Kinematic couplings for precision fixturing — Part 2: Experimental determination of repeatability and stiffness

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Results of tests performed to determine the repeatability of a large kinematic coupling are described. The coupling was constructed from two 356 mm (14 in) diameter 102 mm (4 in) thick cast iron discs with hardened steel gothic arch inserts and 28.6 mm (1.125 in) diameter balls. A special load frame was constructed for performing cyclic tests of kinematic coupling while applying a 5800 N (1300 lbf) preload. Different types of balls and lubrication at the interface were tested. When using lubricated silicon nitride balls, axial and radial 3σ repeatability was on the order of 0.30 μm (12 μin). Worst case axial and radial stiffness was on the order of 1.09×10^8 N m^{-1} (0.62×10^6 lbf in^{-1}) and 1.58×10^8 N m^{-1} (0.90×10^6 lbf in^{-1}), respectively, and at best was twice these values. Machined surface finishes on the order of 0.3 μm (12 μin) were obtained while using the coupling to hold a 304 stainless steel part machined with a depth of cut of 0.13 mm (0.005 in) at a rate of 55 surface metres per minute (180 SFM).

Keywords: *kinematic couplings, precision fixturing, turning, repeatability, stiffness*

Introduction

Large fixtures are used on precision turning centres for holding optics and other precision parts, and changing fixtures often involves extensive manual set-up time to tap them into place. Because of possible loss of repeatability arising from contamination of tooth interfaces, couplings that rely on the principle of elastic averaging to obtain high repeatability cannot necessarily be used as a substitute to speed the process. Kinematic couplings are often used in static operation, but have generally been considered insufficiently stiff to withstand dynamic machining forces.

It has been shown theoretically in Part 1 (see Ref. 1) that a three-groove kinematic coupling could be designed to locate large fixtures with respect to a reference surface with a repeatability on the order of 0.36 μm (14 μin) when subjected to 75 N (17 lbf) cutting loads and anchored with a 45 kN (10000 lbf) preload. If the preload is high and repeatable, and the ball-to-groove interface properly designed, axial and radial stiffness on the order of 210 kN mm^{-1} (1.2×10^6 lbf in^{-1}) should be attainable. The question unanswered by the theory, however, is whether or not the coupling would be repeatable in the presence of the high contact stresses at the ball-to-groove interface.

Most applications of kinematic couplings for precision fixturing have been in low static force environments, and no reference was found with regard to their use in high speed machining operations. Thus in order to determine the accuracy of the calculations in Part 1, tests were made on a full scale model to determine the repeatability of large preloaded kinematic couplings. In addition, to increase the ease of implementation (both of the experiment and in actual use) it was decided to test the coupling only using preload forces that could be generated by a vacuum acting over the area of the coupling.

Engineering principles of kinematic couplings

A coupling has the property of being 'kinematic' if the number of intended contact points between the two bodies it couples equals the number of degrees of freedom it is intended to restrain. For most fixturing operations, six degrees of freedom are to be restrained. In order to provide six discrete contact points, various combinations of curved surfaces can be used. The geometry and arrangement of the surfaces is critical to give maximum stiffness with minimum contact stress at the interface. The detailed methodology for accomplishing this is discussed in detail in Part 1.

If the number of degrees of freedom equals the number of intended contact points, then the system

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is deterministic, and its performance can be predicted in closed form using the theory of elasticity. Also, since only six contact points exist between the two bodies of a kinematic coupling, the probability of foreign matter contaminating the interface and decreasing the repeatability is reduced. Furthermore, particles or films on the point of contact will very likely be squeezed out by the high contact pressures at the interface. However, since there cannot be true point contact between two surfaces, the one unknown in the use of the theory is the extent of nonrepeatability caused by the fact that a finite contact area and associated frictional forces do exist. Having six discrete contact points also enables the structure to be manufactured without the need for extremely high tolerances. Thus the repeatability of the coupling can be orders of magnitude greater than the accuracy to which the coupling was manufactured. Furthermore, because the coupling is not overconstrained, an extensive wear-in period should not be required.

