tribology in industry

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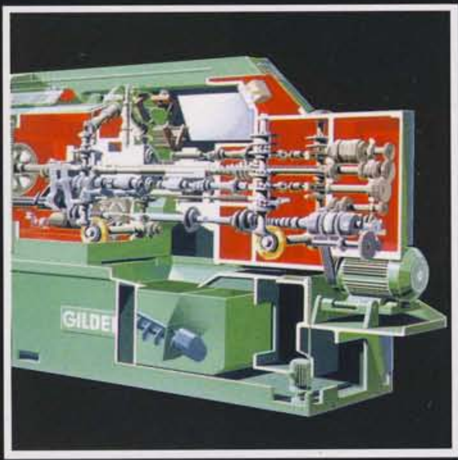
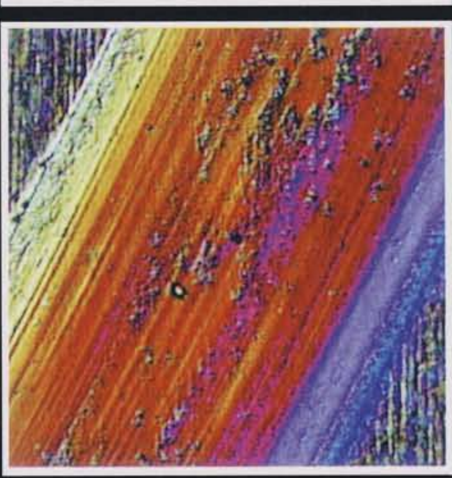


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contents

M. STEFANOVIĆ

Tribology on Symposium in Cellebration of The 100 Years Anniversary of The Laboratory for Machines at University of Gent

In Gent (Belgium), on May 7th to May 8th 1998., was held THE SYMPOSIUM ON COMPUTATIONAL AND EXPERIMENTAL METHODS IN MECHANICAL AND THERMAL ENGINEERING, for the occasion of 100 years anniversary of The Laboratory for Machines and Machine structures of the Faculty for Mechanical and Thermal Engineering of University of Gent. The Laboratory for Machines and Machine structures that was founded by Prof. J. Boulvin, was the basis for development of different scientific areas such as fluid dynamics, piston machines, internal combustion engines, turbomachines, heat transfer, as well as tribology.

At the Conference were presented 70 papers, out of which 20 were from the area of tribology, with authors from different countries, and numerous R&D institutes from industry, joined on common European projects. Papers from this selection are related to different fields and will be here presented in more details:

Special plenary lecture was presented by professor D. Dowson, the winner of University of Gent Award for this occasion, entitled Tribology from Leonardo to the third millenium; millimeters to nanometers (Symposium Proceedings, Editor Faculty of Applied Sciences, Gent, 1998., pp. 187-197). This paper in the interesting way presents the history of tribology and it is divided into several sections: Synopsis, Introduction, Leonardo da Vinci and tribology, Early scientific studies and engineering progress in tribology (1500-1850), The golden period of tribology since 1880., Development of bearings in the first half of the twentieth century, Tribology in the second half of the twentieth century (elasto-hydrodynamic lubrication, friction and wear), Conclusion. This paper, as well as the famous book by the same author "History of Tribology" contains abundance of original quotations from the very rich list of references.

In the area of tribo-investigations in the machining processes there were several papers that were related to the tribology of deep drawing. Especially were considered the fields of laser preparation of rollers' surfaces for the final rolling of thin sheets aimed for machining by deep drawing, with special emphasis on the complex requirements towards topology of the thin sheet surface in the further machining process (e.g. the SIBITEX thin sheets). The form of craters and the distance between them, as well as their depths, significantly influence the appearance of the galling process, reduction of the local friction, decrease of the required paint layer, etc. In the similar way, it is possible, by laser preparation, to bring the ceramic tools surfaces into the state that is the most convenient for realization of the hydrostatic and hydrodynamic lubrication.

The separate group of papers was related to the machine elements tribology - gear pairs and bearings. Considered were the influence of speed and load in realization of conditions for elasto-hydrodynamic lubrication, then there were presented evaluations of additives' reactivity in lubricants for gears, compressor's and turbines' oils. Besides the dimensional analysis, in experimental work, are also applied the known tribo-testers: the four-ball devices, SRV device with the oscillating upper contact pair, FZG-construction with the gear pair.

In considering the gas-dynamic bearings, it is stated that it was not possible to realize the consistent construction without effective modeling of the dynamic behavior of such systems. The results were presented of determination of the optimum clearances with respect to the working parameters in exploitation. The tribological phenomena in frictional clutches were modeled on the PIN-on-Disc tribometer, where it was proven that such modeling is reliable in studying the friction. The wear testing requires other way of modeling.

From the area of coatings, presented were the investigations related to behavior of the solid lubricating layers, e.g. MoS_2, which is deposited onto the steel material. Such coatings exhibit high efficiency in the vacuum conditions. Also were presented results of studying the behavior of surface layers in corrosion fatigue and wear.

Special results were related to detection of the fretting wear products, taking into account the extremely low values of the measured quantities. In this case the method of activation in the surface layers is applied, namely the known radioactive method for monitoring the intensity of wear on the corresponding fretting tribometer.

Tribology of composites was presented by investigations of the Al-composites' behavior in contact with the steel materials. Al-matrix composite, obtained by sintering, includes copper or 3% of MoS_2, and all investigations were performed on the block/ cylinder tribometer. The comparative results for sliding bronze over steel were presented also. Results show possibility of sliding pairs without lubrication and specific tribological phenomena.

Within this section were also presented papers that are related to modeling of dynamic systems in conditions of the micro-gravity, interaction between friction and dynamic systems during the stick-slip process, tribological investigations in agricultural and food production engineering.

In the tribology section were presented the two papers from Yugoslavia. The first is the paper by M. Stefanović and S. Aleksandrović, from faculty of Mechanical Engineering in Kragujevac, entitled Tribo-modeling in Stretching of Thin Sheets from the area of the deep drawing tribology. In the paper are considered: drawing, typical stress-strain history that exists in deep drawing of complex geometry parts, and that, by its characteristics, represents the complex tribo-model. Experimental investigations were conducted with the classical thin sheets and thin sheets with anti-corrosive coatings, with tools of different geometries (two drawing tool diameters with several combinations of the rounding radius of the drawing tool front), in different contact conditions. The simple or complex strain history was realized, with proportional load paths, in individual phases, or for the complete forming. For this tribo-model, results were divided into tow groups: in the first one are the so called macro indicators, like the deformation force, limiting depth at destruction, average friction coefficient. In the second group are parameters that are directly related to realized deformation field-realized strain distribution, position in the limiting formability diagrams, etc.

The second paper was from the area of the gear pairs tribology, by authors R. Rakić and Z. Rakić, from the NIS-Naftagas Marketing and Vojvodina Bank from Novi Sad, entitled The Influence of Lubricants on Gears Failures. In the paper was pointed to the importance of gear as a representative of the very important tribo-mechanical system in machines and mechanisms. The basic assumptions are given for elasto-hydrodynamic lubrication and the importance of lubrication is pointed out. The detailed classification was performed of the gear oils, where the basic criteria are temperature of the environment and working conditions - load and speed. The algorithm is presented in details for the lubricant selection adjusted to valid standards. The causes for the gears in machine tools damages were analyzed, and the relation is given of the gear life as a function of tribological characteristics of the applied lubricants.

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RESEARCH

S. SEKULIĆ

Correlation Between The Bearing Ratio And Maximal Roughness Height of Machined Surface in Surface Grinding

The relationship between individual roughness parameters of a machined surface is approximately given by tables. In order to determine more accurate relationships, experimental results were processed for statistically valid sample N=9650 and pointed strong correlation between roughness parameters.

Keywords: *roughness, correlation, bearing ratio, grinding.*

1. INTRODUCTION

Relationship between particular parameters of roughness is given very often in simplified form independent of kind of process and work piece material, and other conditions which follow the process.

For example, relationship between the maximum roughness height and arithmetic deviation of the profile from the mean line, i.e. their numerical values, is given in a table (German standard DIN 4767/70) and relationship of the mean height in ten points and the arithmetic deviation of the profile from the mean line, according to Yugoslav standard JUS M.A1.020/79, with a remark on its approximation.

Relationship between maximum height of roughness and the average arithmetic deviation of the profile from the mean line $R_{max} = f(R_a)$, in exponential form

$$R_{\max} = 6.1595 \cdot R_a^{0.98}$$

is given independent on the condition which follows the process. However, since the exponent in the last equation is approximately one, it can be concluded that, between the maximum height of roughness and average arithmetic deviation of profile, there is a proportionality [1], i.e.

$$R_{max} = 6.16 \cdot R_a$$

The bearing ratio and maximal roughness height in surface grinding, for a statistically valid sample, in exponential

$$p_n = B \cdot R_{\max}^a$$

and linear form

$$p_n = a \cdot R_{\max} + b$$

have been sought for in this paper

2. EXPERIMENTAL INVESTIGATION

2.1 The influential parameters of the machined surface roughness

The quality of the machined surface after the finish machining has the most important influence on the exploitation characteristics of the piece (the accuracy and the quality of the surface). The quality of the surface is characterized by many parameters such as geometrical and kinematic parameters, chip deformation, the dynamic system state - the machine tool, the fixture, the work piece and the tool, the state of wear etc.

The approaches to the investigation of the roughness can be divided into three groups: 1. geometrical models, 2. the models based on the tool wear and the other supporting influences, 3. models based on the response surface methodology.

The geometrical and experimental models for cutting with the sharp tool were investigated by: Schmaltz (1936), Opitz and Moll (1940), Galloway (1945), Belekkiy (1946), Skragan (1947), Takenaka (1951), Krivouhov (1958), Bramertz (1961), Olsen (1968) [4], Solaja (1952-1972), Sekulic (1970), Fischer (1971).

