INFLUENCE OF SURFACE TEXTURING ON LUBRICANT FILM FORMATION AND SURFACE FATIGUE

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This paper concerns a study of the lubricant film formation and behavior of a point contact under non-steady state conditions. Transient Elastohydrodynamic (EHD) lubrication, where operating parameters such as speed and load vary over time, occurs in many machine elements including cams, gears and roller bearings. Therefore, an attention in last few years was focused on behavior and formation of a lubricant film in Elastohydrodynamic lubricated (EHL) contact under non-steady state conditions. The critical running sequences of EHL contacts include e.g. starting or halting of contact surfaces and also abrupt increases or decreases of surface speed and load. These cases can cause a rupture of a lubricant film and in consequence of this action also damage of contact surfaces. This study is devoted to the experimental research of the behavior of EHD films during reversal of entrainment in reciprocating motion. Moreover influence of surface texturing on rolling contact fatigue life of rubbing surfaces was also studied.

Keywords: *mixed lubrication, film thickness, surface texturing, reversal of motion, non-steady state conditions, rolling contact fatigue*

1. Introduction

Heavily loaded machine parts (ball bearings and cylindrical roller bearings, gearings, and cams) work under the EHD lubrication conditions where contact surfaces are elastically deformed and the lubricant viscosity in the contact area is significantly increased due to the contact pressure. Relative motion of bodies in contact leads to the formation of homogenous lubricating film witch separates contact surfaces. However, operational conditions (load, contact surface speeds and their geometry) are not constant and they are significantly variable in time. Very often the lubricating film is no longer able to ensure full separation of contact surfaces which leads to their contact, wear, and consequent jamming. The aim of this research is to ensure the functioning of lubricated contacts even through the critical operational stages, i.e. through start-up and run-down, sudden speed changes, and contact surface loading.

Unsteady conditions, especially the effects of speed of the surfaces on the formation of lubricating films, were examined only in few small experimental studies. It is incurred thereby that the first studies were specialized only to the behavior of lubricate contacts behind steady operational conditions respectively with reference to accessible measuring and computation aids [1–3]. They have only recently been modeled complex conditions occurring e.g. cam and tappet contact [4–6]. Subsequent works conversant of transient performance in

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lubricated contacts were published by Kudish [7] and Chang [8] who described behavior of minimum thickness of EHD film. Following systematic research of transient performance of EHD lubricating contacts took place in mid-1990s [9–10] using optical interferential method.

Reciprocation motion is one of the fundamental types of motions in mechanics. Over the years, there has been limited experimental research for reciprocating motion. Hooke [11] has analyzed film thickness during reversal of entrainment in EHL contacts and derived film thickness formulae in terms of dimensionless groups. Nishikawa et al. [12] and [13] studied the effect of reciprocating motion under constant load and cyclically applied load on film thickness. Kaneta and Nishikawa [14] studied the effects of a transversely oriented bump on point contact EHL films of reciprocating motion with a short length of stroke. Wang et al. [15] also explored the short stroke reciprocating motion.

Above-cited studies significantly contributed to the understanding of the actions that happen in lubricated contacts under non-steady state operational conditions. However, the behavior of mixed lubricating film under the conditions where the lubricating film breaks and the rubbing surfaces touch remains unexplained.

In such a case, surface topography plays great role in life of machine parts. High loads and low friction leads to surface contact and consequently to surface damage. It is important to consider machine part behavior under these conditions. Hence, Rolling contact fatigue (RCF) tests were carried out.

Last decades have witnessed, thanks to improved quality of materials and progress in production technologies, a significant enlargement of fatigue life of machine tribological systems such as rolling bearing or gears. One of the most important limit states of these systems is fatigue damage initiated on the surface; it occurs more frequently than the fatigue damage initiated by inclusions. The most common cause of this limit state is the contamination of lubricant with solid particles occurring as early as in the production stage; their concentration further increases due to running-in and wear [16]. Foreign matters from external sources such as dust or sand can be another cause of lubricant contamination. The size of contaminants (up to $100\,\mu$m) is usually much larger than the thickness of lubricating film (less than $1\,\mu$m) so that when they pass through the contact area, they are pressed into contact surfaces. These defects act as stress concentrators and due to variable loading there occur surface cracks that are further ramified up to the stage of spalling or pitting of the material from the contact surfaces [17]. Recent numerical and experimental studies have enabled clearer understanding of the dent creation mechanism e.g. [18–21]. A next variant how to improve lubrication decrease friction and wear is modification of frictional surfaces. It is creation of micro systems of dents on frictional surfaces [22]. The observation of the effects of surface texturing produced on the ball helped to understand better the behavior of real surface topography. It was found that the presence of shallow surface features can help to separate lubricated rubbing surfaces more efficiently than smooth surfaces. Surface topography of the rubbing surfaces can help to reduce the fiction and wear under transient operational conditions [22–23].