If the theory could be proven, then kinematic couplings could be easily designed for various precision fixturing applications in a production environment. For example, if the grooves are located on the part that is fixed to the machine, then each fixture can have its balls at a unique radius. Thus the contact points on the fixed grooves will be unique for each fixture, and one fixture cannot affect another. In the event of a crash (eg tool post feeds into the fixture), only one fixture and its associated seating point would be destroyed. Furthermore, because each fixture's balls have a unique seating point a fixture can be added to the group without requiring all fixtures to be simultaneously re-worn in.

Thus it seemed plausible that the theory could have practical engineering application if the effects of finite contact areas and frictional forces could be assessed.

Critical issues in the design of kinematic couplings

Part 1 concluded that ideally, to hold a fixture for a 254 mm (10 in) hemishell with 0.36 μm (14 μin) accuracy when subjected to a 75 N (17 lbf) cutting force, a 356 mm (14 in) diameter coupling with 28.6 mm (1.125 in) balls in contact at 45° with 17.15 mm radius (0.675 in) gothic arches, and 45 kN (10000 lbf) preload was required.

However, there are several factors which theoretical design considerations cannot readily address, including the effects of

- friction,
- contact stress,
- surface finish,
- surface contamination.

The best way to determine the effects of these factors on repeatability is to test a full scale model.

Experimental procedure

Before embarking on an elaborate experimental investigation of the effect of various real-world parameters on kinematic coupling repeatability, it was decided to see how good the coupling could be when fabricated with a modest budget.

Fig 1 Experimental apparatus used to test the repeatability of the three-groove kinematic coupling

A steel load frame was constructed and a pneumatic piston used to raise, lower, and provide the preload between two 356 mm (14 in) diameter, 102 mm (4 in) thick, kinematically coupled cast iron discs, as shown in Fig 1. A 5800 N (1300 lbf)* preload with 1% repeatability was used in all experiments. The lower disc was itself mounted on a pseudo-kinematic mount of tapered bolt heads threaded through the steel frame and seated into grooves in the lower disc. The piston would raise the upper disc about 13 mm (0.5 in) above the lower disc, then lower it onto the lower disc and apply the preload.

The piston ram transferred its force through a shear beam type load cell to a 38 mm (1.5 in) thick aluminium plate. The plate was loosely connected to the upper cast iron disc with three 10 mm (3/8 in) bolts in 13 mm (1/2 in) clearance holes located over the discs' contact points: 13 mm (0.50 in)

** The theory recommended a 45 kN preload; 5800 N preload corresponds to the preload attainable with a vacuum acting on the discs, and thus was the preload used in the experiment* thick, 5 cm (2 in) diameter neoprene rubber pads were placed between the aluminium plate and the upper cast iron disc to ensure uniformity of the load distribution only over the contact points between the discs. This prevented warping the discs upon application of the preload.

To measure the repeatability of the kinematic coupling, only relative motion between the discs had to be measured. As shown in Fig 2, 50 mm × 100 mm (2 in × 4 in) steel brackets bolted and epoxied to the lower disc, held spring-loaded LVDTs against ground and polished surfaces on the upper disc. The upper disc was only raised about 13 mm (0.50 in) between cycles. This design formed a very tight structural loop which minimized mechanical and thermal noise. The massiveness of the system coupled with temperature stability of $\pm 1\,^{\circ}C$ rendered thermal growth errors in the measurements negligible. The sensitivity of the system was about 6.5 mV μm^{-1} (0.17 mV μin^{-1}). Stability of the system output over a 24 h period was on the order of 0.05 μm (2 μin).

