ANALYSIS OF WEAR EFFECTS IN CYLINDER-PLANE CONTACTS AFTER WORKING IN BOUNDARY LUBRICATION CONDITIONS

R.Bassani, E.Ciulli, F. Di Puccio and M.Lorenzetti

Dipartimento di Ingegneria Meccanica, Nucleare e della Produzione; Università di Pisa
via Diotisalvi, 2 - 56126 Pisa – Italia

ABSTRACT

An experimental investigation on friction in mixed and boundary lubrication regimes has been carried out for rectangular conjunctions, due to the contact between a cylindrical specimen and the plane surface of disc. Since very low values of the Stribeck number have been considered, resulting also in low dimensionless film thickness (□<1), the morphology of the surfaces and the material have had a remarking influence. In order to explain some particular trends of the friction coefficient, a deep study on the surfaces condition by image and roughness profiles analyses has been conducted. As expected, some wear has occurred during the contact, causing a continuous alteration of the surface condition. Results obtained from this study have been correlated with friction coefficient diagrams, emphasising interesting remarks for certain combinations of materials and roughness.

LIST OF SYMBOLS

E	Young modulus
f	friction coefficient
F	applied load
h	film thickness
R_q	root mean square roughness
S	slide-to-roll ratio, $\Delta u/u$
St	Stribeck number, $\mu_0 \cdot u/w$
t	axial width of the specimens
T	temperature
u	rolling speed, $(u_D+u_S)/2$
u_D	disc surface speed
u_S	specimen surface speed
Δu	sliding speed, u_S-u_D
w	load per unit length, F/t
μ_0	lubricant viscosity at inlet
Λ	dimensionless film thickness, $h/\left(R_{qS}^2+R_{qD}^2\right)^{0.5}$

1. INTRODUCTION

The nature of friction phenomenon has already been studied in relation to a large number of parameters such as lubrication conditions, material hardness, surface roughness, slide-to-roll ratio, etc. [1-4]. In previous works rectangular conjunctions have been studied in different working lubrication conditions [5-6]. In particular mixed and boundary regimes have been investigated experimentally through an apparatus for measuring friction force and film thickness by optical interferometry method. The apparatus, schematically shown in Fig.1, is described in [7]. A cylindrical specimen, having diameter Φ 42mm and axial width t=3mm, is held in contact at the desired force with the plane surface of a disc, whose diameter is Φ 160 mm. Both the specimen and the disc are moved at the desired speeds by two electric motors controlled by a personal computer. The computer aided testing system also saves data relative to the inlet lubricant temperature, the speeds and the traction force acting on the specimen. Each contact has been tested in four different rolling to sliding conditions and with six different speeds [6]; values adopted for the slide-to-roll ratio S are 0, 0.25, 0.5, 1 and for the rolling speed u 0.0125, 0.025, 0.05, 0.075, 0.1 and 0.2 m/s. The traction force measured for S=0 (pure rolling conditions) has been used as reference zero value. Every specimen has been tested with every disc, for the whole 24 combinations of u and S. As each test condition has been kept for one minute, the complete run for specimen has taken about an hour, including acquisition, set-up and control times.

In order to investigate the influence of the material properties and of the surface roughness six different discs and specimens have been used: two discs made of aluminium alloy (AA6082, Al), three of stainless steel (X5CrNiMo1810, Sc) machined in different ways and a glass disc with a semi-reflecting chromium layer protected by a SiO_2 coating. This last disc has been employed also to analyse the contact by the interferometric method. The same metals have also been used for the specimens: three were made of stainless steel and one of aluminium alloy; in addition a sintered alloy of tungsten carbide and cobalt (K40, Tc) and a steel more suitable for grinding (88MnV8, Sm) have been selected. In the following, discs and specimens will be identified by notations referring both to material and roughness (e.g. C6-Sc_{1800} stands for stainless specimen with R_q 1.8 m). The main data of the discs and specimens are reported in Tab.1.

The root mean square roughness R_q has been measured along the radial direction on the plane surface of the discs and along the axial direction on the cylindrical surfaces of the specimens. Approximate values of the Vickers hardness of the metallic materials are also reported in the table. No value is quoted for the hardness of the glass disc because the contact with it is mediated by the chromium layer (0.02μm) and by the SiO_2 coating (0.1μm), so no meaningful value can be easily defined.

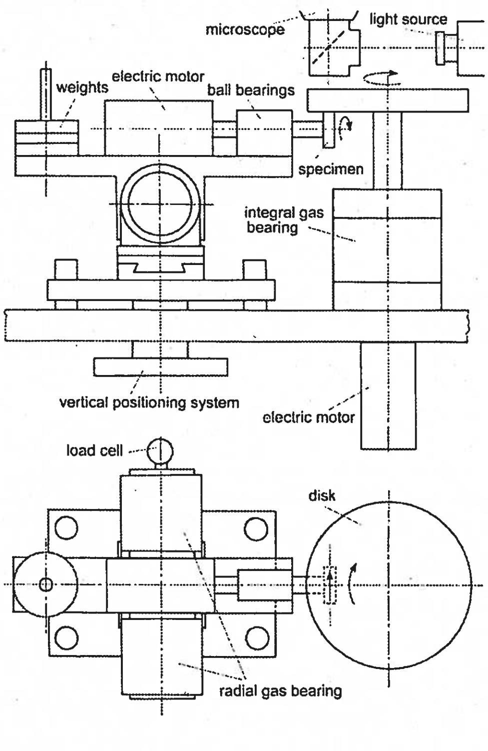

Figure1. Experimental apparatus, scheme.

Tab. 1 – Main data for discs and specimens.

DISC	R_q [µm]	MATERIAL	MACHINING	HARDNESS [HV]	E [GPA]
D2-Gl_{20}	0.02	CROWN GLASS	LAPPING	-	78
A1-Al_{1000}	1	Al 100-AA6082	FACING	110	70
A2-Al_{250}	0.25	Al 100-AA6082	FACING	110	70
A3-Sc_{1800}	1.8	X5CrNiMo1810	FACING	135	210
A4-Sc_{700}	0.7	X5CrNiMo1810	GRINDING	135	210
A6-Sc_{130}	0.13	X5CrNiMo1810	GRINDING	135	210
C2-Al_{600}	0.6	Al 100-AA6082	STRAIGHT TURNING	110	70
C4-Sm_{60}	0.06	88MnV8	FINE GRINDING	800	210
C5-Tc_{35}	0.035	K40	FINE GRINDING	1300	580
C6-Sc_{1800}	1.8	X5CrNiMo1810	STRAIGHT TURNING	155	210
C7-Sc_{1100}	1.1	X5CrNiMo1810	GRINDING	155	210
C8-Sc_{300}	0.3	X5CrNiMo1810	GRINDING	155	210

A pure diester, the bis(2-ethylhexyl)phtalate, has been used as a lubricant. Load F and temperature T were kept constant during tests (F=20N, T=33°C). The viscosity of the lubricant at the test temperature is μ_0=0.036 Pa s.

In order to avoid big variations of the test condition, each specimen has been tested starting from the discs with lower roughness: the first one has been D2-Gl_{20} followed by aluminium discs A2-Al_{250} and A1-Al_{1000}, and then the three steel ones A6-Sc_{130} ,A4-Sc_{700} and A3-Sc_{1800}.

