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Observations of shear adhesive force and friction of *Blatta orientalis* on different surfaces

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Abstract

The shear adhesive force of four non-climbing cockroaches (*Blatta orientalis* Linnaeus, 1758) was investigated by the use of a centrifugal machine, evaluating the shear safety factor on six surfaces (steel, aluminium, copper, two sandpapers and a common paper sheet) with different roughness. The adhesive system of *Blatta orientalis* was characterized by means of a field emission scanning electron microscope and the surface roughness was determined by an atomic force microscope. The cockroach maximum shear safety factor, or apparent friction coefficient, is determined to be 12.1 on the less rough of the two sandpapers, while the minimum shear safety factor is equal to 1.9 on steel surface. A two-sample Student *t* analysis has been conducted in order to evaluate the significance of the differences among the obtained sSF and the role of roughness with respect to chemistry on these six surfaces. An interesting correlation between cockroach shear adhesion and surface roughness emerges with a threshold mechanism dictated by the competition between claw tip radius and roughness, indicating that the best adhesion is obtained for roughness larger than the claw tip radius.

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Keywords

Adhesion, Shear force, cockroach, Safety factor.

1. Introduction

The adhesive abilities of insects, spiders and reptiles have inspired scientists and researchers for a long time. In particular about frictional and adhesion forces and related climbing ability, all these organisms present the highest climbing performances among the animal kingdom.

Many authors have studied a multitude of insects, especially thanks to the availability of microscopic analysis instruments (Field Emission Scanning Electron Microscope (FESEM) and Atomic Force Microscope (AFM)), in order to understand and measure their adhesive abilities in the course of the last decades, such as beetles [1-6], aphids [8-10], flies [7, 11-12], bugs [13], ants [14-17], cockroaches [18-24], spiders [25-27] and geckos [28-38].

The biological adhesion can be obtained through different mechanisms (e.g. claws, clamp, sucker, glue, friction), even if during evolution the insect attachment pads have evolved in two main types, which are hairy (thousands of flexible hairs, as fly pulvilli and beetle pads) or smooth (with high deformable material, as grasshoppers and cockroaches): both the systems are able to adapt to the substrata, maximizing the contact area [39-41]. For example, geckos present a dry adhesive surface, organized in a hierarchical structure [28, 42], like anoles [35, 43, 44], skinks [35, 45] and spiders [26, 27]; while other animals present secretion-aided fibrillas or secretion-aided pads, which are common in some insects [46], like ants [15], cockroaches [18], mites [47] and beetles [48]. The adhesive organs of these insects consist in smooth pads and the adhesion is mediated by a few volume of fluid secreted into the contact zone that influences the attachment performance [49, 50]. In general, the adhesive structure and mechanism could be correlated with the micro-structured roughness of the substrata (e.g.

plant surfaces): animals normally interact with the substrata roughness [51, 52] and it is shown that roughness has a strong influence on their adhesive abilities [53].

The normal and shear adhesive forces of several animals have been determined in order to evaluate their climbing ability. As a matter of fact, to run and climb animals have to deal not only with perpendicular but also with shear forces. For examples, the adhesion of the Tokay gecko (*Gekko gecko*, ~100 g), which has the most widely studied biological adhesion system, has been analyzed in terms of normal force [29], shear force [30], adhesion time [31] and influence of surface roughness on adhesive properties [32, 34], finding out an experimental normal safety factor (SF) of ~10 [29].

In particular, the shear adhesive force, and so the shear safety factor (sSF) obtained dividing the shear adhesive force by the body weight force, thus an apparent friction coefficient, was previously determined for few living animals through different techniques [20] and reported in Table 1.

We have focused on the shear adhesive force of cockroaches (*Blatta orientalis* Linnaeus, 1758), that is a species belonging to the Blattodea order. There are around 4000 species of cockroach and only a few species live in human environments. The species of Blattodea are divided between climbing (i.e. *Blattella germanica* Linnaeus, 1767) and non-climbing (i.e. *Blatta orientalis*), basing on their ability of climbing on smooth vertical surfaces, like Poly(methyl methacrylate) (PMMA), Poly(ethylene terephthalate) (PET), sheet metals, even upside down.

