling that must repeat to a few microradians and have an unheard of minimum life of 20,000 insertions and extractions? Actually 120,000 cycles were achieved, at which point testing was stopped.

When the level of repeatability required of a kinematic coupling is in the realm of nanometers and microradians, instead of micrometers and microinches, serious attention must be paid to every detail.

At the first physical contact between the component parts, of the two platforms, of kinematic system, elastic compliance sets in. The deterministic limits, of the repeatability, of the system, begin to manifest themselves, right here.

Rather than dwelling on the inherent weaknesses we will concentrate on those positive factors that we can control to maximize function. The sum total of all the features of a serious kinematic system is that it must provide a “slippery slope” between the elements.

Slipping fosters continuous motion, of the removable platform, as contrasted with a premature sticking or stopping. The slippery part of this axiom can be enhanced by using the stiffest material possible. Stiffness here is simply the highest Young’s modulus and the lowest Poisson’s ratio possible. Imagine the asperities on the surfaces coming into contact, between two very stiff and then two very compliant materials. The enhanced propagation of continued movement between very stiff surfaces will be apparent.

The practical choices of ideal materials for these high-end devices are greatly simplified by the limited availability and extreme price sensitivity of most of the candidates. In addition friability is a very undesirable quality for kinematic systems, but it is very characteristic of many of the apparent candidates. Good examples of friable materials are sapphire and silicon carbide.

Cermets such as tungsten and titanium carbides, where the particles of ceramic are cemented together with a binder metal, are much tougher than true ceramics where only partial fusion of the particles occurs. Cemented carbides have the additional advantage, in that they are electrically conductive, so that they can be inexpensively machined using the EDM (electrical discharge machining) process. An additional advantage for the cemented carbides is that they are available in micro-grain (sub-micrometer particle size) material that is hot iso-static pressed (HIPED) for near 100% density.

The material chosen for this specific project was a 94 percent tungsten carbide 6 percent cobalt, micro grained, hot iso-static pressed material. This material has a Young’s modulus of elasticity that exceeds 100,000,000 psi (in compression) and a hardness of 91 HRA.

The second element in the slippery part of the axiom is the surface texture. Here we are emphasizing total surface texture over simple micro finish, because the waviness element of surface texture literally provides teeth in the surfaces that can lock together and impede the slippage of the system to true mechanical equilibrium. Conventional ground surfaces have tiny undulations that aren’t really slippery. Just try sliding the ends of your finger nails over a ground surface. Even the finest ground surfaces, will feel “chalky”.

A really slippery surface has the grain structure of the material truncated off to a single plateau.

A good gage block has a surface texture of about one microinch (0.025 micrometer) Ra. In contrast, the surface quality of really high quality kinematic components is between 0.1 to 0.2 microinches (0.003 micrometers), (2.5 to 3 nm) Ra.

The slope part of the equation starts with the contact angle between the component parts of the system. Although a 45 degree angle is commonly used in conventional components, the very best slope for repeatability is 60 degrees. Tests have been conducted that showed repeatability of plus or minus one nanometer at this angle. Although this quite steep slope gives the best location, it dramatically reduces the load carrying capacity of the system.

Immediately, after coming into contact, with each other, the components of the two platforms slide, in at least two directions. As they move together, they rotate, and slide as they find mechanical equilibrium. To minimize stiction between the elements, the overall two-axis slope can be increased by using a sphere against two cylinders, instead of a sphere against flat prismatic surfaces. Unfortunately this increased slope is achieved with a considerable sacrifice in load carrying capacity. The total load (platform and payload) on this project was six pounds.

When the surfaces of the component parts come into physical contact, they are placed under high Hertzian elastic stress. The slipping between the two contacting surfaces, as they move to achieve mechanical equilibrium, can be a serious source of wear.

It is imperative that we understand the mechanism of this tendency for wear, if we are to minimize or eliminate it. This initial wear mechanism is similar to fretting in many ways but we prefer to use more accurate description of short stroke wear, to separate it from the true, in place fretting that can occur when the two kinematic platforms are fully engaged.