One of the ultimate goals for this type of kinematic coupling is to hold the fixture for parts on a turning machine; thus error motions of the upper disc in axial and radial directions as well as tilt motions about two orthogonal axes are of interest. In order to measure these error motions, six LVDTs were used. Three of these LVDTs were mounted vertically in the steel brackets around the circumference of the disc and 120° apart from each other. These LVDTs were used to measure axial and two tilt error motions. The other three LVDTs were mounted radially on the same brackets that held the vertical LVDTs. They were used to determine the radial error motion of the upper disc with respect to the lower disc. One of the radial LVDTs was redundant, and was used to determine closure of the measurements.

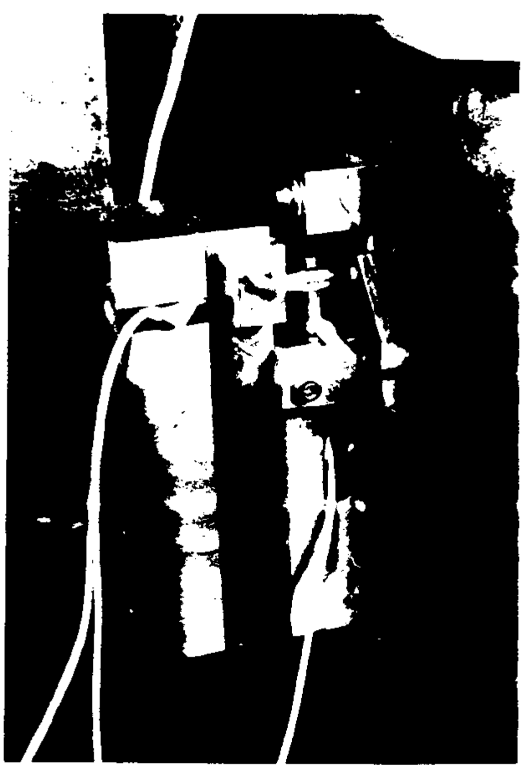

Fig 2 LVDT probes for detecting relative motion between coupling halves

The data acquisition system consisted of a desktop computer, a relay-activated transducer amplifier for the LVDTs, a load cell to measure the preload, and several digital voltmeters to monitor the load cell and LVDT outputs. The computer controlled and monitored the entire experiment: raising and lowering of the disc, reading the LVDT outputs, and calculating the error motions using these outputs. After each application of preload, the data acquisition software waited for about 20 s to allow for the system to settle. After this delay, the computer started scanning the LVDT outputs. For each LVDT, it took 10 readings and stored the average. Finally, after taking the load cell reading, the computer raised the upper disc. This cycle was repeated 600 times with 15 s intervals between each cycle. In this manner, automated testing could take place over a period of days to obtain several sets of data for each condition tested.

Results

The first round of experiments was performed using steel balls epoxied into hemispherical seats in the lower disc, and hardened steel gothic arches in the upper disc. Radial repeatability was on the order of 0.5 μm (20 μin). However, with time, repeatability decayed to only about 2.5 μm (100 μin). To check the reliability of the measurements, radial LVDT outputs were used to back-calculate the radius of the coupling. Agreement between sets of measurements at the start of the tests and the end was about 0.0025 μm; thus, accuracy of the measurement was confirmed. Upon examining the ball–groove interface, it was found to have brown rust marks. This occurrence of fretting corrosion, which was anticipated in Part 1, thus precludes the use of steel balls in steel grooves.

The steel balls were then replaced with silicon nitride balls, but the repeatability was found to be only on the order of 2.5–12.5 μm (100–500 μin). It was thought that the ball was rocking in the hemispherical seat despite the epoxy. At the ball–groove interface, no fretting was observed, but the interface did contain 'smear marks' visible with the naked eye, as shown in Fig 3. No brinelling was observed. Oddly, when the marred region was observed under a microscope, its surface, which had grinding marks from the manufacturing process, could not be discerned from the surrounding area.

The hemispherical seat was then ground out into a gothic arch shape to match the other groove. The logic was that in production, it would be cheaper to make all hardened steel inserts the same. Even when epoxied in place, the balls migrated along the grooves with changing load eccentricities and repeatability was found to be only on the order of 12.5–25 μm (500–1000 μin).