In this report, we present the measurement of the sSF, and its roughness-dependence variation, using a centrifuge technique of four non-climbing cockroaches (*Blatta orientalis* Linnaeus) on six surfaces: two different sandpapers (Sp50, Sp150), common paper (named Cp), steel, aluminium and copper) with different roughness. Four cockroaches with three repetitions per individual were used for the sSF determination on each surface, in order to get consistent biomechanical data correlated to the surface roughness, quantified using the AFM. The adhesive system of *Blatta orientalis* was characterized by field emission scanning electron microscope (FESEM) at the end of the experimental session. Since the adhesive system of *Blatta orientalis* consists of two claws for each leg with a sub-obsolete, non-functional arolium and euplantae may be absent from one or more tarsomeres or be completely lacking [19], the adhesion is just a mechanically-based interlocking by claws with a primary role of surface roughness.

2.Experimental set-up

A self-built centrifugal testing device was used to directly measure the sSF of cockroaches. The centrifugal machine allowed us to avoid any prior treatment of the cockroaches, which are left free of motion and of assuming a natural attachment position inside the experimental box. In addition, looking at previous data [14], the centrifugal testing device probably yields higher values of adhesive force than any other force-measuring procedure.

Since the distance between the cockroaches and the rotational axis is constant, the sSF measurement depends just on the angular speed.

The experimental configuration is shown in Figure 1A (side view) and 1B (top view). The experimental device is put on a passive rotating linchpin (M1), which is connected through a transmission belt to an active electric motor (M2), which forces the system to rotate and is connected to the 220 V, 50 Hz, AC and controlled through a frequency controller (VFD004L21E of Delta Electronics, Taipei, Taiwan), named FC, that modulates the current frequency in the range 1-400 Hz.

Attached to the passive rotating linchpin (M1), there are the main box (B_1) of 25 x 25 x 25 cm^3, the camera (C) which is applied in correspondence with the rotational axis (RA) of the system and records the cockroach's movements, and the counterweight (CW). Inside B_1, we have another small box (B_2) of 7(w) x 4(l) x 3(h) cm^3, where we put the animals in (so the uncertainty on the radial position of the insect is reduced to ±2.0 cm). The body axis of the cockroach is radially oriented, so perpendicularly to the outer rim. The inner box (B_2) has an interchangeable floor in order to realize the tests on different surfaces.

The angular speed was measured with a standard bicycle computer (BCP-01 of BBB cycling, Leiden, The Netherlands), named BC, using a magnetic sensor and an LCD screen fixed to the radially external wall of the B_1 box. To minimize the cockroach experience of the rotation, we have decided to insulate the box from the environment using a dark paper to obscure the box and adding a lamp (L) inside the box.

Since the camera C is rotating together with the box, in the movie (in Figure 1A and 1B, the dashed lines identifies the video shot) it is possible to see both the cockroach and the speed measurement, so the correct speed corresponding to the detachment is determined. The BC was calibrated using the reference distance (51 cm) between the rotational axis and the middle (M) of B_2. Known the reference distance, it is possible to get the angular speed from the linear speed read on the LCD screen of the BC. The BC gives the linear speed in the range 0.0-199.9 km/h (measured speeds are inside this range) with an accuracy of ±1% of the read value.

Experiments were conducted upon four adult cockroaches (B_1, B_2, B_3 and B_4) of the species *Blatta orientalis*. Before the whole experimental session, we performed a preliminary session to fine-tune the experimental procedure and to estimate the reasonable number of insects to be tested. During this preparatory session, we tested a dozen of specimens (no recorded results) and we obtained almost the same results with no significant variation among the specimens, so we decided that 4 insects could be sufficiently representative of the *Blatta orientalis* population. They were kept alone and were fed chicken feed *ad libitum*. The insects were maintained at ~25 °C and ~50 % of humidity, which corresponds also to the experimental conditions.