The first aim of the investigation has been the study of the friction trends in lubricated conditions [6]. Due to the mixed and boundary regimes in which some of the tests have been carried out, very particular friction values have been found. Since also wear effects have been observed, a deeper investigation has become necessary.

2. FRICTION ANALYSIS

Test results are mainly reported by means of Stribeck diagrams, which correlate the friction coefficient f to a dimensionless quantity St, denoted as Stribeck or Sommerfeld or Gumbel number, [8]. Such number is commonly adopted as it includes some of the main parameters of the tests ($St=\mu_0 \cdot u/w$). In addition Stribeck diagrams are a useful tool to recognise different regimes of lubrication: very low values of St correspond to a "boundary lubrication" condition where the friction coefficient is almost constant; increasing St the regime changes into a "mixed lubrication" with a decreasing trend of f, and finally for higher St a "fluid film lubrication" condition is reached characterised by increasing trend of friction.

An overview of the Stribeck diagrams obtained for a slide-to-roll ratio S=0.5 is shown in Fig.2, gathering results for each disc. The continuos decreasing curve of f clearly shows that the fluid film lubrication has never occurred during the tests. Mixed and also boundary lubrication for the lowest values of St were the lubrication regimes for the adopted working conditions.

In general, higher values of friction have been obtained with rougher discs and specimens, but together with these expected results, some particular trends appear. For instance, it is to be noted the behaviour of the stainless steel specimens coupled with the aluminium and glass discs: the friction coefficient is considerably higher than for the other specimens, showing a certain influence of the materials. Very particular trends are then the ones obtained with the

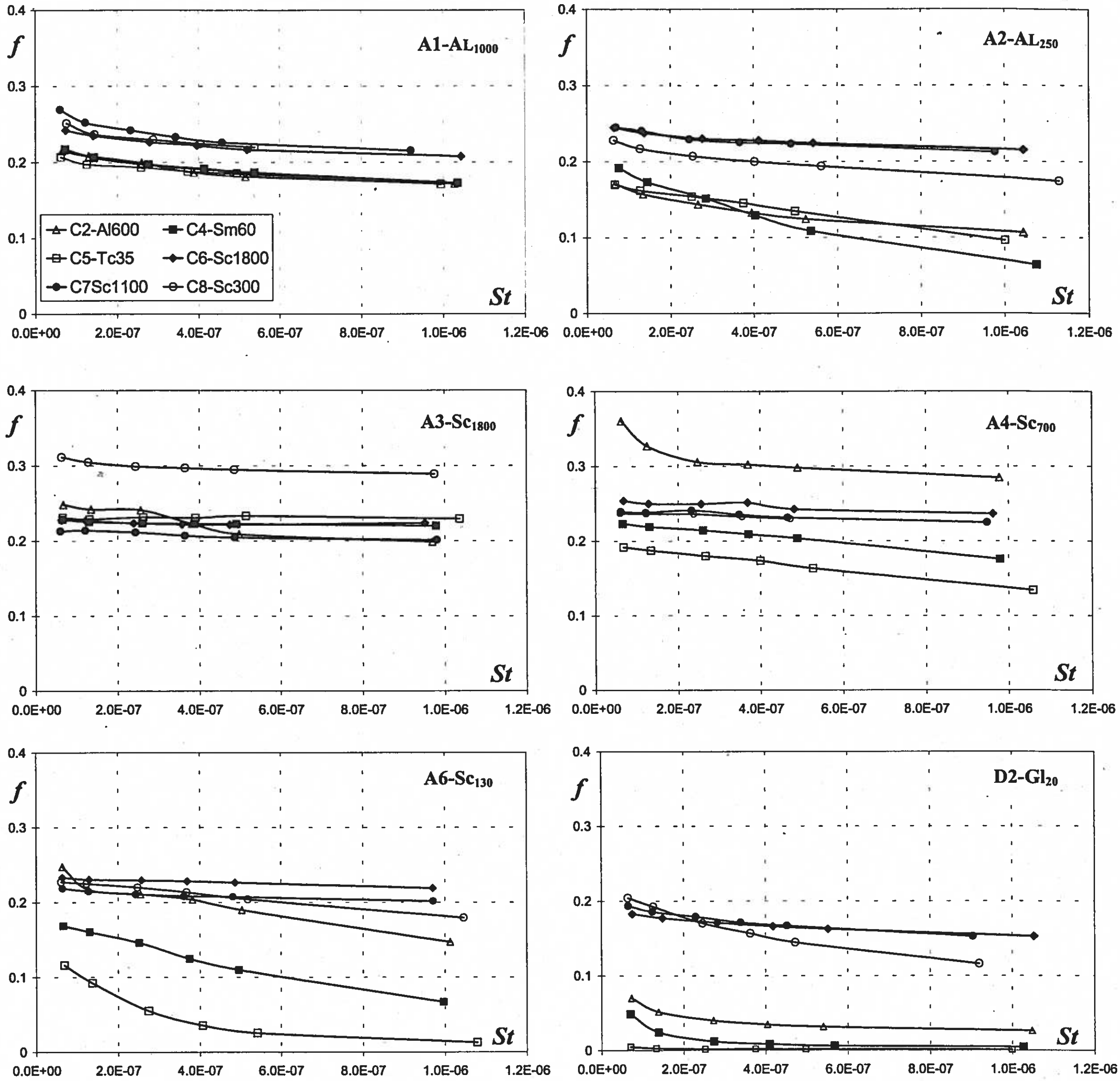

Figure 2. Friction coefficient vs. Stribeck number for the six discs, S=0.5.

stainless steel disc A3-Sc_{1800} with the highest roughness; in this case the different orientation of the surface texture (circumferential machining grooves instead of mainly radial ones as for the other steel discs, as shown in the following) seems to play an important role. The importance of the roughness orientation is well known (see for instance [9] and [10]). Usually in mixed lubrication conditions a roughness transversally oriented with respect to the motion direction tends to give a film thickness higher than a longitudinally oriented one so that lower values of friction are expected. However this behaviour has been proved for $1<\Lambda<5$, whilst the results shown in this paper have been obtained for $\Lambda<1$, as reported in [6].

It should be noted also that in some cases the values of f relative to the disc A3-Sc_{1800} are lower than the ones obtained with the A4-Sc_{700}. This behaviour could be explained as a possible effect of "micro-guide" played by valleys of the disc tool marks with respect to the specimens' asperities. Finally, the trends of the friction coefficient for the aluminium specimen C2-Al_{600} are very particular in many cases. Slope variations of the friction curves suggest the presence of some changes in roughness due to wear effects. In order to investigate thoroughly these behaviours, an analysis of the surfaces of the discs and specimens after working has therefore been carried out.