The next step was to EDM a trihedral pyramid seat into three of the vee blocks for holding the silicon nitride balls. This trihedral seat ensured that the balls themselves were kinematically mounted. The balls were placed in the trihedral seats, and the preload mechanism was cycled. The upper disc was then raised, and liberal amounts of epoxy poured around the balls in the trihedral seats. The preload was then applied and the epoxy allowed to cure. A ball epoxied in a vee block with a trihedral seat is shown in Fig 4.

Fig 3 Smear mark (circled) in gothic arch groove

Fig 4 Silicon nitride ball epoxied in trihedral mount located in vee-block

The balls and grooves were carefully cleaned with freon to ensure that the test would not have an error component caused by foreign matter contamination. The results are shown in Figs 5–8 and Table 1. The radial repeatability was only 1.40 μm (55μin), and the system never stabilized. A careful analysis was made of the situation, and first order calculations indicated that the error could result from friction in the system. When stability tests were made, the system would take hours to stabilize. This indicated high interface stresses that were slowly trying to relax. The solution, therefore, seemed to be to lubricate the ball–groove interface.

The next series of experiments was preceded with a generous application of grease to the balls and the gothic arch grooves. As the upper disc was raised and lowered by the piston, it wobbled considerably, and would thus wipe a new smear of grease onto the contact points before the preload was applied. Settling time for this system was on the order of 10–20 s. The results obtained from three different sets of 600 readings each are shown in Table 2. Figs 9–12 show a typical set of data from these tests.

With respect to the first cycle, when lubricated, the coupling repeats radially to about 0.68 μm (27 μin), and axially to about 0.76 μm (30 μin). After a wear-in period of about 50 cycles the system quickly stabilized. The average repeatability after wear-in was 0.30 μm (12 μin) radially and 0.33 μm (13 μin) axially as shown in Table 2. The wear-in period is attributed to the 'rough' surface finish of the ground arches (0.5 μm). If polished arches were used to begin with, the wear-in period should not be necessary.

When subjected to a 90 N (20 lbf) radial force applied 5 cm above the line of coupling action, the coupling was still very repeatable, as shown in Table 3. Table 3 also shows the average stiffness of the coupling along and about its axes. The three-