2. Experimental apparatus for film thickness measurement and for RCF measurement

A self-constructed simulator (a modified version of the automatic system for the real-time evaluation of EHD film thickness) has been used for modelling of the conditions that

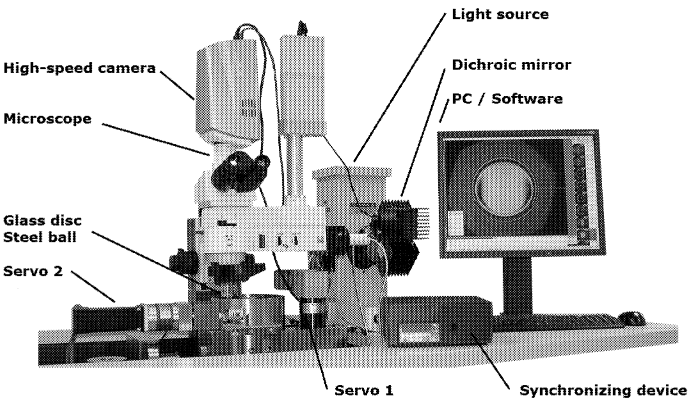


Fig.1: Experimental apparatus to study behavior of ultra-thin lubricating films

occur in real tribological systems (Fig. 1), where a thin lubricating film is formed through the contact between a rotating glass disc and a rotating steel ball.

The rotation axes of both contact surfaces being mutually perpendicular. The upper surface of the disc is covered with an anti-reflecting layer while the lower with a chromium layer. The contact is loaded via a glass disc that is mounted on a lever along with a moving weight. Both contact surfaces are controlled by servomotors. This enables experimental modeling of operating conditions that occur in machine assemblies. A temperature stability of tribological system is ensured by thermal insulation of the machine chamber and by the use of a closed heating circuit. The shape of lubricant film is set by means of colorimetric interferometry, a measuring method designed to set and visualize the distribution of lubricating film thickness in a spherical lubricating contact with a substantially higher accuracy and spatial resolution than is possible with conventional interferometry. Lubricated contacts are examined by means of microscope imaging system based upon the industrial microscope Nikon Optiphot 150. A xenon source of white light in combination with a color high-speed camera IDT X-Vision 3 has been used for research into mixed lubrication and processes occurring under unsteady operational conditions.

The experimental apparatus R-MAT has been used for contact fatigue measurement (RCF). It consists of two disks, one is driving other is driven. Test specimen is placed between them (Fig. 2). Both discs were made of AISI 52100 steel with Ra 0.2 μm surface

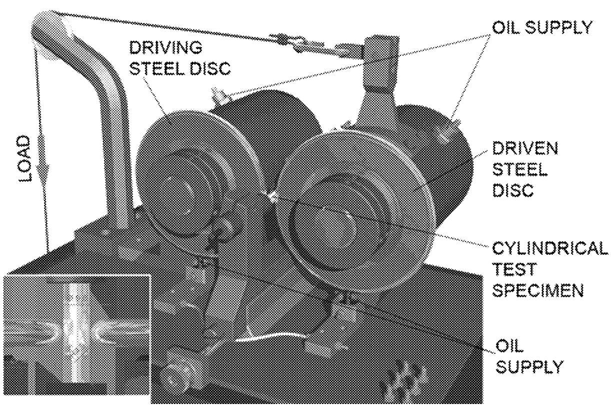


Fig.2: Experimental apparatus for RCF measurement

roughness. Chemical constitution of AISI 52100 steel is given in Table 1. Contact area is lubricated with base mineral oil. Tests were performed under mixed lubrication conditions.