3. SURFACE ANALYSIS

The tests have been carried out putting in contact each specimen with each disc at a different radial position, so every track can be recognised. In Fig.3 images of the surfaces of the discs after the tests are shown, where some wear tracks are clearly evident. In fact, in the operating lubrication conditions where $\Lambda<1$, some contact between the asperities of the surfaces is

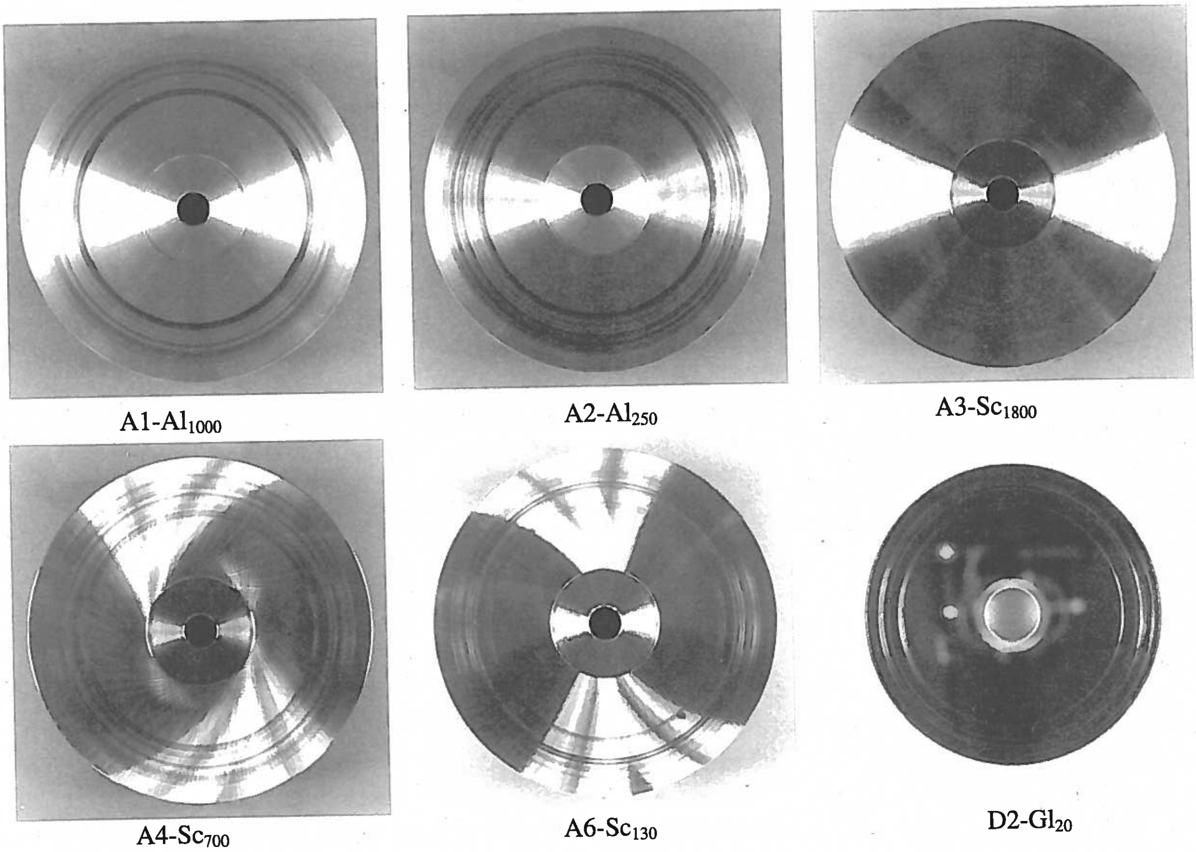

Figure 3. The tested discs after working.

expected, with consequent wear which may be depend from roughness, material properties, texture, etc. [11].In order to gain a wider comprehension of the phenomenon and of the previous results, the morphology of the surface and the wear effects have been examined considering firstly the tracks left by the specimens on the discs. The shape of each track has been observed by an optical microscope connected to a computer and by a stylus profilometer. Images acquired from the microscope (692x545px) have been digitised at 72dpi giving a 244.1x192.3 mm picture. By operating on the microscope settings, two different magnifications have been obtained, one giving the complete track width of 3 mm (x37) and the other one (x300) details of it. The whole width images are used to have a global view of the contact surface condition; in particular they are helpful to recognise a full or partial contact connected to misalignments or non perfectly planar condition. For instance tracks being less than 3 mm wide, indicate that a light inclination of the specimen has occurred. Actually a linear (rectangular) contact between disc and specimen is not always perfectly assured due to surface unevenness of the specimen and to unavoidable errors of shape of the disc surface. On the other side, higher magnification images reveal the changes of the discs surface caused by the contact with the specimens. The interpretation of these images is sometimes made particularly difficult by the unevenness of some circumferential tracks, when the contact is not regular.

In figures 4 and 6-7, 9-10, collections of typical tracks images for each disc are shown. It is worth noting that, because of space limitations, images in the following are smaller than the ones used for the analysis. For each track two pictures, corresponding to the lower (x3) and higher (x27) magnifications are reported, together with the indication of the specimen that has run over it. In order to simplify the comparison of the unworn with worn condition, the unworn disc surface is shown in bottom of the figures.

The surface analysis of the aluminium disc A1-Al_{1000} is described in Fig.4.

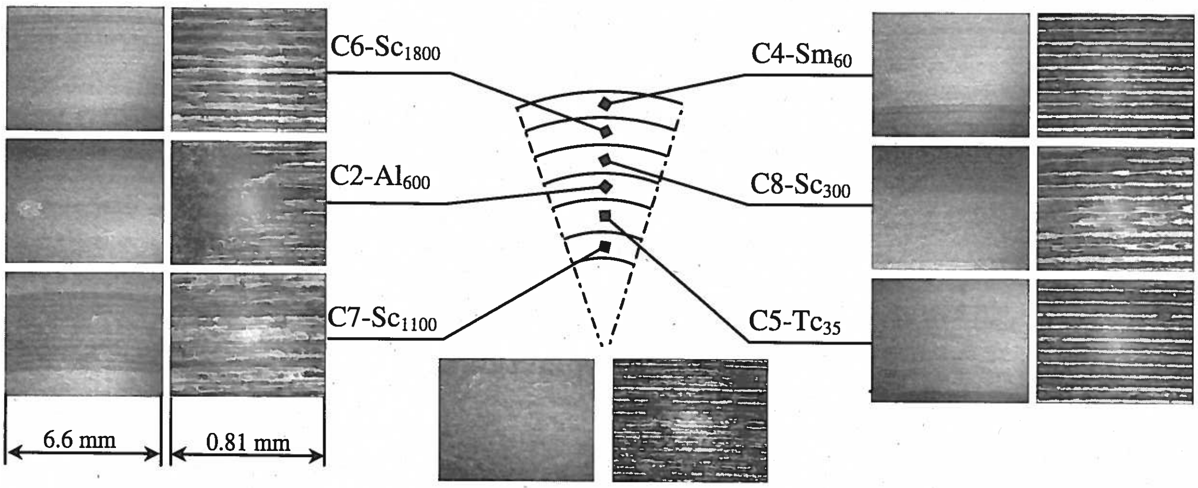

Figure 4. Analysis of disc A1-Al_{1000} by images.

The original disc surface is rather matt and shows evident circumferential tool marks, with small diffused pits. The contact of each specimen has resulted in a more or less evident alteration of these original marks on the relative track, with a rather general enhancement of the lustre of surface. Some of the tracks are not clearly visible in the images with minor magnification because of the not favourable light incidence and of the already mentioned possible inclination of the specimens. More in detail, from worn tracks observation, the specimens C4-Sm_{60} and C5-Tc_{35} appear to have simply rounded the tips of the tooled profile, partially covering the initial pits, while C6-Sc_{1800} and even more C8-Sc_{300} and C7-Sc_{1100} have markedly flattened them. The last two tracks present traces of adhesive wear and evident signs of deep plastic deformations, locally for specimen C8-Sc_{300} and extended for C7-Sc_{1100} where the initial tool marks are no more visible. The contact of the C8-Sc_{300} specimen appears not complete as the track is narrower than 3mm and it is more marked on the inner side towards the centre of the disc. The contact between disc A1-Al_{1000} and specimen C2-Al_{600}, both of aluminium, shows the typical phenomenon of material transfer with the consequent creation of a crater in the track. Connect to this patch, a marked path is observable, which has undergone to the local redistribution of material.