The sSF measurements were conducted as follows. Four cockroaches with three repetitions per individual were used for the sSF determination on each surface. Every time the cockroach was put on the bottom of the box it was necessary to wait two minutes to make it familiar with the room. We have observed that it first took one or two round walk along the walls and just then it started to stay far from then, reaching the correct starting experimental position, with no interaction with box walls. During the biomechanical experiments, we provided a slow speed-up to avoid high acceleration that can get an early detachment and to satisfy the hypothesis of constant angular speed for the evaluation of the sSF. During an unacceptable test, the animals tend to go in a corner or against a wall and this represents the aborting condition of an experimental test. During an acceptable test, we observed that at low speeds the animal can still run on the bottom of the box, when the centrifuge speeds up it walks more slowly and finally it stands still until it detaches, contacting the substratum with all legs and assuming the 'freezing' position advantageous to attachment, also reported in [14]. By standing motionless with all the legs spread out, the cockroach assumes a position that maximizes its adhesion ability and so the detachment is not caused by its natural movement but just by the shear force acting on the animal. The inner box (B_2) has an interchangeable floor in order to realize the tests on different surfaces

Before changing the interchangeable floor of the inner box (B_2), so the substrate to test, we performed the experiments for all the specimens, which were tested in the same order on every surface. The tested surfaces were: Sp50, Sp150, Cp, Steel, Aluminum, Copper. We didn't test an animal over more than two surfaces every day. We measured the body mass of the four insects (equal to 405.9 ± 22.9 mg), using a balance with a precision of ±0.1 mg (EB200 of Orma, Milano, Italy).

3. AFM characterization of surfaces

The characterization of surfaces (sheet of common office paper (80 g/m^2, named Cp), steel, aluminum and copper) was performed in 'contact mode' with an AFM (Solver Pro M) with NSG01 tips, from NT-MDT, Moscow, Russia (Figure 2). The parameters tuned during the analysis are the measurement speed (14.2 μm/s), the measured area (100 x 100 μm^2 for 3 tests on metals and 50 x 100 μm^2 for 6 tests on Cp) with a final resolution of 512 points/profile. All parameters were referred to a 100 μm cut-off. The cut-off length defines the length on which the roughness parameters are calculated and therefore it strongly influences the roughness values. The roughness parameters were determined with software NOVA from NT-MDT, Moscow, Russia. No roughness data was obtained for the two types of sandpaper (the roughest sandpaper is Sp50) because their roughness is beyond the working ranges of the AFM used, and the mean nominal surface asperity diameter was used to compare them with the AFM-measured surfaces. S_a represents the arithmetical average roughness, S_q the mean square deviation of the profile from the middle line, S_p is the height of the highest peak, S_v the depth of the deepest valley, S_z is the average distance between the five highest peaks and the five deepest valleys. S_{sk} characterizes the surface skewness: it is equal to 0 for the same distribution of peaks and valleys, it is negative for a surface made up of plateaus and deep valleys, or positive for a surface made up of plateaus and peaks. S_{ka} is the kurtosis parameter and indicates the distribution of the surface heights: when close to 0 the distribution of the surface heights is like a Gaussian distribution; when higher than 0 the height distribution is more sharp then a Gaussian distribution (so the heights of peaks are close to the mean height), when lower than 0 the height distribution is more spread. See [29, 31-33] for a detailed explanation of these classical roughness parameters.

4. FESEM characterization of *Blatta orientalis*

We observed the adhesive system of *Blatta orientalis* by means of a FESEM (Inspect^{TM} F50, FEI, Hillsboro, Oregon) equipped with a field emission tungsten cathode. Samples were amputated from adult cockroaches and immediately put in 70% ethanol solution and such maintained for 4 days. Then, samples were dehydrated at ambient temperature and atmospheric pressure for 12h before analyzing under the SEM. Thus, they were fixed to aluminium stubs by double-sided adhesive carbon conductive tape (Nisshin EM Co. Ltd., Japan) and scanned without metallization at an acceleration voltage of 1 kV.

Figure 3 confirms by images the adhesive system description recently reported in [19], showing a sub-obsolete non-functional arolium (no better adapted for climbing a smooth vertical surface) and lacking euplantae with two claws for each of the six legs of *Blatta orientalis*. The claw tip diameter is equal to 12.3 ± 4.73 µm, determined using the software ImageJ 1.41o.