The influence of the groove wear and other parameters on the roughness of the surface was investigated by: Galloway (1945), Akinaci (1949), Pekelharing and Schu-

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ennan (1953), Thompson, Schatt and Stabler (1953/54), Solaja (1957-1972), Bramertz (1961), Sekulic (1962), Pekelharing and Giesen (1967-1971), Selvam and Radhakrishnan (1973 and 1971), Snunmugam (1974), Lonardo(1976), Bailey (1977), Wallbank (1979), Monheim (1981).

The statistical approaches to the determination of the dependence of the surface roughness based on response surface methodology were developed by Rasch (1971), Kuljanic (1971), Taraman (1974-1977), Nassirpour and Wu (1977), Miskovic (1978), Sekulic and Kovac (1979), Kovac (1980), Kovac and Sekulic (1981).

2.2 Mathematical model of correlation

In order to determine correlation relationship between the bearing ratio and the mean arithmetic deviation of the profile from the mean line of the machined surface, the voluminous experimental material on two types of construction steels in finish turning were performed in exponential form

$$Y = B \cdot X^a \quad y = bxN$$

and in linear form

$$y = a \cdot x + b .$$

Logarithmic transformation of the first equation gives

$$\log Y = a \cdot \log X + \log B$$

Denoting by

$$y = \log Y ; x = \log X ; b = \log B$$

in bilogarithmic scale, linear relationship is given and, in both cases identical procedure can be applied for experimental data processing (in the first case, the input values are logarithms and in the second one, direct parameters of surface roughness).

Starting from the linear equation

$$y = a \cdot x + b$$

and using the least square method gives:

$$\left(\sum \Delta_i^2\right)_{\min},$$

where Δ_i is the error of the i-th observation. From the condition of minimum, the normal equations are

$$\sum (x_i \cdot y_i) - a \cdot \sum (x_i)^2 - b \cdot \sum x_i = 0$$

$$\sum y_i - a \cdot \sum x_i - N \cdot b = 0$$

and consequently

$$A_1 \cdot a + B_1 \cdot b = C_1$$

$$A_2 \cdot a + B_2 \cdot b = C_2$$

where

$$A_1 = \sum (x_i)^2 ; A_2 = \sum x_i = B_1 ;$$

$$B_2 = N ; C_1 = \sum (x_i \cdot y_i) ; C_2 = \sum y_i$$

the solutions for the above system are

$$a = \frac{D_a}{D} = \frac{\begin{vmatrix} C_1 & B_1 \\ C_2 & B_2 \end{vmatrix}}{\begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}} = \frac{(C_1 \cdot B_2 - C_2 \cdot B_1)}{(A_1 \cdot B_2 - A_2 \cdot B_1)}$$

$$b = \frac{D_b}{D} = \frac{\begin{vmatrix} A_1 & C_1 \\ A_2 & C_2 \end{vmatrix}}{\begin{vmatrix} A_1 & B_1 \\ A_2 & B_2 \end{vmatrix}} = \frac{(A_1 \cdot C_2 - A_2 \cdot C_1)}{(A_1 \cdot B_2 - A_2 \cdot B_1)}$$

The constants $A_1,...,C_2$ can be found in the appropriate tables. The constants a and b are detained by substitution.

The correlation coefficient is

$$r = a \cdot \left(\frac{\sigma_x}{\sigma_y}\right)$$

where the variance of x-value

$$\sigma_x^2 = \frac{1}{N} \cdot \sum x_i^2 - \bar{x}^2 = \frac{A_1}{B_2} - \left(\frac{A_2}{B_2}\right)^2$$

and variance of y-value

$$\sigma_y^2 = \frac{1}{N} \cdot \sum y_i^2 - \bar{y}^2 = \frac{E}{B_2} - \left(\frac{C_2}{B_2}\right)^2 ; E = \sum y_i^2 ;$$

The average of x-values

$$\bar{x} = \frac{1}{N} \cdot \sum x_i = \frac{A_2}{B_2} = \frac{B_1}{B_2}$$

and average of y-values

$$\bar{y} = \frac{1}{N} \cdot \sum y_i = \frac{C_2}{B_2}$$

Corresponding substitution for correlation coefficient gives

$$r = \frac{C_1 \cdot B_2 - C_2 \cdot B_1}{A_1 \cdot B_2 - A_2 \cdot B_1} \cdot \left\{ \left[\frac{A_1}{B_2} - \left(\frac{A_2}{B_1}\right)^2 \right] : \left[\frac{E}{B_2} - \left(\frac{C_2}{B_1}\right)^2 \right] \right\}^{\frac{1}{2}}$$

If the correlation coefficient is near one, the correlation between variables is stronger

2.3 The environment of the experiments and statistical data processing

The material of the work piece was: 1. constructional steel for the improvement C.1730 (JUS) (DIN C60) dimensions *50x50x130 mm*. According to JUS standard, the chemical composition is provided as follows: *0.65% C; 0.35% Si; 0.80% Mn; 0.045% P* and *0.045% S*, and mechanical characteristics: tensile strength of material $\sigma_m = 700\text{-}1050\ N/mm^2$, yield strength $\sigma_v = 500\ N/mm^2$ and elongation $\delta_5 = 14\%$. 2. steel for carborizing C.4721 (JUS) (DIN 20CrMo5). Chemical composition: *0.1,40% C; 0.35% Si; 1.20% Mn; 0.035% P* and *0.035% S*. Mechanical characteristics: tensile strength of material $\sigma_m = 1000\text{-}1300\ N/mm^2$, yield strength $\sigma_v = 700\ N/mm^2$ and elongation $\delta_5 = 8\%$.

Grinding was performed using the wheels: B60H8V, B60K8V, B60N8V and B60R8V.

The experiments were performed on surface grinding machine type URB-750, made by LZTK, table dimensions *1130x300 mm*, the cross feeds *2* to *20 mm/l*, the surface velocity of work *2* to *25 m/min*, spindle electromotor power *4 kW* and number of wheel revolutions *1500* min_{-1}.

The roughness parameters were measured using the Perth-O-Meter, type "Universal".

For the purpose of providing sufficiently reliable relationships between variable values, for both of investigate materials, the statistically valid samples of $N = 96 > 50$, are taken.

The measured values of the bearing ratio p_n and the maximal roughness height R_{max} are classified in tables T.1. The graphical presentations were given on the figures Fig. 1 to Fig 4.

The results of measured numerical data processing, are given in Table T.1.

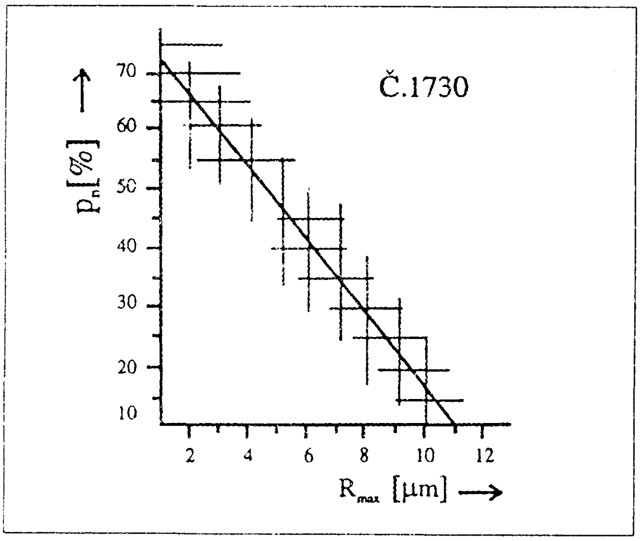

Fig. 1.

Table T.1.

Workpiece mat.	Č. 1730		Č. 4721	
Model	$p_n = B \cdot R_{max}^a$	$p_n = a \cdot R_a + b$	$p_n = B \cdot R_{max}^a$	$p_n = a \cdot R_a + b$
b (B)	572,818	78,573	173,468	74,040
a	-1,294	-6,075	-0.721	-4,954

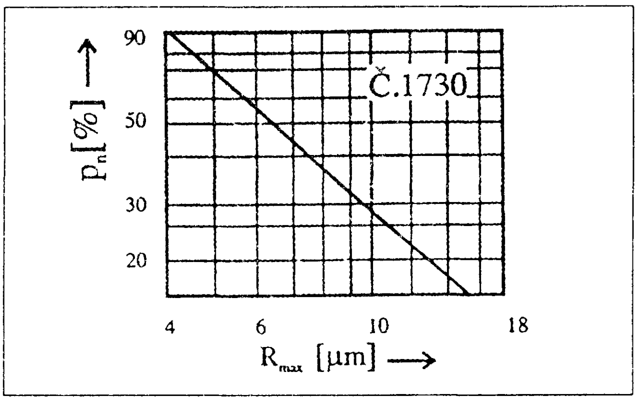

Fig. 2.

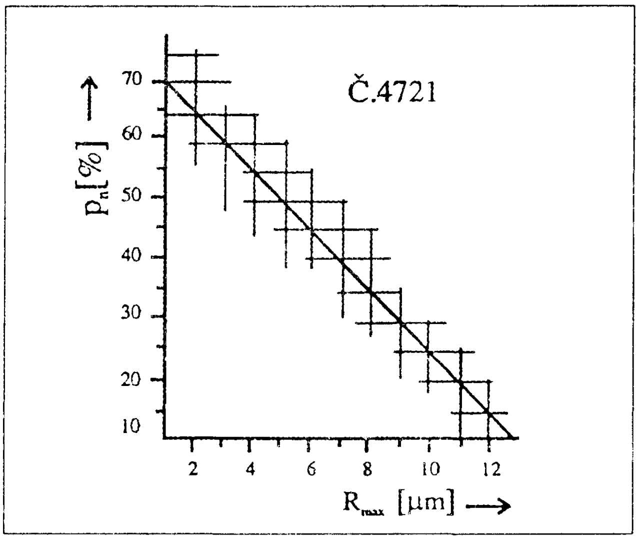

Fig. 3.