A comparison between images and roughness profiles has also been carried out to investigate wear effects; some remarkable examples are shown in Fig.5. As already observed in Fig.4, the specimen C7-Sc_{1100} has deeply changed the original surface profile, reported above the dotted line. It can be noted also that a marked abrasive and adhesive wear has flattened the hills and generated new valleys. The disc surface appears generally smoothed, with a new roughness of 0.30 μm against the initial 1μm.

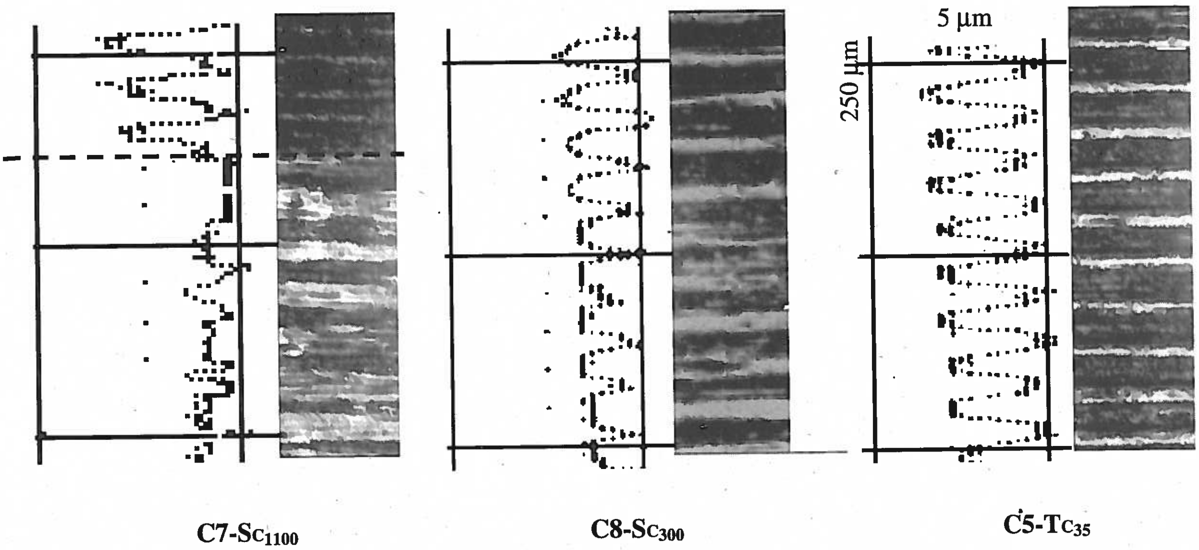

Figure 5. Comparison between images and roughness profiles (disc A1-Al_{1000}). Unworn track above the dotted line of C7-Sc_{1100}.

The track relative to specimen C8-Sc_{300} shows clearly the "cut" of the peaks (R_q reduced of 0.15µm) with a growing depth that indicates a possible inclination of the specimen. As it was evident from the image, the contact of the specimen C5-Tc_{35} has simply rounded the tips of the hills, leaving the initial profile almost unchanged. From these few examples, it is evident that surface profilometer analysis enriches images information by adding a quantitative estimate of the worn track through final R_q values, collected in Tab.2 for each disc.

In Fig.6 the analysis for the disc A2-Al_{250} is shown. The original surface is similar to that one of the disc A1-Al_{1000}, but with narrower tool marks.

Table 2 R_q (µm) of worn tracks for each disc (* two repeated tests on the same track).

	C2 Al_{600}	C4 Sm_{60}	C5 Tc_{35}	C6 Sc_{1800}	C7 Sc_{1100}	C8 Sc_{300}
D2-Gl_{20}	0.02	0.02	0.02	0.03	0.03	0.13*
A1-Al_{1000}	0.95	0.99	0.98	0.40	0.30	0.85
A2-Al_{250}	0.25	0.2	0.2	0.21	0.28	0.26

	C2 Al_{600}	C4 Sm_{60}	C5 Tc_{35}	C6 Sc_{1800}	C7 Sc_{1100}	C8 Sc_{300}
A3-Sc_{1800}	1.80	1.80	1.80	1.80	1.80	1.80*
A4-Sc_{700}	0.62	0.66	0.57	0.65	0.59	0.53
A6-Sc_{130}	0.14	0.11	0.10	0.12	0.14	0.08*

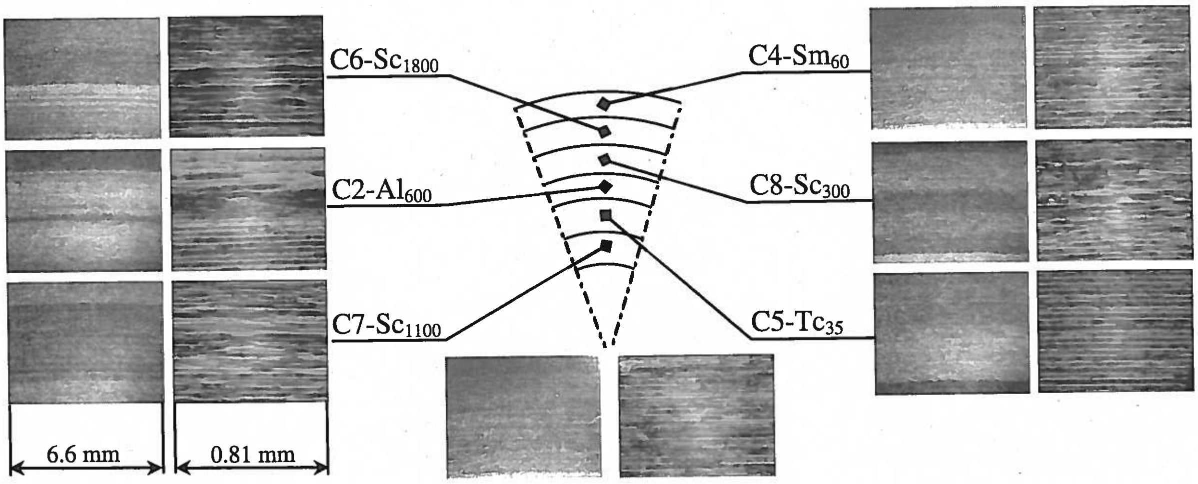

Figure 6. Analysis of disc A2-Al_{250} by images.

Small changes have been caused by the contact with cylinders C4-Sm_{60} and C5-Tc_{35}, with a general flattening of the asperities and a reduction of the roughness. Deeper deformations have been generated by the steel specimens, with a complete irregular squeezing of the track in the case of C7-Sc_{1100}, same but reduced effect for C8-Sc_{300} and C6-Sc_{1800}, and only partially in the last case. In these three contacts, the final roughness of the surface is slightly increased. A particular consideration is required for the aluminium cylinder C2-Al_{600}, whose track shows a central deep scratch, caused by an inclusion of SiO_2 left in the specimen surface after the immediately previous contact with disc D2-Gl_{20}. The heavy wear observed in the aluminium discs has also been witnessed by the presence of a large quantity of very fine particles deposited in the lubricant filter.