5. sSF evaluation

Our goal is to measure the sSF, which is defined as the ratio of the shear detachment force ($F_{\text{detachment}}$) by the mass (*m*) multiplied the gravity acceleration (*g*), so it is adimensional and represents also the apparent friction coefficient:

$$sSF = \frac{F_{\text{detachment}}}{m \cdot g}$$

We focused on the shear adhesive force and thus we just considered the radial force (F_{radial}) acting on the insect, thus in our case $F_{\text{detachment}}$ = F_{radial}. Supposing a constant angular speed (ω), the radial force is proportional to the distance of the insect from the axis (the radius, R = 51 cm), the square of the angular speed and the insect mass:

$$F_{\text{radial}} = m \cdot \omega^2 \cdot R$$

Thus, we can easily evaluate the sSF as:

$$sSF = \frac{\omega^2 \cdot R}{g}$$

that does not depend on the body mass of the insect. Knowing the radius that is constant and not considering the drag force, since the insects are in a closed box, we can measure the sSF just from the value of the angular speed, that we get from the BC.

6. Statistical Analysis

A two-sample Student *t* test was performed to determine if a significant difference exists among the mean value of the sSF for each cockroach on the six different surfaces.

7. Experimental results

We could simply average the results of the twelve tests for each surface (Figure 4). Summarizing, Table 2 reports the sSF and the F_{radial} for each surface (mean±st.dev.) and shows a clear separation between rough (Sp50, Sp150, Cp) and smooth (steel, aluminium, copper) surfaces and just small differences among the surfaces of the same class.

The two-sample Student *t* test demonstrated high significant difference among the sSF between different types of substratum (sand papers, common paper and metals), while within the Sp surface group (P=0.70) and within the metal surface group (P>0.05) a no statistically significant difference clearly emerges (Table 3).

8. Discussion

AFM characterization of surfaces and the roughness-related sSF of cockroaches

We note that the Cp surface is characterized by the parameters S_a, S_q, S_p, S_v, S_z one order of magnitude higher than those of metal surfaces with a distribution with a large standard deviation of the heights of peaks (S_{ka}<0), whose number exceeds the number of valleys (S_{sk}<0) which are deep, wide and so probably complementary to the geometry of the claw tip (Figure 2 and Table 2).

Looking at the metal surfaces, it clearly emerges the noteworthy difference among copper and aluminium if compared with steel (on which we recorded the lowest sSF). The steel surface is denoted by a higher number of valleys than peaks (S_{sk}<0), whose heights are very close to the mean value of heights (S_{ka}>0) and which are usually at a distance lower that 1 µm. Thus, the lowest performances of *Blatta orientalis* on steel surface are clearly explained by the objective impossibility of the cockroach to interlock its claws inside the peak-to-peak distance.

The aluminium and copper surfaces are comparable for all the roughness parameters, apart for S_{sk}, which allow us to highlight that the cockroach *Blatta orientalis* performs higher sSF on surfaces with a lower number of peaks than valleys, which probably become the fundamental interlocking point for its claws.

For each surface it is possible to compare the variation of sSF data as the global average sSF, which refers to the entire ensemble of cockroaches, and to the single specimen average sSF of each cockroach (Figure 4). We observed that the difference between the single sSF and the global average sSF is usually less than 15% for sand papers and common paper, while it is up to 30% for metals. Even if metals present quite high scatters, the data can be considered reliable since the results obtained from the three metals are consistent. Then, computing the single specimen average sSF, it is observed that the repetition variations are similar to the differences among the cockroaches (up to 20% for Sp and Cp). So, since the results obtained with different cockroaches have the same scatter of those of the same cockroach, considering 4 insects is enough to represent the population and no significant scatter reduction is expected by testing a larger number of specimens.

Discussion on correlation between surface asperity size vs claw tip diameter

In general, claw-mediated adhesive insects can attach to a horizontal or vertical surface only by interlocking and so the adhesive abilities increase with the surface roughness [5, 19, 20], in agreement with our observations. In particular, the claw-mediated adhesion occurs when the surface asperity size is comparable or larger than the claw tip diameter [3, 4, 51], here estimated to be 12.3 μm. Table 2 summarizes the calculated or estimated roughness parameters. The unmeasured asperity diameters (*Ad*) for Cp, steel, aluminium and copper (marked with (*) in Table 2) are estimated multiplying the parameter S_q by the value of 3.6, which is computed as the mean value Ad/S_q for sandpapers (Sp) from previous published papers with known *Ad* on which the roughness parameter S_q has been calculated (see Table 4).