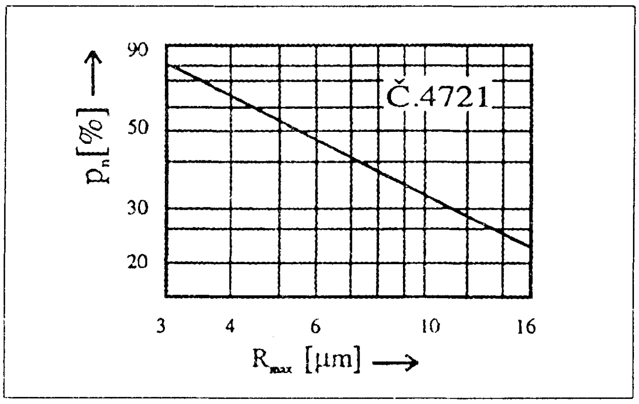

Fig. 4.

3. ANALYSIS OF RESULTS

After the experimental data processing, convenient mathematical models are evaluated by the coefficient of correlation value and on the basis of the magnitude of exponents in the exponential relationships. However, if the exponent in exponential relationship is close to one, the linear relationship between variables exists. In accordance with the presented, we can generally conclude that, for all proposed models, corresponding coefficient of correlation are sufficiently high ($r>0.88$).

In exponential relationship, if the value of exponent is not close to one, the linear relationship can be generally ignored.

The numerical values of exponents in relationship $p_n=B\cdot Ra^a$ are, for steels: C.1730 $a=-1.29$ and C.4721, $a=-0.72$, which points strong deviation from linear relationship, for both investigation materials. For steel C.1730, for both kind of mathematical models the lower values of correlation coefficients are given. However in exponential mathematical models the values of correlation coefficients are some heighter then in linear.

4. CONCLUSIONS

Referring to the above mentioned, we conclude:

- for mathematical models of correlation that connected individual roughness parameters of the machined surface in finish turning, the exponential and linear relationships can be used.
- for investigated materials, in proposed mathematical models, there is a very strong correlation between the observed parameters.

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UDK 621.833.004.6

RESEARCH

D. NOVAKOVIĆ,O. LUŽANIN, Ž. ZELJKOVIĆ, J. HODOLIČ

Enhancement of Tribological Characteristics of Gears by Application of Software Package for Gear Trains Design

The introductory part of the paper underlines the importance of formation of the concrete calculation model and systematization of influential factors used in calculation, which have the significant influence on final gear train solutions. The systematization of influential calculation factors and calculation models is a good basis for automated calculation by computers. The design automatization gives the opportunity of getting more variants of gear train solutions faster and their comparison can lead to the most desirable solutions.

The second part of this work emphasizes the parameters, which significantly improve the tribological characteristics of gears, especially the equalization of sliding speeds at teeth flanks. This has an important influence on teeth flanks wear and by this on the safety coefficient increase. The goal function in the calculation model is also defined and explained in this part of the work.

The third part contains the presentation of the software package model for automated calculation and verification of spur and helical gears, and a short review of the characteristics of certain model.

The final part illustrates the segment of verification of the given model with the focus on concrete output calculation results.

Keywords: *gear, design automatization*

1. INTRODUCTION

Gear train design usually involves methodology for calculation of gear geometry and allowed transmission moment. Design procedure requires selection of a number of parameters, which means that optimal solution necessitates use of multiple calculations and comparative analysis of computed values.

The calculation procedure is related to the choice of various factors which are recommended in a particular range and which influence the output solutions. A large number of factors presented in the form of functional relationship in graphical or some other way can be found in bibliography. In order to make possible for this data to be used on a computer, they have to be transformed into a convenient form for a work on a computer.

Naturally enough, this process is most conveniently realized by use of computers. The effort is hereby concentrated on the preparation of the necessary information base, which would allow the preset goal to be attained, as well as on the programming work. The usage of computers enables the automated multi-variant design which can be used for a choice of the optimal solution, on the basis of the set optimization goal. The most convenient solution is obtained by using various procedures of iterative searching of prepared data base.

Segment of the developed program with the focus on the set goal function in the design procedure is presented in this work.

Criteria of optimization and limitation function which create the base for the most convenient gear trains solutions are incorporated in the goal function.

2. FUNDAMENTALS OF DESIGN PROCEDURE

The design procedure implemented in this software is based on analysis of a number of significant parameters and various design procedures for spur and helical gear trains. The analysis involved the following:

- gear train functionality and relevant factors of influence
- various elements of design procedure
- analytical models for design of geometrical features
- analytical models for estimation of allowed transmission moment

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- existing constructive solutions
- standards, recommendations, etc.

The adopted concept of design procedure involves methodology for selection of optimal parameters and can be therefore considered an optimization model with the following goal function

$$Fc=Fc(H, B, D, G, M, Sh, SS, O) \qquad (1)$$

Gear geometry should satisfy optimization criteria.

This function presents the formal mathematical description of the goal which is identified by optimization criteria of the function that needs to be satisfied by the gear. Gear geometry should satisfy the optimization criteria which, in this particular case, can be:

- minimal wear of tooth flank (H)
- minimal noise (B)
- minimal dynamic strikes (D)
- minimal gear heating (G)
- minimal geometric dimensions of the form (minimal material consumption) (M)
- maximal safety coefficient regarding the tooth flank wear (Sh)
- maximal safety coefficient regarding the tooth flank bending (geometrically formed) (Sc)
- other influential geometric parameters (O)

$$F_g=\frac{V_{kl1}-V_{kl2}}{V_{kl1}}\cdot 100 \leq |A| \qquad (2)$$

where: V_{kl1} - relative sliding speed at the tooth flank of the gear (1),
V_{kl2} - relative sliding speed at the tooth flank of the gear (2),
A - quantitative value of the allowed difference of relative sliding speeds ($A=0.001$)

Limitation function is very important in the realization of the goal function Fc.

Speeds at the contact of two gear teeth (Fig.1) are different and this difference gives the sliding speed.

$$V_{kl}=V_{1t}-V_{2t} \qquad (3)$$

This speed, i.e. its intensity significantly influences the friction, wear and heat generation during the gear action. By analyzing these speeds the relation for their derivation can be set, which is not shown in this paper due to limited space.

If the sliding speeds are presented by ordinates of their values (η_1 and η_2) and shown in graph, y_I and y_{II} hyperbolas are obtained which cross at one point (Fig.2.). In Fig.2 we can see that the maximal values of sliding speeds are at end points of contact lines k_1 and k_2, so that the maximal sliding is at k_1, i.e. at the base of the small gear.

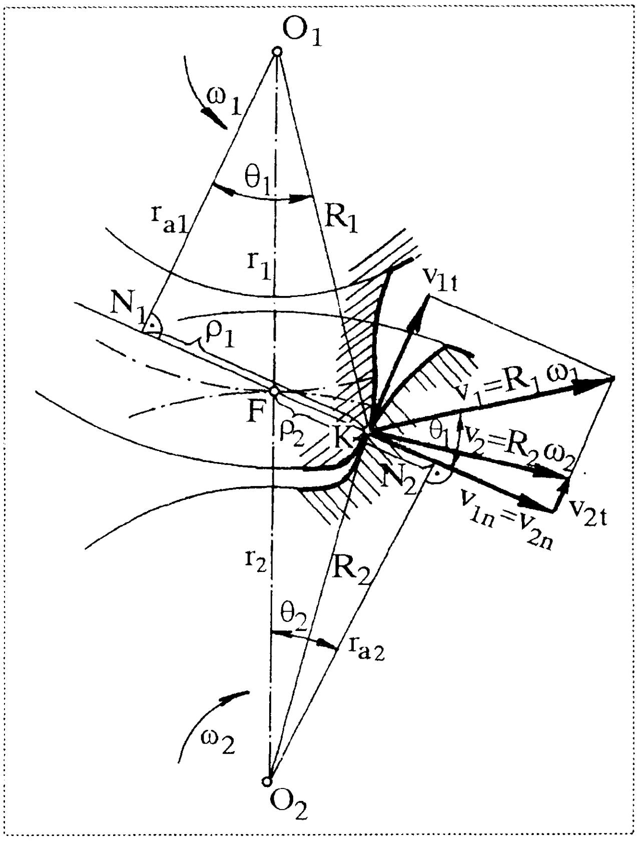

Fig 1. Contact speeds at teeth flanks

Because of this, the smaller gear wears out faster at the base if the gears are of a same material, as it is usual. Equalizing of speeds by the hyperbole analysis can be performed in the graphical and analytical way by trying procedure. This is a rather long and complex job. Obtaining gears with equal sliding speeds was kept strictly confidential by the famous gear producers.

The procedure in the adopted mathematical calculation model through iterative search enables the selection of such correction which gives an equal sliding at the gear tooth flanks. In this way, the value of the limited function that satisfies the stated goal function regarding the module segment for the calculation of geometrical values of the gear is obtained.

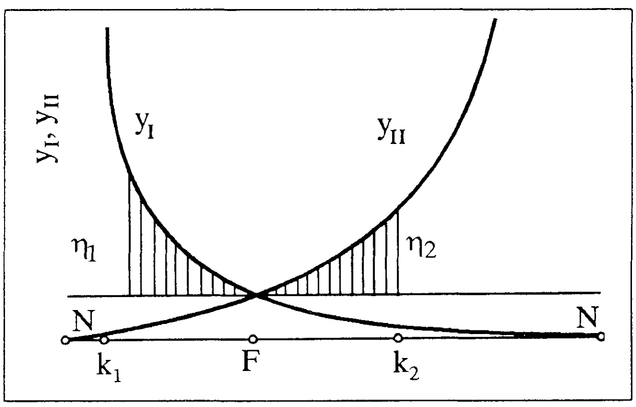

Fig 2. Slide curves along the pressure line (N-N)

Parameters for the calculation of transmission moment of gears are usually defined by the boundary function based upon the particular function wich is:

$$A \leq F_g \leq B \tag{4}$$

where: A - lower boundary for the parameter of mathematical model,
B - upper boundary for the parameter of mathematical model

The boundary function defined in this way gives the opportunity of intuitive choice of parameter values while working manually, which requires experience. In this way the values obtained in the final result can only by chance be the optimal ones.