Alloying constituents (%)	
C	0.95–1.10
Si	0.15–0.35
Mn	0.25–0.45
Cr	1.35–1.6
Allowable impurities (max %)	
P	0.03
S	0.025

Tab.1: Chemical constitution of AISI 52100 steel

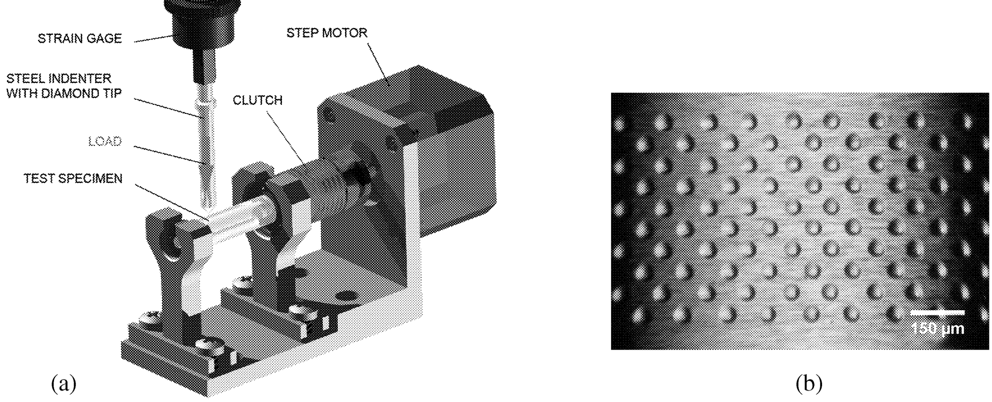
3. Surface texturing

A mechanical Rockwell C type indenter has been used for indentation of specimen surface (Fig. 3a, 4a). Indenter had a diamond tip with radii of curvature 0.2 mm. Indentation process is fully controlled by PC, so it allows us to create a well defined surface textures. Geometry of textures can also be easily controlled. Several types of arrays of dents were realized. Realized textures on roller and ball are shown in Fig. 3b and 4b respectively. The aim was to find suitable surface texture, which can help to avoid friction and wear and which can prolong RCF life of a test specimen. Single dent shape is characterized by radial load force.

3.1. Indentation process of steel roller

Forces applied for surface texturing were 8 N and 20 N for the roller. This allows create dent with depth of 400 nm and 800 nm respectively. Geometry of arrays of dent was set up to 75 μm between rows and 75 μm between slopes. It gives us well defined surface texture (Fig. 3b).

Indentation process is very time consuming, hence not whole specimen surface was indented. Textures were applied only to fill the range of contact area, which was circular with 0.6 mm in diameter. After the indentation, RCF tests were carried out on textured specimen.



(a) (b)

Fig.3: a) indentation process of steel roller,
b) triangular arrangement of steel roller texture

3.2. Indentation process of steel ball

The micro-dents are dislocated around the specimen in six lines. The arc length between two micro-dents in one line is about 150 μm. This means that 532 micro-dents are placed around the specimen at central angle $0^\circ 40'$. The main difference is in the loading of indenter. For the second specimen was the load 8 N. By using this load the depth of micro-dent reached 800 nm. The Fig. 4b shows the pattern of micro-dents on the specimen with real topography.