In Fig. 7 the images of the steel disc with the highest roughness (A3-Sc_{1800}) are shown. The surface of this disc has been obtained using a lathe (facing) as for the aluminium discs and this is evident from the regular circumferential tool marks in pictures with higher magnification. It is not easy to individuate the tracks made by each specimen since all of them have simply rounded the hills of the tooled profile, leaving unchanged the initial roughness of the surface. Special observations revealed some damage of the surface in the contact with C6-Sc_{1800}, and some deposits of aluminium in the track relative to specimen C2-Al_{600}.

The track of the specimen C8-Sc_{300} indicates some damage of the tips, which result deformed and carved. The presence of micro-pitting is visible on the surface after the contact with C4-Sm_{60}; in order to show more clearly the effects of this phenomenon a larger image of the track (x 150) –half of the original one- is reported in Fig.8.

For the steel disc A4-SC_{700} shown in Fig.9, the contact tracks are visible overlapped to the oblique honing lines of the initial texture, clearly evident. At a first sight, with respect to the aluminium disc, the tracks are less deformed and also wear debris can be detected.

A general reduction of the roughness has been observed, due to a rounding of the tips of the hills. In some cases scuff marks are present, as for C4-Sm_{60} and C8-Sc_{300} and especially for the rough steel specimens C7-Sc_{1100} and C6-Sc_{1800}. In the last two cases, the peaks of the specimens profile have markedly scraped off the disc surface and probably they came out smoother.

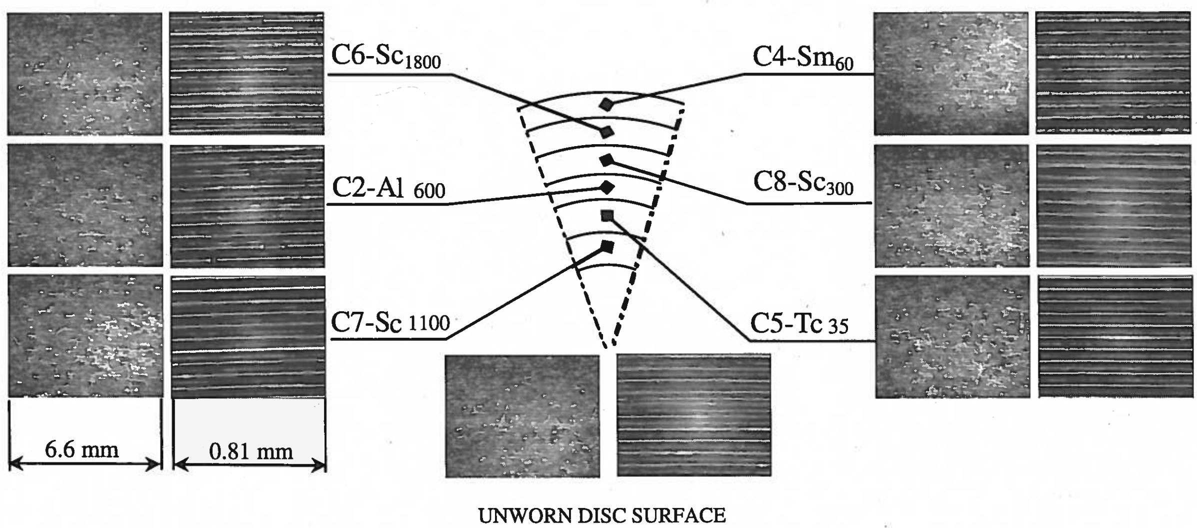

Figure 7. Analysis of disc A3-Sc_{1800} by images.

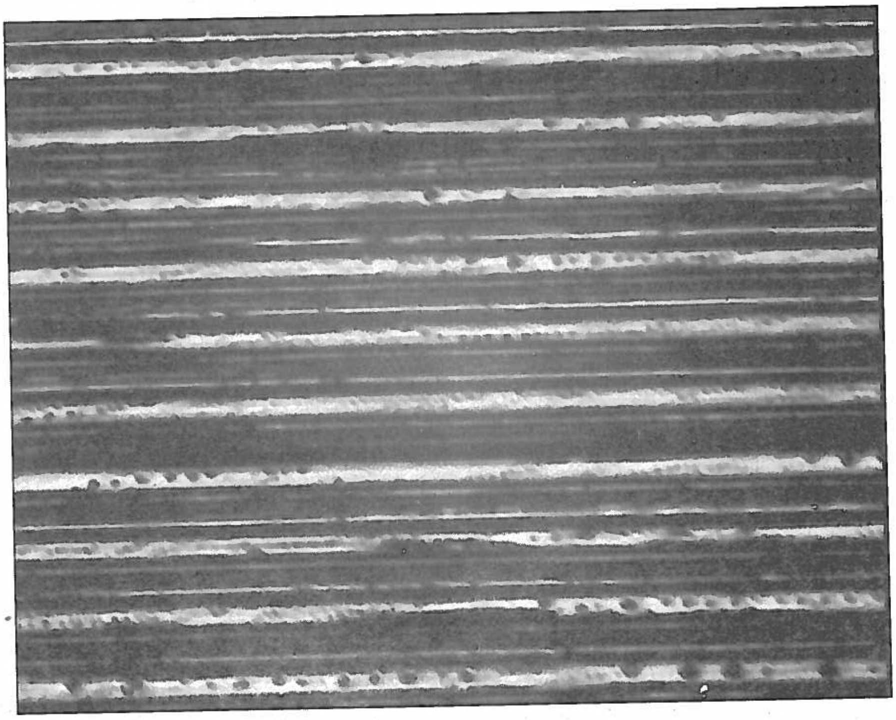

Figure. 8 Magnification (x 150) of C4-Sm_{60} track.

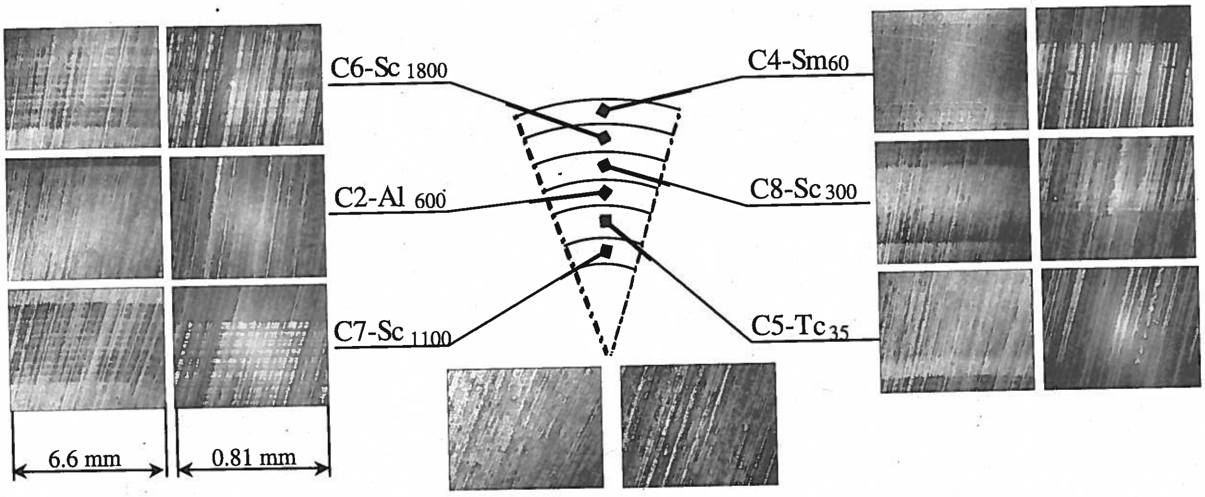

Figure 9. Analysis of disc A4-Sc_{700} by images.