In mathematical calculation model of gears, the most convenient solution is obtained by appropriate methodology of choosing the parameter out of specially prepared data bases. Data bases are prepared according to qualitative experimental data about parameters (curves of parameter dependence) along with the certain mathematical form of data choice. Boundary functions are mostly structured in the matrix form.

$$F = \begin{array}{c} \\ x_1 \\ x_2 \\ \cdot \\ x_n \end{array} \begin{array}{c} \begin{array}{cccc} y_1 & y_2 & \cdot & y_n \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \cdot & a_{1n} \\ a_{21} & a_{22} & \cdot & a_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ a_{n1} & a_{n2} & \cdot & a_{nn} \end{bmatrix} \end{array} \tag{5}$$

where: x_i, y_i are parameters
a_{in} are parameter values i.e:

$$Fg(a_{ij}) = Fg(x_i, y_j) \tag{6}$$

3. ARCHITECTURE OF SOFTWARE PACKAGE

Model of software package for gear calculation and verification is made so that the calculation model (Fig.3) is chosen at the beginning of the work.

One of the calculation models is the model of sliding speeds equalization, which is emphasized in the work, and its output results can be compared to other calculation models.

Calculation is realized within three modules.

The first module-GEPROR-performs the calculation of geometrical gear values based upon the given values.

In the current version it was developed in Windows graphical interface and tested for spur and helical gear trains. It has been used and tested in practice over the years.

The second module-TRANSMISSION-checks the transmission moment of gears, based upon the values calculated within the first module, by using additional data for calculation of transmission moment.

The third module - OUTPUT - within this module, the output results are obtained in the form of a listing with the data necessary to generate technical documentation and detailed gear drawings.

Software package development - since the beginning it has been realized by applying various programming techniques. This was put under limits of available computer and software systems.

The first developed version was realized in DOS interface with the fixed flow of program execution, simple user interface and possibility of the data base generation with output results. This version used the operative data base to allow the transmission moment calculation module to acquire input data from the module for geometry calculation.

Based upon the first version of software package, the improvement has been made through:

- applying the new software tools for application development in Windows interface
- creating the data base with output calculation results
- creating the data base to allow the use of CAD system for generation of detailed drawings would be enabled
- enabling the graphical output of calculation results

Some of the output results from this module are stored in the data base for later use by the module for transmission moment calculation.

Auxiliary tools such as the application for gear module conversion in various unit systems, have been developed within the system. Module outputs can be chosen separately. The possibility of examining the output results in the appropriate data base is given in all calculation variants.

Logical organization of the software package enables independent usage of certain system modules.

4. SOFTWARE REALIZATION OF THE STATED CONCEPT

Software package has been developed and tested a PC compatible computer. The GEPROR module is developed for Windows interface, unlike the TRANSMISSION module which uses the DOS operative system and is yet to be ported to the Windows OS. Calculation output results of the module OUTPUT exist in the form of listing and/or detailed gear drawings.

After the calculation model has been selected (Fig 4.), the data (Fig 5.) which form the basis for calculation of geometrical values of gears task are entered.

Display of output results of the calculation of geometrical values of gears is given in Fig. 6 and exists in the form of output results listing.

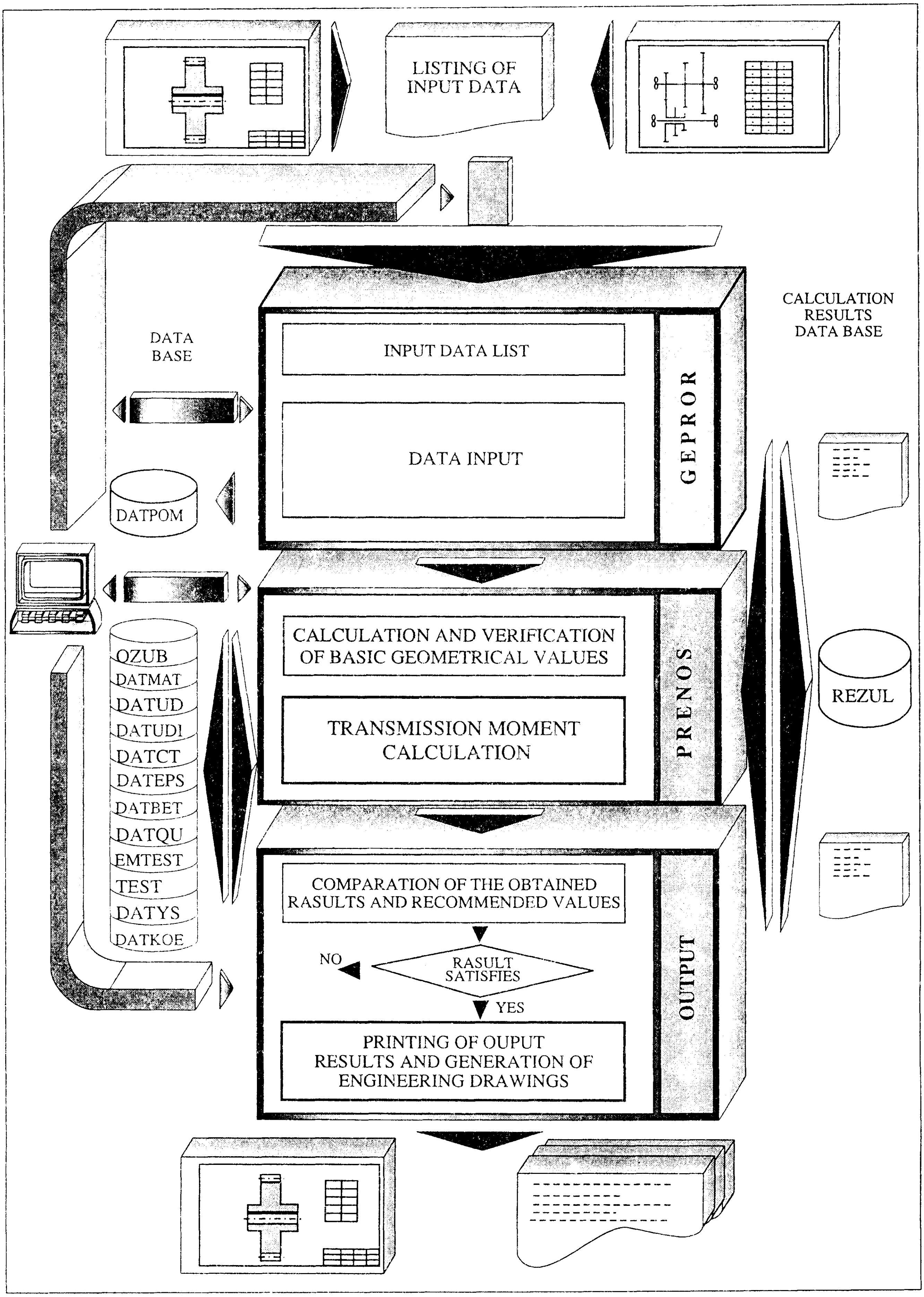

Fig. 3. Architecture of software package for calculation and verification of gears

Calculation results of geometrical values are stored in the results data base for later use by the module for transmission moment calculation.

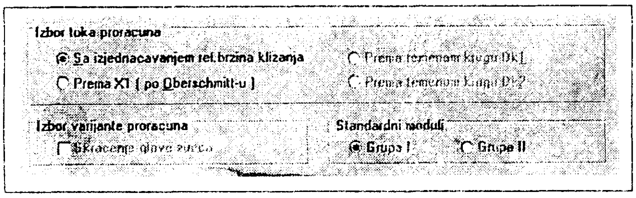

Fig 4. Option "selection of calculation model"

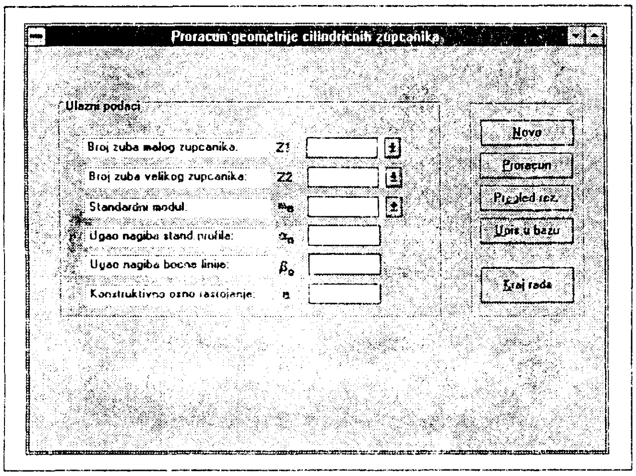

Fig 5. Data - input dialog box

TRANSMISSION module also requires the data which are necessary for the calculation of transmission moment (P, η, ...).

The calculation procedure itself is carried out automatically or interactively. The data base has also been developed for this module (Fig 3.).