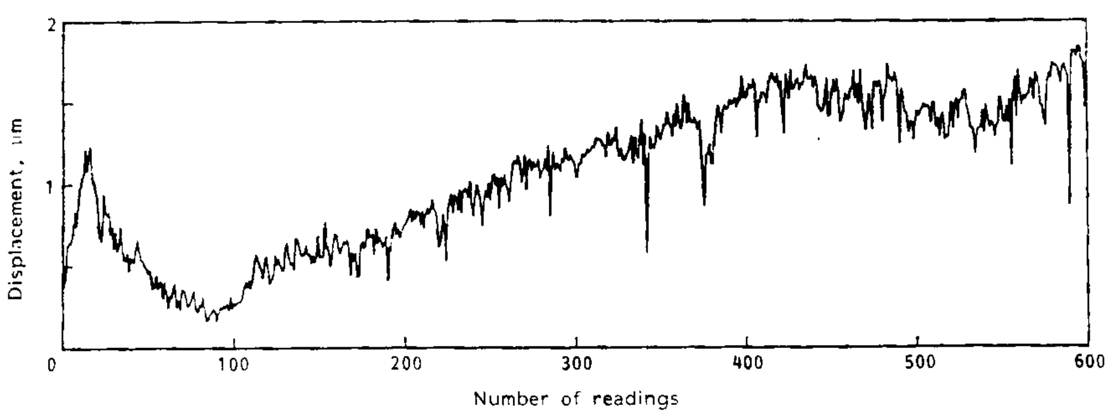

Fig 5 Radial repeatability of unlubricated kinematic coupling

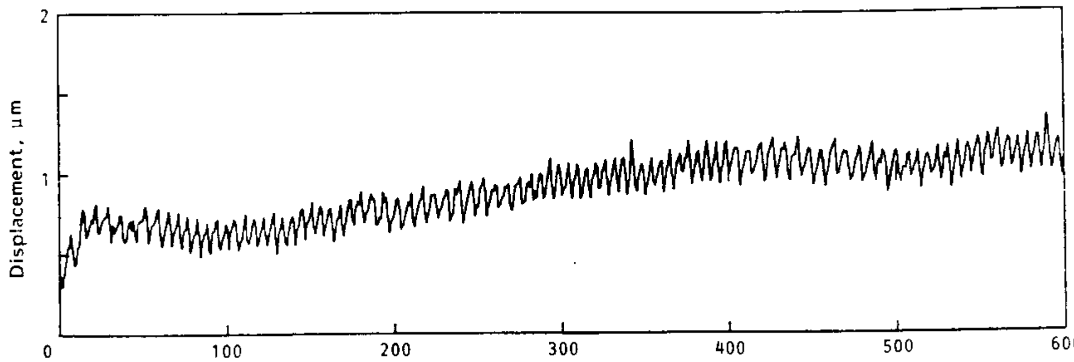

Fig 6 Axial repeatability of unlubricated kinematic coupling

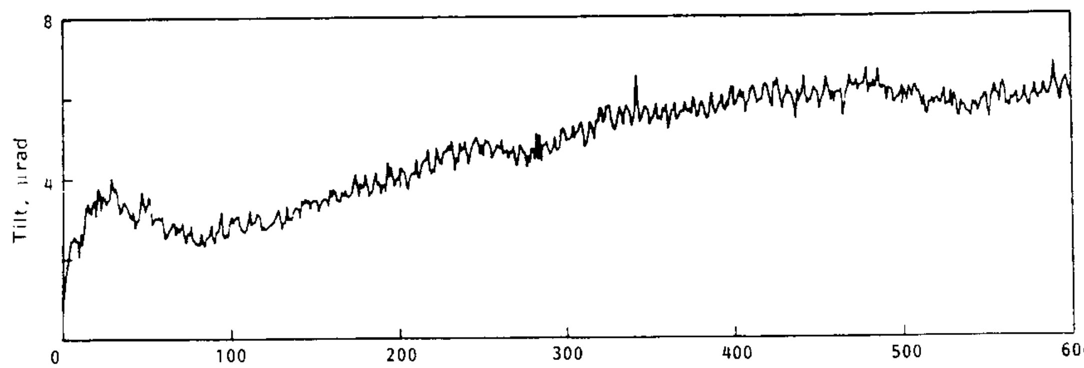

Fig 7 X axis tilt repeatability of unlubricated kinematic coupling

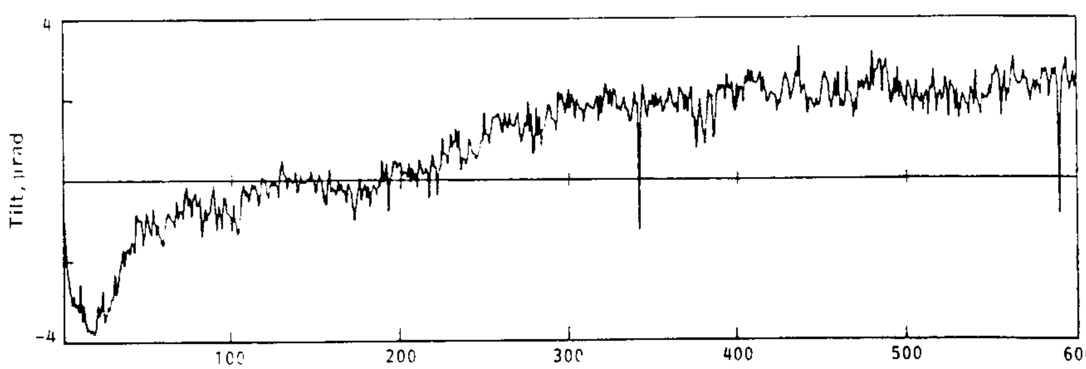

Fig 8 Y axis tilt repeatability of unlubricated kinematic coupling

Table 1 Unlubricated kinematic coupling 3σ repeatability

Axial:	0.90 µm (35 µin)
Radial:	1.40 µm (55 µin)
Tilt-X:	~ 5 µrad
Tilt-Y:	~ 5 µrad

groove kinematic coupling is definitely stiff enough to withstand light machining forces, such as encountered in diamond turning operations, and still maintain submicron accuracy.