When the two component parts of the kinematic system come into physical contact, the molecular interfaces actually adhere to each other. This adhesion can be so strong that it approaches or even equals the shear strength of the materials involved. As the two surfaces, which are under high Hertzian stress, slide over each other, the molecules in the surface layers become confused. They lose their identities, and easily separate from their native materials. Under the high stresses involved at these sliding interfaces, the surface temperatures at the molecular level can be raised to a reaction level and chemical by products result. The amount of these compounds generated is minute for each insertion or extraction, but they are steadily fused by the pressure and temperature into sizable platelets. Compressive stresses exude this material from the interfaces as a thin plate. This thin sheet of chemical compound is usually an oxide of the base material, and it is very brittle. The compressive stresses that exude this material out of the intersection between the kinematic elements results in tensile stresses within the thin brittle plate that causes it to break up into small thin bricks. The thickness of these bricks, in the system under study, appears to be on the order of one micrometer, as estimated from the SEM. photomicrographs.

This relatively thin turbidity causes a significant decrease in the repeatability of the kinematic coupling. The almost certain cause of this dilemma is that these brick-lets lodge under the sphere as it approaches mechanical equilibrium. These brick-lets act as chocks that stop the sliding motion of the platform far short of its proper end position.

As is often the case in kinematic coupling systems, the allowable freeboard on this system was very limited. A six-pound load may not seem like much, but as the ball size is driven down by the constraints of the allowable free board and is exacerbated by the steep sixty-degree contact angle and the need to use cylinders instead of prismatic surfaces, the requirement for a large support radius for the cylinders becomes imperative. The ball diameter was limited to one half inch (12.7 mm), which required a three quarter inch (19.05 mm) diameter cylinder, to give an adequate safe load factor. The freeboard constraints wouldn't allow these large diameter cylinders, to be used, so the quarter round concept was employed. In this scheme the cylinders are split up into four individual components. This dramatically reduces both the height and the width of the structure.

The very rigid system employed for mounting the half-inch diameter ball consisted of burying one half of the ball in a spherical pocket and holding it in place with an M4X0.7 cap screw from behind. This configuration is a good example of the need for electrical conductivity, so that the threaded hole could be machined in the incredibly hard tungsten carbide ball, by EDM.

The three quarter inch (19.05 mm) diameter quarter rounds were housed in three sets of precision-machined trenches and were held in place by M4X0.7 cap screws.

The layout of the kinematic system was a nice symmetrical Maxwell setup, with the three vees laid out in an equilateral 120 degree pattern. The platforms were both simple aluminum plates, without any whistles or bells.

One of the factors that have not been discussed is the basic, coefficient of friction, between the materials rubbing against each other. We haven't found a lot of published data on either the breakout or running friction of the otherwise desirable materials, but we have been privy to limited information from tests performed by the materials manufacturer that indicate good to excellent performance.

After 7500 insertions and extractions were made some sporadic disparities in location began to appear. A slight modification of the coupling that connected the robotic arm to the upper platform was made. This modification changed the angle of attack very slightly. This slight change altered the path of the upper platform minutely and restored the original accuracy that repeated thru 12,000 cycles.

I believe that there is considerable significance to this ploy. By systematically altering the attack angle between the platforms, a significant improvement in the accurate life of kinematic systems could be assured.

This kinematic system was designed to ultimately be used in a moderate vacuum. After achieving excellent repeatability, but less than desired longevity, a vacuum compatible lubricant was applied to the elements of the kinematic system. Extensive testing under ambient conditions showed good results, so the system was placed in vacuum and the test was resumed. At 120,000 cycles the repeatability was still within specification and the test was concluded.

In seeking even further improvements in the performance of this really “serious kinematic coupling” testing of titanium carbide cylinders against tungsten carbide balls and against silicon nitride ceramic balls is being pursued.