Detailed presentation of output results from the TRANSMISSION module, together with the detailed gear drawings which are generated according to the output results, have been omitted for brevity and can be found in [4]

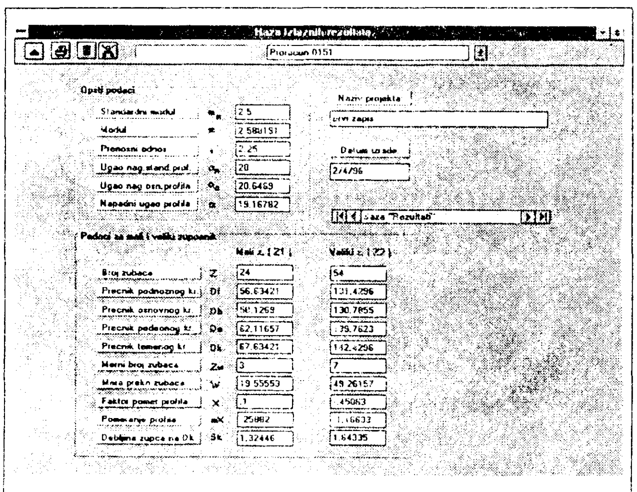

Fig 6. Display of the output results from the geometrical values calculation

5. CONCLUSION

By summarizing the results presented in this paper it can be concluded that the authors' efforts have, above all been focused on two main directions:

- enhancement of quality of the procedure for automated design of gear trains by applying mathematical model which will enable the optimization of parameters that have significant influence on tribological characteristics of gear trains
- enhancement of the software package quality with the emphasis on the modern graphical interface which should enable simplicity of user interface and comfort during work. In this way, software package for calculation and check of spur and helical gear trains allows fast and simple calculation as well as the creation of engineering drawings.

Presented design model is based on the equalization of the sliding speeds at tooth flanks. In this way, the enhancement of tribological characteristics of gears is achieved.

Created models and algorithms of the developed software package present the efficient base for the development of calculation procedure for other types of gear trains.

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RESEARCH

UDK 621.892:620.919

R. STOJČINOVIĆ, M. PANTIĆ

Application of Emulsion Oils for Cold Rolling of Steel Strips Having Thickness of Up To 0.50 mm

One of the basic factors for cold rolling of steel strips, having thickness of up to 0.50 mm, is the emulsion oil at the rolling plant "5-Stand Tandem Mill" within the Cold Rolling Mill. The emulsion oils must meet a number of complex requirements in the modern cold rolling process viewed from technical, economical and environmental aspect. Viewed from the technical aspect, the emulsion oil used in the cold rolling process must reduce friction, resistance to deformation, and it must be stable at high temperatures and pressures, must have a stable thickness of lubricating film, sufficient concentration of lubricating EP additives, good anticorrosive protection, good emulsion lubricating properties in order to reduce rollers wear, reduces sheet damage and has a good dispersion property, i.e. steel strip rinsability. From the environmental aspect, the rolling emulsion oils must be biodegradable. Viewed from the economical aspect, oils must be usable for a long time period and must have an acceptable price. The application of rolling emulsion oils is under regular control. This control is performed by using modern methods over a number of physical-chemical parameters directly affecting the quality of cold rolled steel strip.

Keywords: *rolling emulsion oil, friction, wear, EP-additives, lubricating properties, dispersion properties, biodegradability, emulsion properties, economical and environmental aspect.*

1. COLD ROLLING OF STEEL STRIPS

Metals rolling without previous heating is meant by cold rolling of steel strips, whereby metal thickness reduction takes place by passing the same through rotating rollers system of "5-Stand Tandem Mill". Lubricating and cooling of rollers is of great importance for the quality of cold rolled steel strip external surface. Cold rolling of steel strip is performed by using emulsion lubricant, resistance to deformation is thereby reduced and strip elongation increased. The friction ratio between work rollers and rolled strip is reduced by means of emulsion lubricant. The characteristic phenomena in the steel strip cold rolling process are friction and wear - tribological elements being decisive for rolling effects in the final product quality domain, direct energy consumption and indirect economic parameters. For that reason, besides a number of influential factors in the cold rolling process, the emulsion agent, the so-called technological rolling lubricant, i.e. quality thereof, has a predominant role. Practically, the aim of this study is to show the overall complexity of technological rolling lubricant quality, its importance and influence, with a remark that other more significant parameters cannot be ignored either.

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The most influential cold rolling parameters are as follows:

1. Emulsion lubricants for cold rolling of steel strip.
2. Rolling plant type and characteristic.
3. Process parameters.
4. Rolled material quality and nature.
5. Work rollers surface microgeometry.
6. Pickling process technology.
7. Type of system wherein rolling means is placed.
8. System maintenance during exploitation.

In order to notice the effects conditioned by the applied high-grade rolling means in the most adequate way, it is necessary to maintain the working conditions of the above mentioned parameters at constant value to the greatest possible extent.

2. INFLUENCE OF QUAKEROL N1905 EMULSION LUBRICANT ON STEEL STRIP COLD ROLLING PROCESS

Quakerol N1905 is a lubricant from which a *2-3%* emulsion solution is prepared intended for rolling, directly affecting the steel strip reduction size, rollers resistance, energy consumption, rolled strip thickness and its surface quality. The emulsion solution effect is reduced to external friction diminution and rolled steel strip surface layer mechanical resistance reduction. By diminishing external friction the emulsion lubricant reduces metal resistance to deformation, thereby reducing pressure of metal on the rollers; the lower the pressure, the elastic deformity of rollers being smaller, what causes an increased steel strip reduction. The dependence of metal pressure on the rollers on external friction at cold rolling of steel strips is shown in Fig.1 (the numbers on curved lines designate friction ratios).

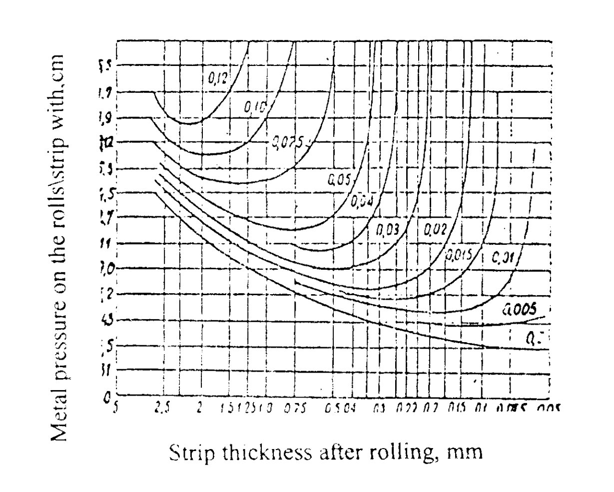

Fig.1. Dependence of steel strip pressure on the rollers on external friction at cold rolling

The thickness of emulsion oil film affects the steel strip cold rolling process, which oil exists on the strip surface at the exit side of rollers. Wetting of steel strip depends on the greatness of surface tension between the emulsion oil and rolled strip. The emulsion oil having low surface tension spreads over the steel strip, covering it with a thin film. The emulsion oils with a large content of free fatty acids have a small surface external tension. The optimal emulsion oil film thickness on a steel strip is about 0.185u. In the circulation systems of "5-Stand Tandem Mill" the emulsion oil separates from the emulsion on strip surface and on the rollers surface forming films of uniform thickness on them. The separation process is of short duration and lasts a few seconds. The oil separation is also induced by emulgators affecting fast oil separation from water, and in addition to that they increase even the oil film thickness. In that way, lubrication and reduction of external friction is considerably improved by means of emulgators. *2-3%* Emulsion is prepared with process water.

Technological characteristics of process water are:

PH	7.10
Conductibility *μS/cm*	160
Chlorine concentration *mg/l*	4
M-alkalinity *mVal CaCO3/l*	1.6
P-alkalinity *mVal CaCO3/l*	<0.1
Water hardness *OdH*	4.2

Technological characteristics of steel strip rolling emulsion for strips having thickness of up to 0.50 mm:

Working emulsion concentration % 2-3

pH value	*5.5-8*
Iron concentration *mg/l*	*max 500*
Chloride concentration *mg/l*	*max 30*
Ashes *mg/l*	*max 2000*
Active oil content	*% 70*
Saponification number *mg KOH/g of oil*	*130*
Acid number *mg KOH/g* of oil	*3.5*

Applying of excessive lubricant is not desirable when rolling. The excess of lubricant increases the elongation degree. In order to ensure the peak lubrication effect when rolling, as much lubricant as necessary is to be applied for complete wetting of strip surface with thin film. When applying a thicker lubricant film, the lubricant excess is extruded on strip edges. The collected lubricant on strip edges also exists on strips wound in a coil. When annealing of strips in coils complete combustion of lubricant is difficult to perform, so the strip surface becomes stained with solid residue (gas at the edges).

The technological lubricant must not leave scabs on the strips during annealing. Special attention should be paid during rolling to the emulsion purity. The dirt remainder from emulsion may be the reason for free carbon formation during thermal treatment. The emulsion used must be clean and without phase separation. It is not desirable that the emulsion stays on the strip, because at annealing, the emulsion remainder causes the emergence of white spots on the strip surface and aggravates the strip surface quality.

3. TYPE OF ROLLING PLANT

The plant is "5-Stand Tandem Mill" for rolling low-carbon steel strips as consumer goods. The reduction grade ranges from *80* to *85%* in view of a large number of stands. Specific and total pressures are *9.81 10 N/m*, therefore, the lubricating function is very important. The total pressure force or absolute is *2040 tons*, namely *20.0124 10 N*, while those pressure forces between the stands are considerably lower, and they range per stand as follows:

Stand 1-2	*686.7 KN*
Stand 2-3	*588.6 KN*
Stand 3-4	*490.5 KN*
Stand 4-5	*421.8 KN*
Drawing stress of stand 1 uncoiler is	*54.34 KN.*
Drawing stress of stand 5 recoiler is	*88.29 KN.*

The annual plant capacity is really high, and is about *600.000 tons* of cold rolled steel strip.

4. PROCESS PARAMETERS

At the plant "5-Stand Tandem Mill" the process parameters affect significantly friction and wear effects. These are mainly variables being chosen relative to the requirements. The most significant are presented in Table 1.

Table 1. Process parameters at cold rolling of steel strip

Variable	Value
Speed m/sec	18.3
Initial strip thickness, mm	6,0-2,5
Final strip thickness, mm	3,0-0,50
Total pressure force, N	20,0124 10
Intermediate drawing stress between stands,N	546,9 10

5. WORK ROLLERS SURFACE MICROGEOMETRY

The work rollers surface hardness and microgeometry considerably influence friction and wear effects. On the other hand, the requirements regarding ultimate geometry of final product depend on the same and they are being chosen within the process. Relative roughness of work rollers depends on the roughness of final product surface.