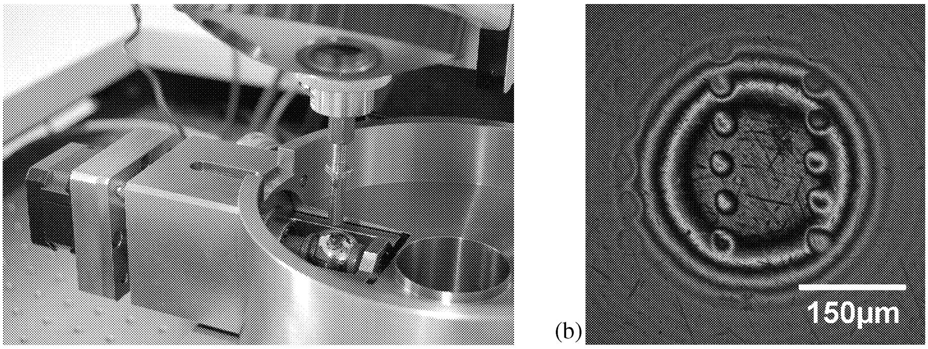


Fig.4: a) indentation process of a steel ball, b) a steel ball surface texture

4. RCF tests

An AISI 52100 steel roller with surface roughness Ra 0.1 μm has been used as a test specimen. Its diameter was 9.6 mm and its length was 50 mm (Fig. 5). Applied load it creates a 5 GPa Hertzian pressure in contact area. Rolling-sliding conditions were applied during experiments. Surface speed was 4.5 $\mathrm{m\,s^{-1}}$ and 3.75 $\mathrm{m\,s^{-1}}$ for disc and specimen respectively, which gives slide-to-roll ratio $\Sigma = 0.05$. Contact fatigue life of specimen can be easily obtained from measurement parameters.

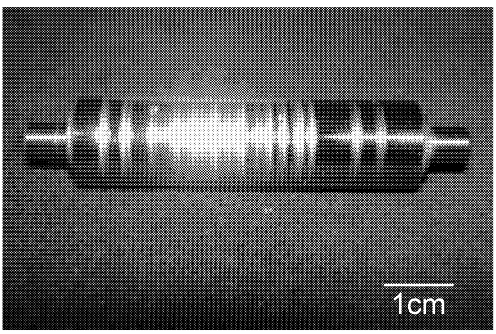


Fig.5: test specimen

RCF tests are performed under mixed lubrication conditions. Mineral base oil with 0.021 Pa s dynamic viscosity and 15 $\mathrm{GPa^{-1}}$ pressure viscosity coefficient was used as a lubricant. RCF tests were carried out at 33 °C. Presence of such surface irregularity on rubbing surface evokes vibrations. These vibrations had been monitored during experiments. When surface defect was observed, measurement was automatically stopped. Rubbing surface was afterwards analyzed.

Film thickness measurement and RCF test of surface textured rubbing surfaces was based on shallow dent having depth 400 nm. Possible beneficial effect of surface texturing on RCF life increase under mixed lubrication conditions was studied. Results of textures surfaces were compared with non-textured surfaces (Fig. 6). The slope diagram shows significant increase of RCF contact life of a specimen with textured surface with shallow dents. It is important to mention, that beneficial effect of surface texturing is increasing with increasing of texture density.

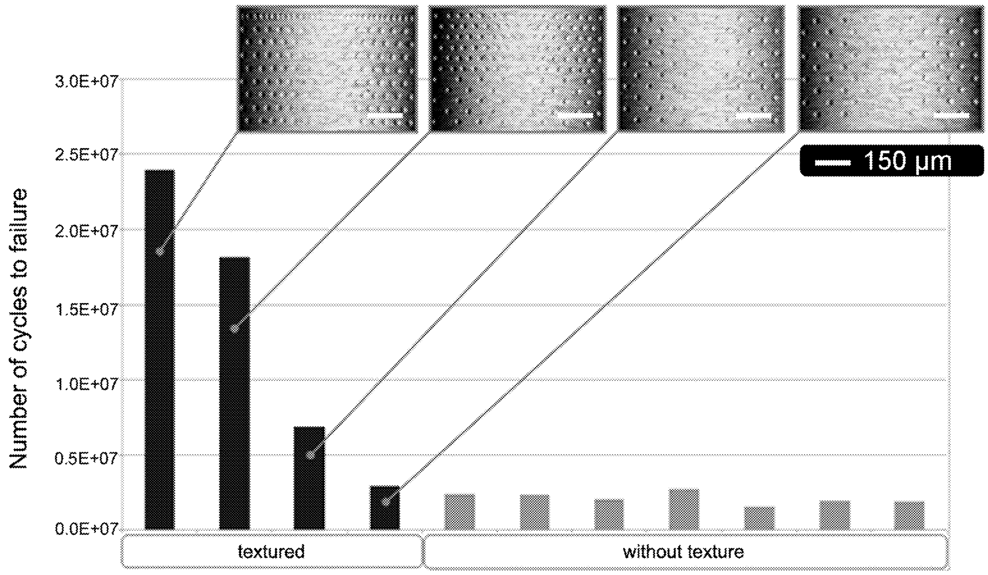


Fig.6: RCF measurement results – shallow dents

Measurements were carried out up to surface failure observation. After observation of surface defects, measurement was automatically stopped and rubbing surface was analyzed. Some resulting surface defects (pitting) are shown in Fig. 7. Nevertheless, surface texture might influence RCF life of machine elements so that the further experiments would be helpful to include the effect of surface texturing on an increase in rolling fatigue life under mixed lubrication conditions.

