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Research on Normal Contact Stiffness of Rough Joint Surfaces Machined by Turning and Grinding

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(*a*) (*b*) (*c*) (*d*)

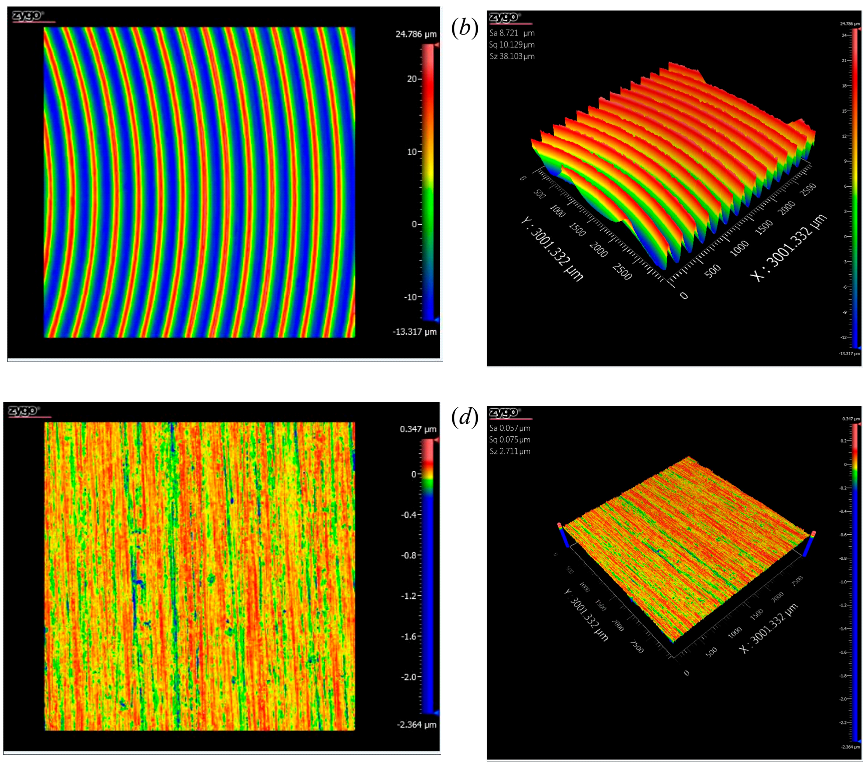

Figure S1. (**a**) Plan view of the measured topography for turning surface; (**b**) 3D topography of measured turning surface; (**c**) Plan view of the measured topography for grinding surface; (**d**) 3D topography of measured grinding surface.

The noncontact micro topography measurement system ZYGONexView (ZYGO Corporation, Middlefield, CT, USA) was used to measure the surface topography of the grinding sample. The measurement methods were based on the white light scanning and phase-shifting interferometry. The noise-separation algorithms were carefully considered the analyzed detail where dimples. The vertical resolution of the system was 0.1 nm and the root mean square (RMS) repetition accuracy was 0.005 nm, which can realize the high-precision measurement of rough surface. The sampling method complied with ISO25178-

3, and the sampling area conformed to the S-F surface. The sampling area was 3 mm × 3 mm and the number of sampling points was 1,024 × 1,024.

Experimental process

The experimental research took 40Cr steel as the research object. First, the specimens were machined to achieve the required size and shape. In order to ensure complete contact, the diameters of the two circular surfaces used for testing are φ30 mm and φ10 mm respectively. Then, the machining parameters were set as required, and the specimens were machined by turning and grinding. After the specimens were processed, the specimens were ultrasonically cleaned and dried.

After the completion of specimen preparation, the next step was to obtain the relevant parameters, including material parameters (Young's modulus E, Poisson's ratio ν, yield strength σ_y, and hardness H) as well as the statistical parameters of the measured surface (average radius of curvature R of asperities, standard deviation σ of surface heights, and areal density η of asperities).

The rough surface contact stiffness test rig was built at Tsinghua University. A schematic diagram and physical drawings of the contact stiffness test rig are shown in Figure S2.

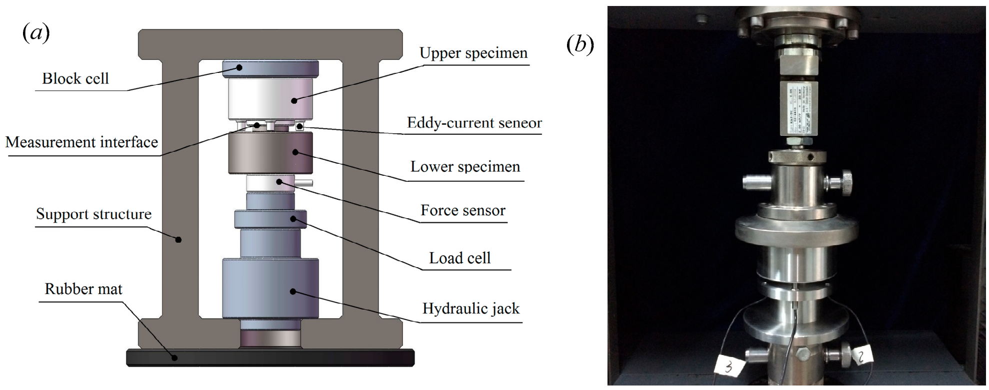

Figure S2. (**a**) A schematic diagram of the contact stiffness test rig. (**b**) Physical drawings of the contact stiffness test rig.