6. CLEANLINESS OF STEEL STRIP SURFACE

The friction and technological lubricant products remain on steel strips surface after rolling. The quantity of various impurities depends on a number of factors. A clean strip surface is obtained as follows: By pickling in hydrochloric acid, whereby a gray surface of steel strip is obtained with minimum quantities of mud (deposit) on it. The influence of pickling on the strip surface quality should be observed together with the hot rolling influence and strip cooling conditions, whereby scale is formed. Insufficient or excessive pickling causes the increase of dirtiness, and thereby defects on the steel strip. Medium dirtiness of strip surface is about *310* mg/m^2, and during insufficient pickling, the dirtiness increases at *350* to *400* mg/m^2. Excessive strip pickling causes surface destruction, giving rise to greater spreading of lubricant, easier wear, and dirtiness increases at *400* to *450* mg/m^2.

7. ROLLING SPEED

The effect of rolling speed on the composition of remaining lubricant film and wear products on thin strip surface is presented in Fig.2.

The rolling speed in maintaining thermal control has little effect on wear products quantity. The remaining lubricant film is an insoluble phase. By increasing the

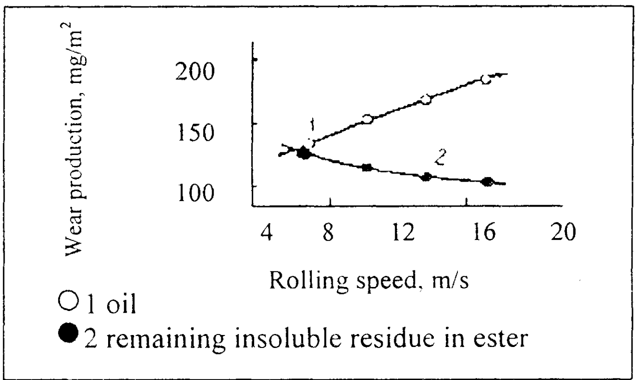

Fig. 2. Effect of rolling speed on the composition of remaining oil film and wear products on a steel strip

speed at elevated temperature, the lubricant decomposes at contact temperature of approximately *200 °C*. All the aforesaid about the effect of rolling speed on precipitate quantity on the strip pertains to excessive oil quantity in front of deformation zone. Generally, the excess oil in front of the rollers is *5* to *20* times greater than behind the rollers.

8. LUBRICANT FILM THICKNESS

The thickness of lubricant film is defined by hydrodynamic conditions of lubricant placement on the strip and rollers, by the speed and specific pressure, temperature conditions and limited friction conditions. The higher specific pressure, the lubricant film is thinner. The strips rolled with lubricant deficiency have rolled-in particles across the surface which cannot be eliminated during special cleaning operations. If the emulsion is insufficiently clean, then the impurities are evenly disposed on the strip in the form of tiny dispersed particles collected locally in the shape of stripes and spots. Insufficient cooling of roller necks may also cause scattered strip overheating, and at some points the quantity of mechanical impurities can be 2 to 5 times bigger than on the remaining strip surface.

9. EMULSION CONCENTRATION

The emulsion concentration has a very important role in rolling. The data presented in the table indicate that the impoverished mixture up to *1:8* increases the strip dirtiness for *25%*. The influence of oil - water ratio on strip dirtiness at cold rolling is presented in the Table 2.

Consequently, as it results from the table, by reducing emulsion concentration when rolling of thin strips, the quantity of wear products augments. The quantity of remaining oil on the strip at the beginning of emulsion utilization and at the end does not practically change. At the same time, the quantity of precipitate when rolling with clean emulsion is *70 mg/l*, the iron content in this being *7 mg/l*, while in rolling with dirty emulsion there is

130 mg/l of precipitate, the iron content in this being *18 mg/l*. Collecting mechanical admixtures in the emulsion during utilization depends on rolling conditions. According to experimental data, about *400 g/t* of wear products (precipitate) is formed when rolling a strip having thickness of up to *0.50 mm*.

Table 2. The influence of oil - water ratio on dirtiness of steel strip having thickness of up to 0.50 mm

Composition of impurities	Mixture ratio	
	1:4	1:8
Oil	200	150
	220	170
Insoluble precipitate	270	340
	300	320

10. RESIDUE DISPOSITION

The residue disposition on strip surface is uneven, even at uniform emulsion action. There is a larger quantity of impurities at strip edges as shown on Fig.3. The comparative data on ratios of residue quantity on the strip after rolling and annealing are presented in the picture. It can be seen clearly that insoluble residue in ether on the strip corresponds by quantity to residues after annealing.

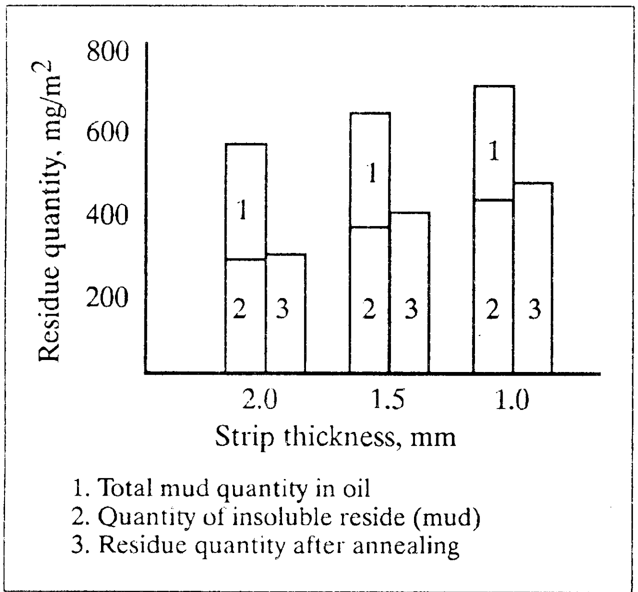

Fig.3. Oil quantity and wear products ratio after rolling and ratio of residues after annealing on steel strips reduced to the thickness of up to 0.50 mm

In the experiments performed when rolling of strips having thickness of up to *0.50 mm* with sand-blasted rollers, a *15* to *20%* larger quantity of insoluble residue portion in ether is obtained than on ground rollers. These residues practically remain on steel strips even after annealing. The oil residue disposition (full lines) and wear products disposition (broken lines) at cold rolling with ground and sand-blasted rollers are presented in Fig.4.

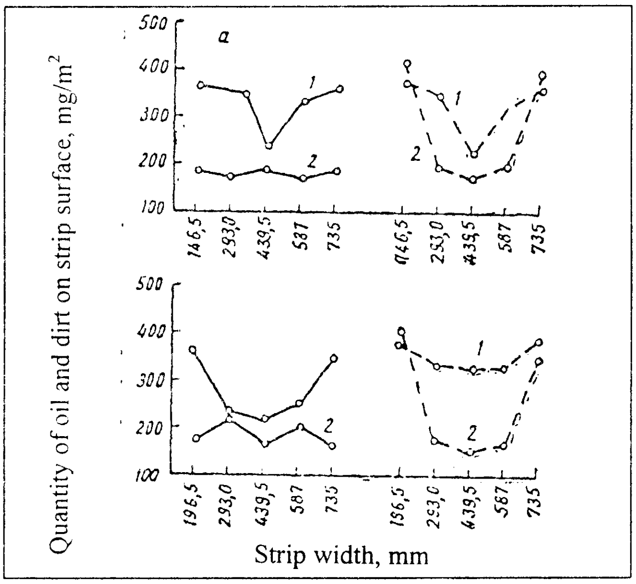

Fig.4 Disclosed layout of oil and wear products residues after rolling with ground and sand-blasted rollers

11. CONCLUSION

The following is required from technological lubricants for cold rolling of steel strips:

- Excellent lubricating properties, long exploitation life, good emulsion behavior, production of extremely clean steel strips and low roller consumption;
- good dispersion and possibility that the emulsion is free from external oils and existing mechanical impurities;
- outstanding stability at high pressures and temperatures;
- formation of uniform oil film which enables good cooling, lubricating and efficient rinsability;
- good anticorrosive protection at least four weeks in plant conditions; and
- acceptable product price.

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RESEARCH

UDK 621.9.015.004.62

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Computer Aided Design of Hydrodynamic Sliding Bearings

Calculation of radial sliding bearings is fair complex and demands large number of iterative steps to accomplish adequate solution. Therefore a software for evaluation of radial hydrodynamic sliding bearings is being developed, for natural and compulsory cooling, and it has been presented in this paper. Modeling of single-piece radial sliding bearings and thick and thin walled bearing shells in Auto CAD and ADS surrounding, for automatisation of the design process is also presented in this paper.

Keywords: sliding bearing, CAD, modeling

1. INTRODUCTION

Modern achievement of the design science still do not include enough tribological demands in the design process. Tribological point of view and tribology in the design process are necessary for correct design. Primary step in design process, regarding the tribological point of view, is adequate choice of elements of machine system, which is to be designed (such as a choice of material, lubricant and lubrication engineering), and then establishing its working and tribological characteristics (service life considering wear process, calculation of oil film thickness, temperature, flow of lubricant, frictional loss etc.). Sliding bearing is by all means, the most interesting machine part in tribological point of view. Sliding bearings have great use in heavy machinery, turbines, mills, crushers, rolling mill and forging machinery, press', gears etc. Relative motion of sliding bearing parts with simultaneous load transmission is realized by friction. Researches that has been made in last few years, enabled significant improvement of sliding bearings. Basic advantage of sliding bearings is their carrying capacity, that is their service life. If hydrodynamic floating conditions of sliding bearings have been established, then its service life is almost infinite.