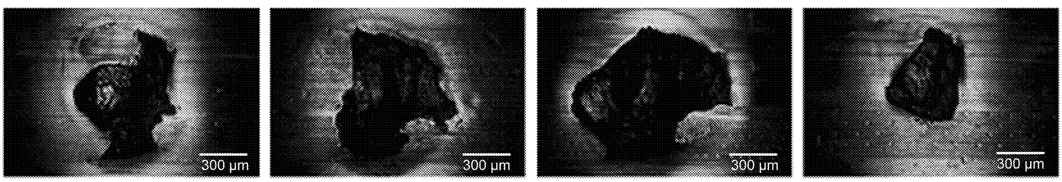


Fig.7: Observed surface damage – pitting

5. Behavior of lubrication films during reversal of motion

In all of experiments was used thin film of primer mineral oil LSBS at room temperature 25 °C. At this temperature the dynamic viscosity of this oil was 0.69 Pa s. The contact was loaded by stationary force 28 N. The speeds u_B and u_D of steel ball and glass disk, respectively, were chosen with respect to ensure the constant value of rolling-sliding ratio $\Sigma = 1$ (1). The surface speed of steel ball and glass disk in the middle of the contact area under constant rolling-sliding ratio was $0.0177\,\mathrm{m\,s^{-1}}$ and $0.0532\,\mathrm{m\,s^{-1}}$, respectively. The rolling-sliding ratio can by determinate by using following equation:

$$\Sigma = 2\,\frac{u_\mathrm{B} - u_\mathrm{D}}{u_\mathrm{D} + u_\mathrm{B}}\ . \tag{1}$$

5.1. Polished steel ball

The commercially supplied steel ball which was used for this experiment has been polished by using buffing composition to reduce the surface roughness. The arithmetical mean roughness of the steel ball after polishing is approximately Ra $= 0.005\,\mu$m. A series of experiments was realized by using polished steel ball and as result of this experiments were taken interferograms which are describing film thickness across contact area. At the beginning of the experiment when the contact run under steady state condition and constant rolling-sliding ratio the contact surfaces are separated by sufficient oil layer and contact is fully flooded. At the beginning of the speed reversal both speeds of glass disk and steel ball are equal to $0\,\mathrm{m\,s^{-1}}$. At this moment lubricant with high viscosity occurs in contact and it can be observed slow decrease of oil film thickness on the periphery of the contact area. The speed reversal causes swop of the lubricant inlet and outlet of contact. In consequence of this action on the new inlet isn't enough of lubricant and it causes starvation.

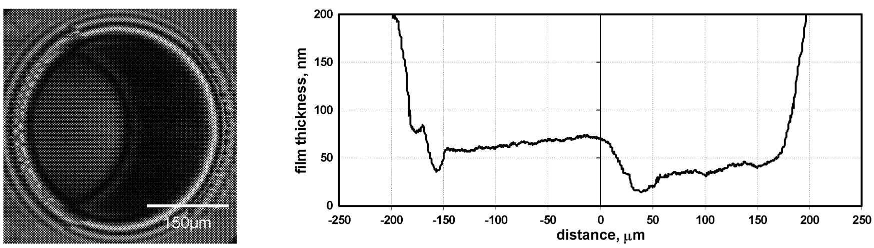


Fig.8: Chromatic interferogram and film profile of lubricated contact

The situation is described by Fig. 8 where can be observed on the right side of the graph sharp decrease of the film thickness. This constriction passes through the EHL conjunction approximately at the entrainment speed. Figure 8 shows also slow increase of film thickness at the inlet and after the time when the constriction will pass across the contact than the film thickness reaches the same value as on the beginning of the experiment.