For the steel disc A4-SC_{700} shown in Fig.9, the contact tracks are visible overlapped to the oblique honing lines of the initial texture, clearly evident. At a first sight, with respect to the aluminium disc, the tracks are less deformed and also wear debris can be detected.

A general reduction of the roughness has been observed, due to a rounding of the tips of the hills. In some cases scuff marks are present, as for C4-Sm_{60} and C8-Sc_{300} and especially for the rough steel specimens C7-Sc_{1100} and C6-Sc_{1800}. In the last two cases, the peaks of the specimens profile have markedly scraped off the disc surface and probably they came out smoother.

Almost analogous is the analysis relative to the tracks of the disc A6-Sc_{130}, shown in Fig.10. Initial honing lines run mainly in the radial direction, with an uneven width of furrows, as for the A4-Sc_{700}. In many contacts some score marks from sliding contact are clearly visible, and maybe even deeper than in the rougher previous disc.

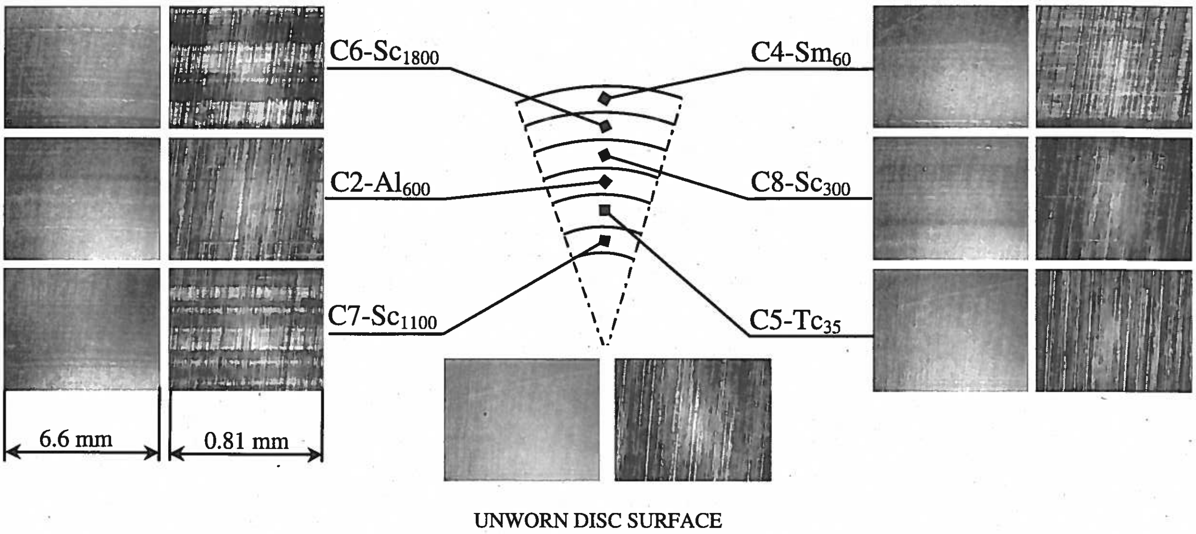

Figure 10. Analysis of disc A6-Sc_{130} by images.

Almost analogous is the analysis relative to the tracks of the disc A6-Sc_{130}, shown in Fig.10. Initial honing lines run mainly in the radial direction, with an uneven width of furrows, as for the A4-Sc_{700}. In many contacts some score marks from sliding contact are clearly visible, and maybe even deeper than in the rougher previous disc.

The tracks relative to specimens C6-Sc_{1300} and C7-Sc_{1100} show evident strips of lustre and matt regions, due to the unevenness of the cylinder surface, resulting in locally different contacts. Something similar may be recognised in the track of C7-Sc_{1100} on disc A1-Al_{1100}.

The final roughness of the surface is only lightly changed, apart from the track relative to C8-Sc_{300} which results very smooth; in this case, however, it should be noted that the tests on this track has been repeated twice (in a preliminary run, also C6-Sc_{1800} was tested at the same radial position).

Even for the steel discs, the presence of wear, lighter than the one observed for the aluminium discs, has been confirmed by the debris found in the lubricant filter.

For the glass disc covered by the very hard SiO_2 layer, no significative wear tracks are present. Although some tracks caused by the stainless steel specimens clearly appear in Fig.3 thanks to the reflectivity of the surface of this disc, they are not so deep as in the cases of the metal discs (values of roughness after tests are reported in the Tab.2). It is also to be noted that the highest wear effects has occurred in the position of C8-Sc_{300} because two tests were repeated as for disc A6-Sc_{130}. The other visible track is the one of C7-Sc_{1100}, while a narrow circumferential groove has been traced by a very hard SiO_2 debris casually detached in the test with the aluminium specimen C2-Al_{600}.

As regards the specimens, it is not possible to note the differences in roughness from the pictures of the complete elements. Just to give a hint of their shape, one of them is shown in Fig. 11.

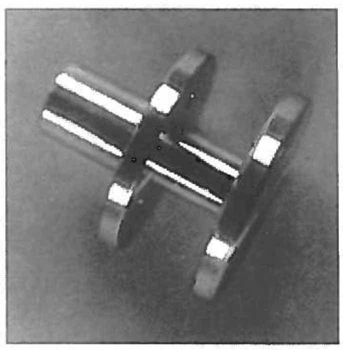

Figure 11. The specimen C6-Sc_{1800}

Apart from the aluminium specimen, whose particular behaviour will be described in the following, all the specimens show in general a small reduction in roughness. Some variations in the surface condition appear, but they are not so evident as for the disc surfaces. Images of the specimens surfaces before and after tests are reported in Fig.12; a mean approximate value of their initial and final roughness is also indicated.

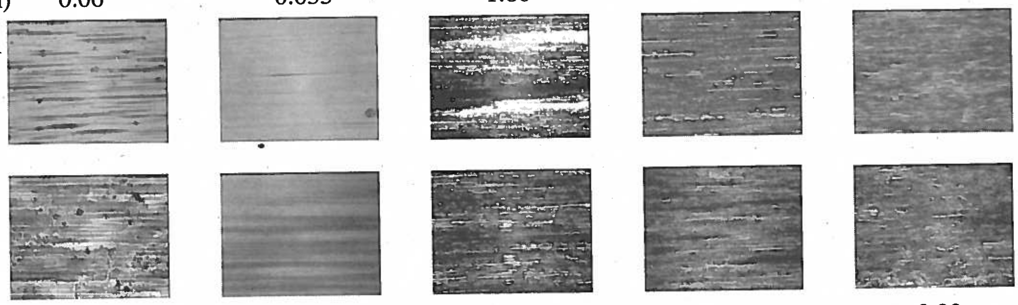

Figure 12. Specimens surfaces and roughness before and after the tests. Images obtained with the higher magnification (width of each image 0.81mm).