In general, with respect to the scatter in the data, consider that the surface finish of the ground gothic arches was only about 0.5–0.8 µm (20–30 µin) rms. Also consider that the coefficient

Table 2 Lubricated kinematic clamp 3σ repeatability

	Set 1	*Set 2*	*Set 3*	*Set 4*	*Set 5*	*Set 6*	*Avg (2–6)*
Axial: (μm)	0.76	0.28	0.38	0.23	0.28	0.35	0.30
(μin)	(30)	(11)	(15)	(9)	(11)	(14)	(12)
Radial: (μm)	0.68	0.35	0.33	0.43	0.30	0.25	0.33
(μin)	(27)	(14)	(13)	(17)	(12)	(10)	(13)
Tilt-X: (μrad)	1	2	1	2	2	1	1.6
Tilt-Y: (μrad)	3	4	3	2	3	2	2.8

Total number of cycles on system = 600 × set number

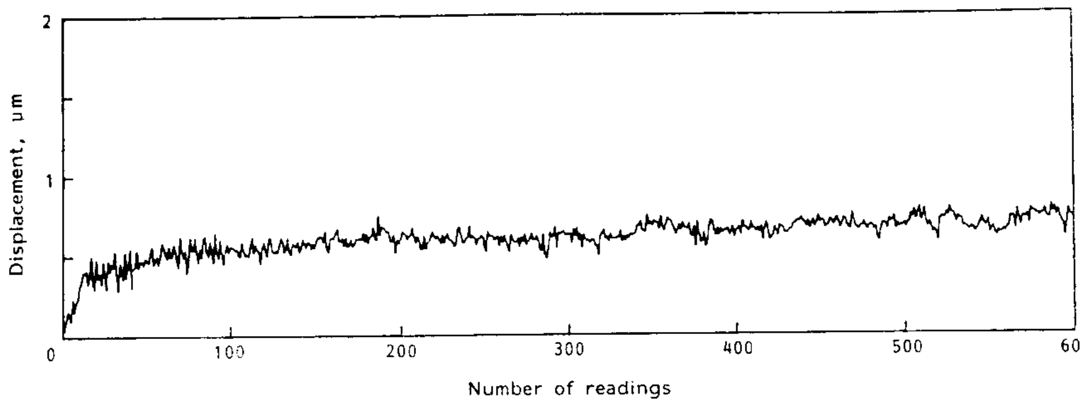

Fig 9 Radial repeatability of lubricated kinematic coupling

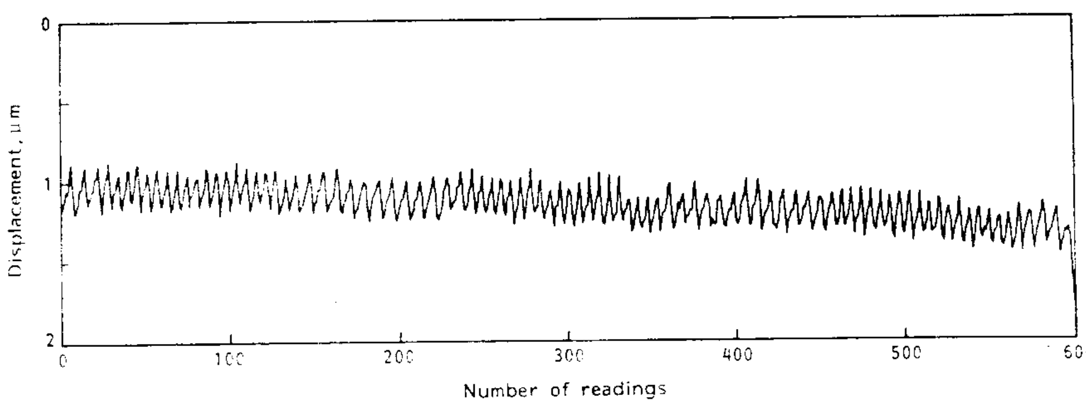

Fig 10 Axial repeatability of lubricated kinematic coupling

of friction of silicon nitride on silicon nitride without lubrication is lower than silicon nitride on lubricated steel. Furthermore, the footprint of silicon nitride on silicon nitride would be about half that of silicon nitride on steel. Thus, a silicon nitride on silicon nitride kinematic coupling would more closely achieve a true kinematic interface, which requires point contact between surfaces.

Since these tests yielded acceptable repeatability levels, it was decided to construct a base and pot chuck, that used the arches and balls from the repeatability tests, to hold and cut a part on a CNC lathe. A vacuum system was not available for the lathe, so three L-shaped brackets were bolted to the lower disc, and setscrews, positioned over the location of the balls in the upper disc, were used to preload the coupling. A 400 mm (8 in) diameter 304 stainless steel blank was held by the pot chuck, and both roughing and finishing cuts were made. It is interesting to note that even though the set screws were only tightened to a few newton metres (snug hand tightened) the setscrews never loosened during the roughing or finishing operations. The depth of the finish cut on the contoured section of the part was 0.13 mm (0.005 in) and the feed rate was 55 surface metres