5.2. Real steel ball

Figure 9 shows an interferogram of experiment when as a contact bodies were used a glass disk and steel ball with real topography. The real topography was achieved by finishing operation of the surface of the steel ball. The arithmetical mean roughness of the steel ball in this case is approximately Ra $= 0.018\,\mu$m. The experimental setup is the same as that in previous experiment. At the beginning of the experiment is contact fully flooded and runs under steady state condition and constant value of the rolling-sliding ratio. The peaks which are occurring in film profile are caused by grooves on the ball surface. Within contact area as in previous case is entrapped a lubricant with high viscosity.

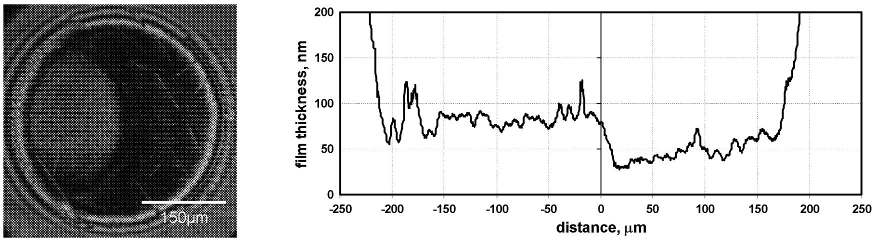


Fig.9: Chromatic interferogram and film profile of lubricated contact

After reversing of speed a constriction is occur as shown in Fig. 9. This constriction passes through the EHL conjunction approximately at the entrainment speed. The contact is fully flooded at the moment when the constriction leaves contact area. Process of flooding is similar to this in previous experiment with polished steel ball.

5.3. Real steel ball with micro-dents

A surface of steel ball was equipped with a pattern of micro-dents for this experiment. A chromatic interferograms are describing a film profile in rolling direction and film behaving in EHL contact with micro-dents. At the beginning of the experiment the contact was fully flooded and runs under constant rolling-sliding ratio. In this case the micro-dents are behaving as a reservoir of lubricant when they passing through EHL conjunction.

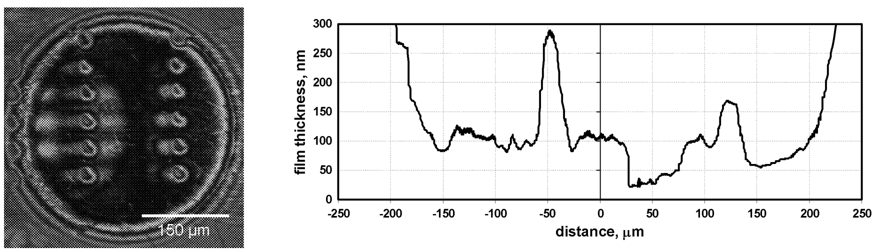


Fig.10: Chromatic interferogram and film profile during the passage of micro-dents through a lubricated contact

In the Fig. 10 can be observed a small increase of film thickness in front of a microdent due to escaping lubricant. Formation of the film profile is almost the same as in previous experiments with polished ball or ball with real topography but here the micro-dents are helping to speed up the full flooding of contact after speed reversal. The contact is supplied by larger amount of lubricant which helps to separate the contact bodies and reduce the probability of film rupture. On the other side with increase of micro-dent depth also increase possibility of film rupture due to disturbance of hydrodynamic conditions at the moment when the micro-dent comes in to contact area.

6. Conclusions

Topography of contact surfaces significantly affects the behavior of lubricating film between highly loaded contact surfaces. It was found that the presence of shallow dents can help to separate lubricated rubbing surfaces more efficiently than it could be suggested from the results obtained with smooth surfaces. Topography of the rubbing surfaces can help to reduce the asperities interactions even during these transient operational conditions. From RCF measurements it was found that the fine textures of micro-dents having depth of 400 nm lead to significant increase of contact fatigue life. It is assumed that local increases of mixed lubrication film thickness have positive influence on contact fatigue life. Presence of a texture on a rubbing surface can also lead to local hardening of the surface. The hardened surface also helps to prolong RCF life of machine parts. But the effect of hardening is significant only in presence of such high density texture on rubbing surfaces. Shallow dents do not affect the hardening process, but they strongly affect the lubrication film thickness. Nevertheless, influence of hardening on RCF life was neglected during this study. The presented technique of surface texturing is now applied to design of suitable textures in order to increase fatigue life of non-conformal contacts operating under EHD and mixed lubrication conditions.

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