The whole test rig was vertically structured. All of the loading test units were connected in series in the support structure. A rubber mat was used for vibration isolation at the lower end of the support structure. The unit was loaded by a hydraulic jack with a target load of 6000 N. A KAP-TC pressure sensor (Kewill GmbH, Hamburg, Germany) was used to measure the contact load of the test surface. Three KD2306-1S eddy current displacement sensors (Kaman, Bloomfield, CT, USA) were installed on the upper specimens and uniformly arranged to measure the normal interference of the contact surface under contact load.

During the experiment, the compression loading mode is selected as the experimental type in this paper. Next, set the preload of the test rig, set the preload to 1 N, and set the preload speed to 30 mm/min. Then, set the specific loading parameters of the test: set the number of loading cycles to 3 times, set the conditional cycle speed to load control 30 N/s, set the upper return point of the conditional cycle to the standard load of 5700 N, and set the return point of the conditional cycle to the standard load of 1 N. The test stage type is set to simple cycle test, the test cycle speed is load control 30N/s, the upper return point of the test cycle is 5700 N, and the lower return point of the test cycle is 1 N. The upper limit of the load is set to 5800 N, and it will return to the starting position after the test is over.

Finally, through data acquisition, the variation curve of the contact load and the interference could be obtained. The curve describing the relationship between contact stiffness and contact load can be obtained by data processing. Each group of experiments was carried out using two specimens. Meanwhile, to ensure the reliability and repeatability of the data, three groups of samples were used for repeated experiments for each group of tests, and the average values were taken as the final data.

Table S1. Comparison results of normal contact stiffness under different methods.

Contact pressure *F* (MPa)	Contact stiffness *K* (MPa/μm)			Relative error (%)	
	Experimental results	Finite element results	Analytical results	Finite element results	Analytical results
0	0.00	0.00	0.00	0.00	0.00
10	11.70	11.81	18.72	0.99	60.07
20	21.11	22.39	31.43	6.03	48.87
30	32.54	31.72	40.59	−2.50	24.75
40	41.12	39.82	47.77	−3.15	16.19
50	47.20	46.68	53.78	−1.10	13.95
60	54.01	52.31	59.02	−3.15	9.28
70	57.54	56.69	62.89	−1.46	9.30

Table S2. Comparison results of normal contact stiffness — different arc radii of turning tools

Contact stiffness *K* (MPa/μm) / Contact pressure *F* (MPa)	Arc radii (mm)			
	0.1	0.2	0.4	0.8
0	0.00	0.00	0.00	0.00
10	10.94	11.81	12.87	13.98
20	20.74	22.39	24.40	26.50
30	29.39	31.72	34.58	37.55
40	36.90	39.82	43.41	47.14
50	43.26	46.68	50.88	55.26
60	48.47	52.31	57.01	61.92
70	52.53	56.69	61.80	67.11

Table S3. Comparison results of normal contact stiffness — different turning feed rates.

Contact stiffness *K* (MPa/μm) / Contact pressure *F* (MPa)	Feed rates (mm/*r*)			
	0.05	0.10	0.15	0.20
0	0.00	0.00	0.00	0.00
10	21.61	17.67	14.45	11.81
20	40.95	33.48	27.38	22.39
30	58.03	47.45	38.80	31.72
40	72.84	59.56	48.70	39.82
50	85.40	69.83	57.09	46.68
60	95.68	78.24	63.97	52.31
70	103.71	84.80	69.34	56.69

Table S4. Comparison results of normal contact stiffness — different grinding depths.

Contact stiffness *K* (MPa/μm) / Contact pressure *F* (MPa)	Grinding depths (%)					
	0.00	20.00	40.00	60.00	80.00	100.00
0	0.00	0.00	0.00	0.00	0.00	0.00
10	3.21	6.05	7.56	9.45	11.81	12.98
20	6.32	11.46	14.33	17.91	22.39	24.60
30	9.34	16.24	20.30	25.38	31.72	34.86
40	12.27	20.39	25.49	31.86	39.82	43.76
50	15.10	23.90	29.88	37.35	46.68	51.30
60	17.83	26.78	33.48	41.85	52.31	57.48
70	20.47	29.03	36.28	45.35	56.69	62.30

Table S5. Comparison results of normal contact stiffness — different fractal dimensions;.

Contact stiffness *K* (MPa/μm) / Contact pressure *F* (MPa)	Fractal dimensions				
	2.10	2.30	2.50	2.70	2.90
0	0.00	0.00	0.00	0.00	0.00
10	8.40	9.96	11.81	13.49	15.15
20	15.93	18.88	22.39	25.57	28.72
30	22.57	26.76	31.72	36.24	40.69
40	28.33	33.59	39.82	45.49	51.08
50	33.21	39.38	46.68	53.33	59.89
60	37.21	44.12	52.31	59.75	67.10
70	40.33	47.82	56.69	64.76	72.73

Table S6. Comparison results of normal contact stiffness — different scale coefficients.

Contact stiffness *K* (MPa/μm) / Contact pressure *F* (MPa)	Scale coefficients				
	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}
0	0.00	0.00	0.00	0.00	0.00
10	11.81	14.98	19.00	24.10	30.57
20	22.39	28.39	36.02	45.68	57.94
30	31.72	40.24	51.04	64.73	82.11
40	39.82	50.51	64.07	81.26	103.07
50	46.68	59.21	75.11	95.26	120.83
60	52.31	66.35	84.15	106.74	135.39
70	56.69	71.91	91.21	115.69	146.74