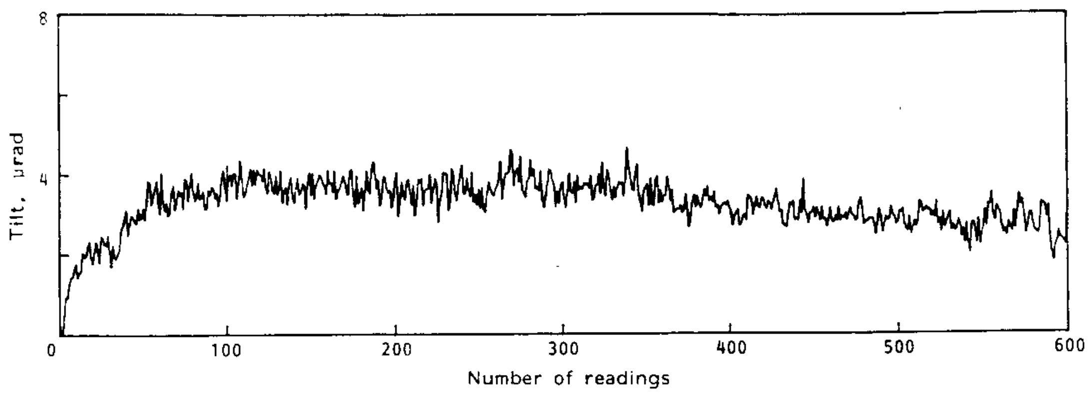

Fig 11 Y axis tilt repeatability of lubricated kinematic coupling

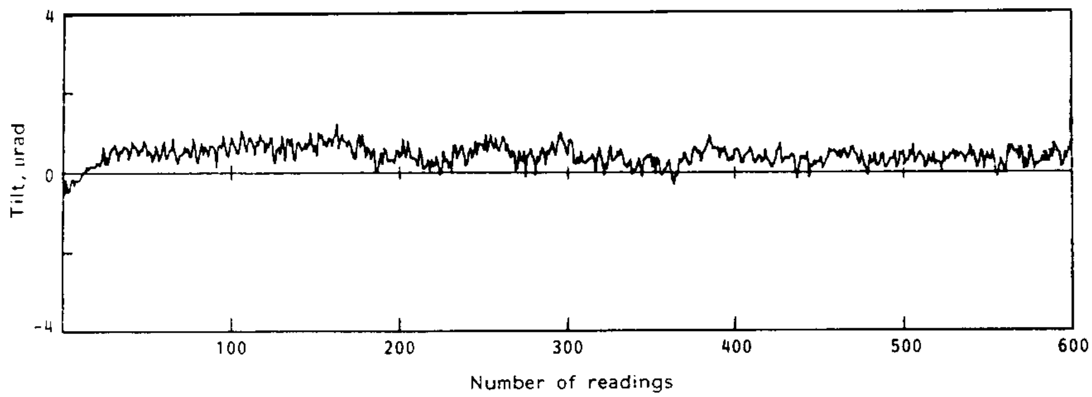

Fig 12 X axis tilt repeatability of lubricated kinematic coupling

Table 3 Unlubricated kinematic coupling repeatability with 90 N applied radial force

	Set 7	*Set 8*	*Set 9*	*Avg (7–9)*	*Stiffness*
Axial: (μm)	0.65	1.25	0.58	0.83	1.09×10^8 N/m
(μin)	(26)	(50)	(23)	(33)	(0.62×10^6 lbf/in)
Radial:	0.23	0.78	0.70	0.57	1.58×10^8 N/m
	(9)	(31)	(28)	(22)	(0.90×10^6 lbf/in)
Tilt-X: (μrad)	11	12	5	9.3	4.83×10^5 N m/rad
					(4.28×10^6 lbf in/rad)
Tilt-Y: (μrad)	25	3	7	11.7	3.85×10^5 N m/rad
					(3.40×10^6 lbf in/rad)

Total number of cycles on system = 600 × set number

per minute (180 SFM). With a new ceramic insert tool, the surface finish was 0.3 μm (12 μin). On a different section, a 0.52 mm (0.020 in) depth of cut was used and the surface finish was 0.4 μm (15 μin). Thus when subjected to the ultimate test, roughing and finishing machining tests in a hard-to-machine material, the coupling performed as well as the machine itself.

Conclusions

Based on the above results, the following conclusions were made concerning the performance of a silicon nitride ball in a hardened steel gothic arch with 0.5–0.8 μm surface finish, 0.36 m (14 in) diameter ball-groove kinematic coupling with 5800 N (1300 lbf) preload:

- Lubricated with no wear-in period the average 3σ repeatability was about $0.68 \mu m$ (27 μin) and 0.76 μm (30 μin) in the radial and axial directions, respectively with $0.5 \mu m$ (27 μin) surface finish components. After 50 cycles wear-in, a factor of 2–3 improvement occurred. This was with 0.5 μm surface finish arches. No wear-in repeatability is a strong function of surface finish.