This is especially important with high speed of rotation, where rolling bearings, because of their limited carrying capacity and limited service life, cannot be used. Besides, tendency of modern machines development is permanent improvement of their performances. It is mostly related to load, speed and rotation increase simultaneously with decrease of dimensions and weight. This trend of development indicates that greater use of sliding bearings is to be expected in future. Research in this field indicate the same thing. Due to large sliding area where bearing pin and brass are in contact and separated with oil film, sliding bearings have the ability to smother noise and vibrations, that is to accept great impact load in their work.

Sliding bearings can be single and double pieced, while rolling bearing can only be single pieced. This advantage enables that sliding bearings can be used in cases where arranging demands two pieces, such as at crank shaft.

Difference in price between serial and individual production of sliding bearings is lower than with rolling bearings. Rolling bearings are competitive in price with sliding bearings only in cases of serial and mass production. For diameters of bearing pin under *10 mm* and over *300 mm* usage of sliding bearings is far more rational.

Advantage of sliding bearings is obvious because of their compact construction. For same bearing carrying capacity, dimensions of sliding bearings are far less than rolling bearings, especially in radial direction. This is important for bearings of two shafts, placed immediately side by side.

2. CALCULATION OF RADIAL HYDRODYNAMIC BEARINGS

Calculation of bearings with hydrodynamic lubrication is checking whether designed bearing can ensure hydrodynamic floating of shaft, for given conditions and lubricant. Calculation is based on Reynolds differential equation, that is determining pressure distribution through lubricant coat and bearing carrying capacity. This equation is very difficult to solve because it describes bearing state only if effective values of lubricant temperature and viscosity are given. These values are obtained from balance of temperature, where friction conditions must be known, exact solution can be obtained only with great simplifications.

Prof. dr Vojislav Miltenović,
Prof. dr Siniša Kuzmanović,
Msc Dragan Milčić, Mechanical faculty Niš

Therefore the most optimal is iterative procedure, so software for calculation of radial hydrodynamic sliding bearings is being developed.

Bearing carrying capacity is the extreme force that bearing can carry, during anticipated service life, by not exceeding working temperature in bearing, inadmissible wearing and volumetric destruction of sliding pair material. In hydrodynamic lubrication, thickness of lubricating coat must not be thinner than it is allowed. In fig. 1 algorithm for calculation of radial hydrodynamic bearing is presented.

Basic dimensions of sliding bearing are bearing pin diameter d, bearing brass diameter D and bearing length B. Minimal bearing pin diameter d is determined by calculation of shaft and axle by strength criteria. Diameter of bearing brass D is equal to diameter of bearing pin d, and bearing clearance ensured by joints choice. Bearing length is determined by bearing design characteristics $\varphi = B/D = 0{,}2...1$. After determining of basic dimensions, bearing brass material is being appropriated and specific bearing load is checked. Then, coefficient of linear expansion of bearing brass and pin (α_P, α_R), environment temperature ϑ_0, bearing pin and brass roughness (R_{zR}, R_{zP}), competent surface for cooling A (based on bearing design), lubrication system, etc. are determined.

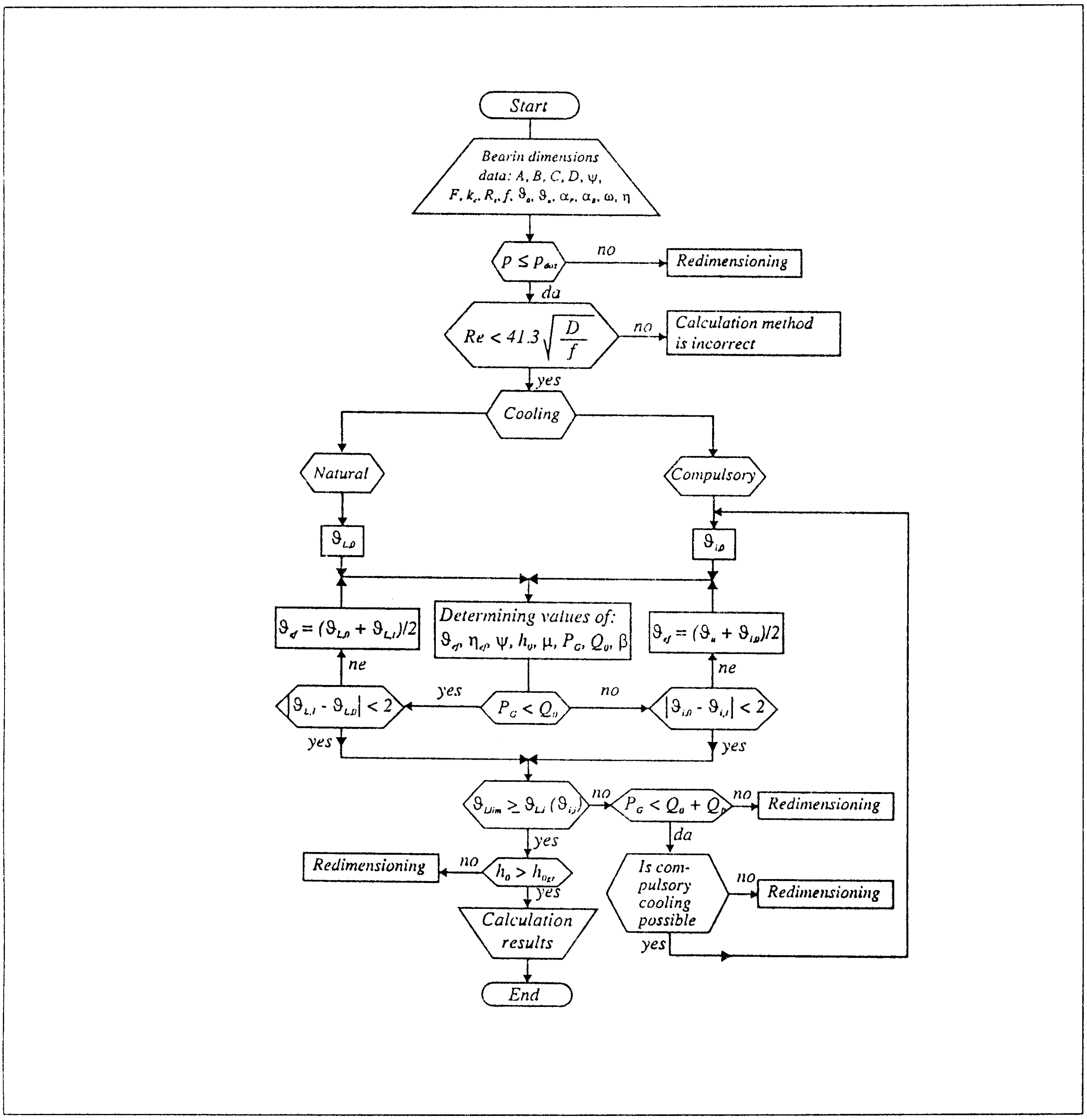

Fig. 1 Algorithm for radial hydrodynamic sliding bearings calculation

In next step kinematic and geometric values are determined: sliding velocity v, angular velocity ω, average relative clearance ψ_m, thermal changes of relative clearance $\Delta\psi$, effective relative clearance ψ and absolute clearance f. After Reynolds number determining, flow lamination is checked and heat calculation is executed. Possibility of natural cooling is also checked (condition $P_G<Q_0$) or effective oil film thickness is being determined and is being compared with allowed. In cases of $\vartheta_{eff}> \vartheta_{Llim}$ natural cooling is not enough, so compulsory cooling is applied. Determining of effective working temperature of oil film ϑ_{eff} is presented on algorithm in fig. 1.

In next step condition of hydrodynamic floating is chekked, which means calculation of minimal oil film thickness h_0 and condition $h_0 \geq h_{0lim}$ is checked. In case that condition is not fulfilled, redimensioning is necessary.

Example of results of developed software based on given algorithm is presented in table 1.

Table 1 Results of sliding bearings calculation

Bearing rotation number	n min-1	620.000
Radial load	F_r N	12000
Bearing diameter	D mm	60.00
Bearing length B mm		50.00
Lubricant according to ISO		ISO VG 46
Coeff. of linear expansion of pin	α_R K^{-1}	11.010^{-6}
Brass material		L.Sn80
Coeff. of linear expansion of brass	α_p K^{-1}	22.010^{-6}
Allowed specific load	p_{doz} N/mm^2	5.0
Specific load	p N/mm^2	4.00
Minimal oil film thickness	h_0 µm	5.11
Allowed oil film thickness	h_{0lim} µm	4
Effective oil temperature	ϑ_{ef} °C	57.09
Working temperature limit	ϑ_{lim} °C	90
Environment temperature	ϑ_o °C	20

3. MODELING OF RADIAL HYDRODYNAMIC BEARINGS

Sliding bearing can be designed as single and double pieced. Intensity and character of bearing load, rotation speed (that is sliding speed), exploitation and maintenance conditions are significant for the design of sliding bearings. Forms of bearing brass' and bearing itself are defined in standards, so designer should only calculate carrying capacity and choose existing bearing.

Bearing shell (brass) is formed as a thin cylinder. It can be thick and thin walled. Thick walled single-pieced bearing shells are being standardized according to DIN 1850 (form G without support and form U with edged support). Thin walled shells are also standardized according to DIN 8221. They are being used for bearings defined in DIN 502, DIN 503 and DIN 504. Former shells and single-pieced radial hydrodynamic sliding bearing are modeled in AutoCAD and ADS surrounding.

Considering that bearing shells and their corresponding bearing are standardized, on basis of obtained diameter d and length B all other dimensions are defined in standards.