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Looking at the results, the assumptions are confirmed: the claws of *Blatta orientalis* would be hardly able to grip surfaces with *Ad* smaller than ~12 µm, which could be considered the critical length scale for *Blatta orientalis*, showing a decrement of the shear adhesive force of about 35% on the Cp surface and of values larger than 80% on metals, if compared with the shear adhesive forces on Sp50 and Sp150. In the logarithmic plot reported in Figure 5, it is clearly shown that sSF scales as *Ad* until the critical length scale is reached. At that point, when *Ad* equals the claw tip diameter, the adhesion reaches the maximum value and does not increase anymore, even for a roughness 1-2 orders of magnitude greater than the critical one. Thus, we could see that there is a sharp transition of the sSF of *Blatta orientalis* around the critical length scale of ~12 µm.

9. Conclusions

We have measured the sSF of four non-climbing cockroaches (*Blatta orientalis* Linnaeus) by a centrifuge technique on six surfaces (two different sandpapers, common paper, steel, aluminium and copper) with different roughness. The cockroach maximum sSF, or apparent friction coefficient, is determined to be 12.1 on Sp150 ($Ad \approx 100$ µm, $F_{radial} = 48$ mN), while the minimum sSF is equal to 1.9 on steel surface ($Ad \approx 0.7$ µm, $F_{radial} = 7.4$ mN). The results of the two-sample Student *t* tests clearly show the predominant role of roughness with respect to the chemistry for the same nominal material (sand paper) and for the same groups of similar materials (sand papers or metals). They also show that chemistry play a significant role when comparing different material groups (sand papers, metals and common paper). An interesting sharp transition has been demonstrated between cockroach shear adhesive force and the surface roughness, indicating that the best adhesion is obtained for roughness larger than the claw tip radius; also surfaces with a higher number of valleys than peaks (S_{sk}<0) and a spread distribution of peak heights (S_{ka}<0) allow large adhesion.

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Fig. 1 Side (A) and top (B) view of the centrifugal machine used to measure the insects sSF (M1: passive rotating linchpin; M2: electric motor connected to M1 with a transmission belt; FC: frequency controller to set the M2 rotational speed; RA: rotational axis; C: camera; B_1: external box; B_2: internal small box where specimens were placed in; M: middle of the internal box; L: lamp; BC: bicycle computer; CW: counterweight)

Fig. 2 Atomic Force Microscopy (AFM) characterization of the (up/left) steel, (up/right) aluminium, (down/left) copper and (down/right) common paper (Cp) surfaces. Note that the different scales are just a consequence of the automatic scale setting of the surface acquisition software. No roughness data was obtained for the two types of sandpapers because their roughness is beyond the working ranges of the AFM used

Fig. 3 Scanning Election Microscopy (SEM) of ventral aspect of tip of pretarsus showing the claw-mediated adhesive system of *Blatta orientalis* consisting of two claws for each leg (*d* is the claw tip diameter; a is the sub-obsolete, non-functional arolium; b is the two tarsal claws)

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Fig. 4 Shear safety factors (sSF) of each individual, grouped by surfaces (B1, B2, B3 and B4 are the four adult cockroaches of the species *Blatta orientalis* used for experiments; x stands for the arithmetical average of the results of the twelve tests, one for each surface)

Fig. 5 Logarithmic plot of the asperity diameters (*Ad*) vs the shear safety factors for each surface (sSF: shear safety factor; Cp: common paper; Sp50 and Sp150 are two different sandpapers)