- Worst case radial and axial stiffnesses are on the order of 1.58×10^8 N m^{-1} (0.90×10^6 lbf in^{-1}) and 1.09×10^8 N m^{-1} (0.62×10^6 lbf in^{-1}), respectively. At best it was about twice these values.
- The coupling could be used in a rough, dirty, industrial machining environment: Surface finishes on the order of 0.3 μm (12 μin) were obtained while using the coupling to hold a 304 stainless steel part machined with a depth of cut of 0.13 mm (0.005 in) at a rate of 55 surface metres per minute (180 SFM).
- Friction and surface finish are the major contributors to nonrepeatability.
- Grease helps to decrease friction between silicon balls and steel arches, but attracts dirt.
- For best performance, it is recommended that the coupling be made from silicon nitride balls and silicon nitride gothic arches; and an oil mist spray be used to clean and lubricate the contact surfaces before coupling takes place.

When used as part of a machining workcell, the following properties of kinematic couplings can be inferred.

- Contaminants will have little effect on repeatability.
- Crashing the machine will only wreck one fixture.
- Silicon nitride kinematic structures have a very brief wear-in period.

Thus it seems that kinematic couplings can be used as devices to enable different fixtures to be quickly and accurately changed without the need for a machinist to tap them into alignment. Kinematic couplings can be useful tools in the quest for achieving an automated precision flexible manufacturing system.

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