The unevenness of the surface of specimens C6-Sc_{1800} and C7-Sc_{1100}, assumed in the analysis of the disc A6-Sc_{130}, appear clearly from the above images; moreover some wear debris stuck on the surface of C4-Sm_{60} may be detected and connected to its last tested track image in Fig.8.

The aluminium specimen has occurred different kind of wear in the contact with each disc. Showing some small scratches before the tests (Fig. 13a), a deep central circumferential groove was created during the test with the glass disc because of the detachment of the SiO_2 particle from the surface of the disc (Fig.13b). A more general wear had occurred during the contacts with the aluminium discs (Fig.13c) whilst a sort of running occurred with the stainless steel discs A6-Sc_{130} and A4-Sc_{700} (Fig.13d). The peak of the roughness of disc A3-Sc_{1800} has finally traced the surface of the specimen, which evidently did not work in perfectly linear contact (Fig.13e).

Some particles have also been detached from the surface of the specimen, as evident from this image.

The above surface analysis can be used to explain some friction results shown in Fig.2. Let us consider for instance Fig.4 and the first diagram in Fig.2, where stainless steel specimens' curves are all located in the upper area of the plot. The highest friction values correspond to the C7-Sc_{1100} specimen, whose track is deeply ploughed. The different behaviour of the other materials may be explained by the low roughness for C4-Sm_{60} and C5-Tc_{35} specimens, while for aluminium C2-Al_{600} a certain decrease of friction coefficient due to wear effects can be observed. A completely different behaviour stems from the contact of disc A4-Sc_{700} with sample C2-Al_{600} which curve is at the top in the corresponding diagram of Fig.2. The related images in Fig.13 highlight the heavy wear and the consequent smoothing of the specimen surface occurred in this contact.

Figure 13. Surfaces of the specimen C2-Al_{600} before and after the tests. Images obtained with the same magnification as the higher one used for discs (width of each images 0.81mm).

4. DATA ANALYSIS

Together with the analysis of the surfaces, also tests data have been further examined in detail and interesting correlation found out. With respect to Fig.3 where only the $S=0.5$ curves are considered, in Fig.14 the complete summary of the test results is represented for every disc. In the following diagrams the friction value is reported for every specimen and for every combination of u and S, apart from S=0 cases where f=0. Each point in the diagram is the mean value of those acquired during the one–minute test. It should be noted that the x-axis, denoted as specimen test number, reflects also the temporal sequence of the tests. Each specimen has been examined beginning with fixed $u=0.0125$ and varying S (0.25-0.5-1); then the combination has been repeated increasing u.

In accordance with Stribeck curves (Fig.3), a decreasing trend of f is observed for every contact. A first examination of the above diagrams, points out a very similar results for the aluminium discs A1-Al_{1000} and A2-Al_{250}, where the maximum friction

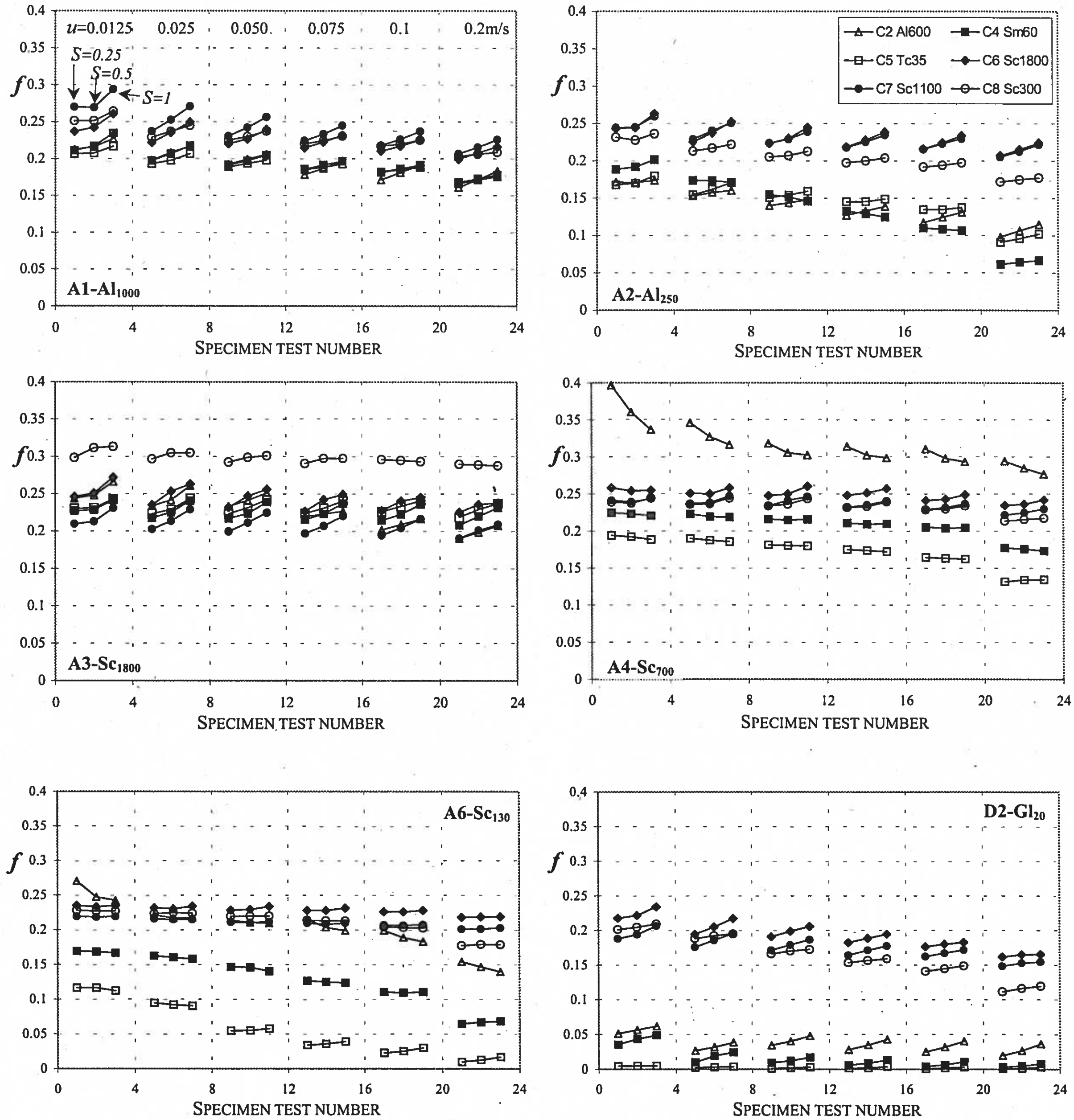

Figure 14. Friction coefficient for each test reported for every disc

is due to the contact with the steel specimens. While the roughness of the cylinders seems to have not a clear influence, especially for A1-Al_{1000} where C7-Sc_{1100} stands above the couple of C6-Sc_{1800} C8-Sc_{300}, the lower roughness of A2-Al_{250} has the effect of shifting downwards all the curves. The specimen C4-Sm_{60} showed a very particular behaviour with the aluminium A2-Al_{250} maybe connected to an initial smoothing of the disc surface (reducing roughness from 0.25 to 0.20 μm) and to some irregularities in the contact resulting in a non-complete track. In general the aluminium discs showed as expected an increasing trend of f with S, more evident for rougher specimens and for low u.