List of tables

Animal	Species	sSF	Mass (mg)	Ref.
Ant	*Oecophylla smaragdina*	~ 843	~ 4	[17]
Beetle	*Gastrophysa viridula*	~ 109	~ 10	[5]
Beetle	*Gastrophysa viridula*♂	~ 317	~ 11	[54]
Beetle	*Gastrophysa viridula*♀	~ 81	~ 20	[54]
Beetle	*Leptinotarsa decemlineata* ♂	~ 70	~ 121	[3]
Beetle	*Leptinotarsa decemlineata* ♀	~ 60	~ 168	[3]
Beetle	*Pachnoda marginata*	~ 40	~ 1000	[4]
Beetle	*Stenus*	~ 73	~ 2	[48]
Codling moth	*Cydia pomonella* ♂	~ 18	~ 19	[52]
Codling moth	*Cydia pomonella*♀	~ 14	~ 20	[52]
Fly	Syrphid fly	~ 43	~ 62	[11]
Blowfly	*Calliphora vomitoria*	~ 28	~ 72	[12]
Bug	*Coreus marginatus*	~ 70	~ 80	[47]
Bug	*Pyrrhocoris apterus*	~ 36	--	[55]
Mite	*Archegozetes longisetosus*	~ 530	~ 0.1	[47]
Stick insect	*Carausius morosus*	~ 3	~ 894	[5]
Bushcricket	*Tettigonia viridissima* (on silicon)	$\ll 1$	~ 1000	[41]
Skinks	(various: mean data)	~ 18	~ 9000	[35]
Anoles	(various: mean data)	~ 60	~ 9000	[35]
Geckos	(various: mean data)	~ 100	~ 10000	[35]

Table 1. Shear safety factors (sSF) of different animals, which are available in literature

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	Sp50	**Sp150**	**Cp**	**Steel**	**Aluminium**	**Copper**
Ad (μm)	336	100	4.5(*)	0.7(*)	0.6(*)	0.8(*)
S_a (μm)	-	-	1.044±0.228	0.145±0.041	0.141±0.026	0.178±0.125
S_q (μm)	-	-	1.248±0.255	0.190±0.053	0.173±0.026	0.215±0.145
S_p (μm)			2.727±0.433	0.801±0.176	0.626±0.045	0.496±0.258
S_v (μm)			3.132±0.112	0.885±0.353	0.434±0.105	0.670±0.237
S_z (μm)	-	-	2.927±0.233	0.838±0.190	0.521±0.051	0.584±0.228
S_{sk}	-	-	-0.31±0.143	-0.78±0.472	0.41±0.331	-0.48±0.590
S_{ka}	-	-	-0.66±0.327	1.31±0.485	-0.08±0.820	-0.04±1.139
sSF	11.7±1.6	12.1±2.0	7.7±1.7	1.9±0.6	2.0±0.7	2.9±1.0
F_{radial} (mN)	46.8±8.5	48.1±9.0	30.9±7.2	7.4±2.1	7.9±3.2	11.6±4.3

Table 2. Roughness parameters, sSF and F_{radial} of the characterized insect/surface systems. The values (*) are computed multiplying the parameter S_q by the value of 3.6, which is calculated as S_q/Ad for sandpapers (Sp) from previous published papers with known *Ad* on which the roughness parameter S_q has been observed. The mean value and the SD of the roughness parameters are calculated from 3 tests on metals and from 6 tests for common paper (Cp), while those of sSF and F_{radial} are calculated from twelve measurements for each surface

Student *t* test of the sSF						
	Sp50	**Sp150**	**Cp**	**Steel**	**Aluminiu m**	**Copper**
Sp50	//	0.7041 (NS)	0.0068 (AS)	0.0003 (AS)	0.0004 (AS)	0.0001 (AS)
Sp150	0.7041	//	0.0032 (AS)	0.0001 (AS)	0.0002 (AS)	0.0000 (AS)
Cp	0.0068	0.0032	//	0.0015 (AS)	0.0019 (AS)	0.0016 (AS)
Steel	0.0003	0.0001	0.0015	//	0.8034 (NS)	0.1087 (NS)
Alumi mium	0.0004	0.0002	0.0019	0.8034	//	0.1289 (NS)
Coppe r	0.0001	0.0000	0.0016	0.1087	0.1289	//

Table 3. Results of the two-sample Student *t* test applied to the sSF on the six different surfaces (sSF: shear safety factor; Cp: common paper; Sp50 and Sp150 are two different sandpapers)

Sq **(μm)**	***Ad*** **(μm)**	***Sq*** **(μm)**	***Ad*** **(μm)**
30.0	6.66	12.0	3.06
16.0	3.75	9.0	2.45
12.0	3.25	3.0	1.16
1.0	0.40	1.0	0.24
0.5	0.13	0.3	0.09

Table 4. S_q and *Ad* values for different sandpapers which are available in literature (left column from [56] and right column from [34]).