As already noted, diagrams relative to the steel discs, point out more markedly the role of the surface texture, both as roughness and tool marks orientation. Results connected to the disc A3-Sc_{1800}, that has a very high roughness, show little differences due to the specimens in terms both of material and roughness; in fact even very smooth specimens, as C4-Sm_{60} and C5-Tc_{35}, show a friction coefficient similar to the one of the rough C6-SC_{1800}. A particular behaviour is the one connected to specimen C8-Sc_{300}, which presents unexpectedly the highest friction coefficient. A deeper analysis of the surface of the disc showed a circumferential scratch mark inside the track, maybe due to a debris or a hard particle that may have influenced the friction measurements.

The other steel discs had a rather expectable behaviour, with specimens curves disposed in order of increasing roughness, with the exception of C2-Al_{600}. The lower roughness of the disc A6-SC_{130} allows a greater differentiation of the curves, underlining the properties of each specimen. It should be noted that steel specimens, which have a rather high roughness, do not reduce their friction markedly as the disc becomes smoother, from A3-SC_{1800} to A6-SC_{130}. Neither seem to have a considerable influence the speed u and the ratio S.

On the other side, in the contact with the very polished surface of the glass disc, their friction values are decreased, especially at higher u, and also the test conditions, i.e. u and S, have a certain importance.

The behaviour of the aluminium specimen C2-Al_{600} with the steel discs, can be explained by extending the results of its surface analysis; during the tests its roughness changes markedly and from rough to smooth and again to rough with varying condition of contact. The particular history of this specimen can be summarised in the diagram in Fig.15, where all the tests for every disc are reported in temporal order. For a comparison also a diagram of a steel specimen is showed, that has maintained its roughness almost unchanged during the tests.

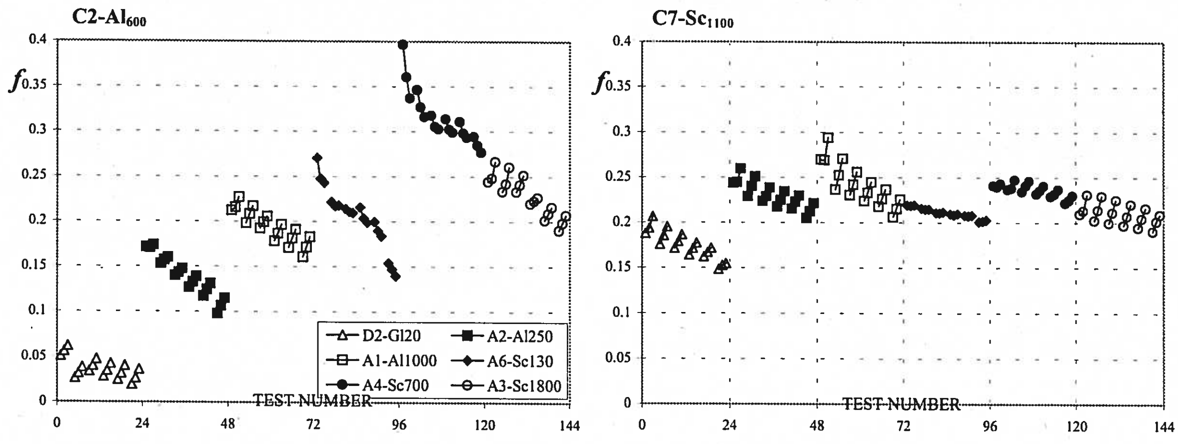

Figure 15. Friction coefficient for each test reported for the specimen C2-Al_{600} and C7-Sc_{1100}.

5. CONCLUSIONS

The contact between cylindrical specimens and the plane surface of several discs has been studied for different materials, surface roughness and texture. A first study was carried out for evaluating the friction coefficient in different rolling to sliding conditions, for all the discs and specimens. Due to the boundary lubrication conditions, both the observation of the surfaces and the Stribeck curves have revealed the presence of wear phenomena, especially for very low Stribeck numbers. As a consequence, the friction analysis is complicated by the continuous variations of the roughness and of the morphology of the surfaces during the tests. Since some unexpected results were found, a deeper investigation of the surfaces and of the data have been defined. The surface conditions of discs and specimens have been observed in detail before and after the tests by profilometric and optical methods. In particular the images of the worn track of the disc surface, after the test with the cylinders, have been acquired and analysed to recognise the possible wear mechanisms occurred during the contact. By comparing images and roughness changes to friction coefficient curves, some interesting correlation has been found out. When both the elements are made of steel, the texture and orientation of the original tool marks may be relevant; when the roughness of the disc was oriented transversally with respect to the motion direction, the friction coefficient shows little influence with the disc surface roughness, rolling to sliding conditions and speed of tests. Very particular is the behaviour of aluminium and steel elements coupled, characterised by deep plastic deformations of the former, together with galling effects.

The deep investigation conducted on the surface of tested elements and on the data, has given some enlightenment of the mechanisms involved during the analysed contact and consequently has been useful for the interpretation of Stribeck curves. Some particular behaviour has also been stressed requiring further studies.

REFERENCES

[1] G. J. Gore, J. D. Gates, "Effects of hardness on three very different forms of wear", Wear, 203-204, pp.544-563, 1997.

[2] W. Cheng, "A New Roughness Parameter Including Hardness and Contact Frequency Effects on Lubricated Rolling/Sliding Wear", Tribol.Trans., vol.40 n°3, pp.486-492, 1997.

[3] C. C. Chou and J. F. Lin, "*Tribological effects of roughness and running-in on oil-lubricated line contacts*", Proc. Instn. Mech Engrs, Part J, Vol.211 n°3, pp.209-222, 1997.

[4] T. Makino, S. Morohoshi and K. Saki, "*The Effect of Roughness Orientation on Mixed Friction*", in *Lubrication at the Frontier*, Elsevier, Amsterdam, pp.355-365, 1999.

[5] R. Bassani, E. Ciulli, B. Piccigallo, "*Theoretical and experimental results on friction for line contacts in mixed and elasto-hydrodynamic lubrication regimes*", in *Lubrication at the Frontier*, Elsevier, Amsterdam, pp.215-222, 1999.

[6] R. Bassani, E. Ciulli, "*Friction in boundary and mixed lubricated line contact with different roughness*", 26th Leeds-Lyon Symposium, Leeds, UK, 14th-17th September 1999.

[7] R. Bassani, E. Ciulli, "*Lubricant film thickness and shape using interferometry and image processing*", in *Elastohydrodynamics-'96*, Elsevier, Amsterdam, 81-90, 1997.

[8] Dowson, D., "*History of Tribology*", second edition, Professional Engineering Publishing Limited, London and Bury St Edmunds, UK, 1998.

[9] J. Prakash, H. Czichos, "*Influence of Surface Roughness and Its Orientation on Partial Elastohydrodynamic Lubrication of Rollers*", ASME, Journal of Lubrication Technology, Vol. 105, pp.591-597, October 1983.

[10] H.S. Cheng, "*Mixed Lubrication and Lubricated Wear*", in *Thin Films in Tribology*, D. Dowson et al. (Editors), Elsevier Science Publishers B.V., Amsterdam, pp.181-191, 1993.

[11] D.H. Buckley, "*Surface Effects in Adhesion, Friction, Wear, and Lubrication*", Tribology Series n°5, Elsevier Scientific Publishing Company, Amsterdam, 1981.