Therefore modeling procedure is simplified. Dimensions of modeled sliding bearing are defined over corresponding parameters. All parameters, depending on diameter, are defined in standards and put in a data base for given form of bearing. Therefore, choice of shell and type of bearing enables automatic drawing of bearing shell, that is bearing itself. Basic modeling problem is choice of correct modeling tool. AutoCAD offers two solutions: AutoLISP and ADS (AutoCAD Development System). AutoLISP, although very powerful, has some serious imperfections. The greatest is, by all means, fact that AutoLISP is interpreter (not a compiler), which can seriously influence the execution speed of some program parts. On the other side, ADS is only an environment with group of functions for relation with AutoLISP functions, and all other operations are executed in pure execute C and C++ code. The next AutoLISP's imperfection is it's code which is, with big program modules unreadable and inconvenient for error detection.

Programming in ADS environment is similar to classical C programming. Great number of functions has same names with prefix ads_.

For easier modeling group of functions in C language are developed. Those functions enable drawing of line, poliline, arc, circle, dimensioning, ratio determining based on chosen format, etc. Fig. 2 shows single-pieced radial sliding bearing according to DIN 504 modeled in AutoCAD in ADS environment.

4. CONCLUSION

Based on former the following can be concluded:

- Development tendency and performances of modern machines together with modern technology impose need for priority development and usage of sliding bearings.
- Because of great number of influencing parameters for calculation, just as importance and significance of mechanical system's bearings, computers should be used for sliding bearing design.
- Developed program package for hydrodynamic sliding bearing calculation and modeling enables automatization of the design process and obtaining of optimal design solutions.

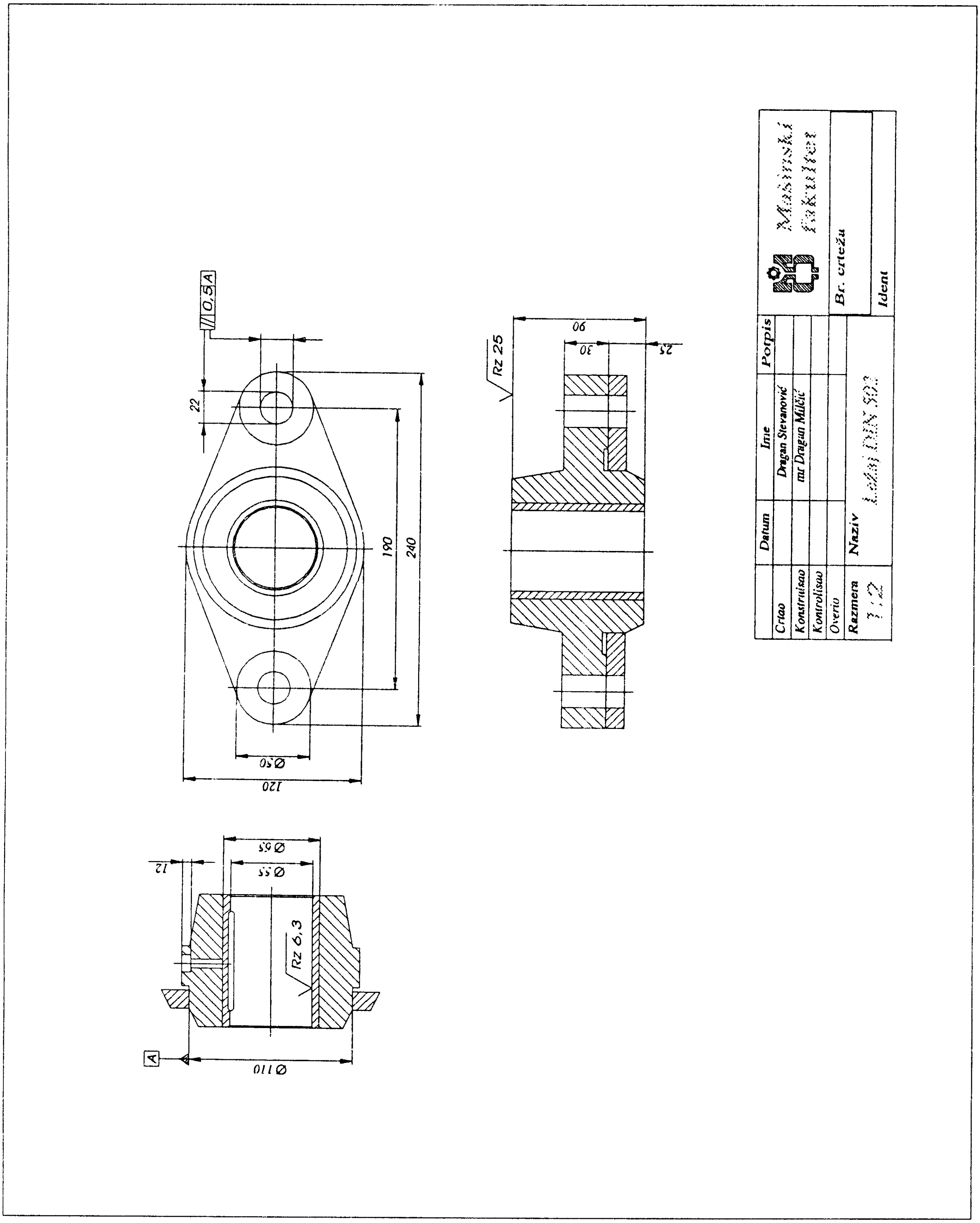

Fig. 2 Single-pieced radial sliding bearing according to DIN 504

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RESEARCH

UDK 621.179:620.891.22

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The Effect of Surface Nitriding Using Tungsten Metal Arc Heat Source on Wear Resistant Properties of Ti-6Al-4V Alloy

Surface nitriding using a tungsten metal arc heat source in a shielding atmosphere of pure nitrogen or in a mixture of nitrogen and argon were performed with the objective of improving the tribological behaviour of Ti-6Al-4V alloy. The use of standard micro-hardness techniques and wear assessment methods show superior wear behaviour of the surfaces treated either under a nitrogen/argon or a nitrogen gas shield. A uniform surface micro-hardness value of 1070 HV0.5 to a depth of 0.9 mm was achieved when using a pure nitrogen shielding atmosphere, compared to 893 HV0.5 for laser nitrided surfaces. The micro-hardness measurements were found to correlate with wear data showing that changes in wear volume, frictional force, wear rate, and coefficient of friction were lower for surfaces treated by the use of a tungsten metal arc heat source in a shielding atmosphere of pure nitrogen than those for laser nitrided surfaces. Metallographic and X-ray diffraction analysis together with ageing treatments attribute this to the formation of titanium nitrides in the resolidified region. Scanning electron microscopy showed that the presence of titanium nitrides at the modified surface alters the mechanism of wear from abrasion to adhesion.

1. INTRODUCTION

Titanium alloys are widely used in the aerospace industry because of their high specific strength and excellent corrosion resistant properties. However, their poor tribological characteristics, mainly due to a high coefficient of friction and low surface hardness give these alloys poor wear resistance and prevent use for instance in the manufacture of titanium bearings or gears. Techniques which have been developed to alter the plastic deformation behaviour of these alloys rely on solid-state diffusion of solute elements such as carbon and nitrogen which have the effect of reducing both the coefficient of friction and surface wear. The disadvantage of these techniques are the long processing times involved and the treated region is usually no more than *60 mm* thick. Other methods which involve the deposition of hard coatings (e.g. CrN, TiN) by physical and chemical vapor phase processes have inherent deficiencies such as the failure at the interface between the coating and the substrate which leads to eventual loss of the coating on repeated applied contact stresses.

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Recently, surface melting techniques have been developed utilizing lasers and surface alloying performed under a nitrogen gas shield [1-5]. Although an expensive alternative, an improvement in the wear resistance of titanium surfaces has been observed, but with some cracking in the laser nitrided layers being reported [6]. However, work by Morten et al. [7] showed that this surface crakking could be eliminated by pre-heating the substrate before laser melting. This has the effect of reducing the steep temperature gradients generated during laser processing and therefore removing thermal stresses.

This paper investigates a versatile process of surface modification of titanium alloys and is an extension of previous work [8], which would significantly improve their wear resistant properties and that would contribute to expansion of their use in tribological systems. A nonconsumable tungsten electrode was used to provide surface melting in a shielding atmosphere of pure nitrogen or argon and nitrogen mixture. The changes in the surface wear characteristics were assessed using metallografic, micro-hardness and dry sliding wear techniques.

2. EXPERIMENTAL PROCEDURE

The commercial alloy Ti-6Al-4V was cut into rectangular plates (50x20x10 mm), and the surface prepared to give a flat, polished finish followed by a degreasing treatment in acetone before surface melting. A *3 mm* diameter tungsten electrode was used to create a metal arc between the tip of the electrode and the titanium alloy surface. This was achieved by holding the electrode stationary, and at an angle of about *45°* to the titanium alloy surface. A metal arc was produced by adjusting the distance between the tip of the electrode and alloy surface, and by careful control of parameters such as current and voltage supply to the electrode. Shielding gases were channeled through the electrode gun, and flow regulators used to control the flow rate to give either a mixture of argon (*80%* by volume) and nitrogen (*20%* by volume) or a pure nitrogen gas shield.

In order to determine the effect of ageing heat treatment on the surface hardness, specimens treated by melting in pure nitrogen and in nitrogen/argon mixture were aged at *450 °C* using different ageing times from *1-20* hours.

Microstructure was undertaken using both light microscopy and X-ray diffraction. Micro-hardness depth profile measurements were performed using a Leitz microhardness tester with an indentation load of *0.5 N*. Changes in the wear behaviour of the modified surfaces were assessed using a block on ring test which was carried out in air under dry sliding conditions. The test block was loaded with *9.81 N* against a hardened tool steel ring which rotated at a surface speed of *4 m/s*. Sliding was interrupted at suitable intervals and the scar size was measured. The wear volume, and hence wear rate, was calculated from the scar size and the ring dimensions (*106 mm* in diameter and *7.62 thick*), as described in the ASTM standard G77-83 [3]. The friction force, and hence coefficient of friction, was also measured in the test. Scanning electron microscopy was used to examine the wear groove and identify any changes in wear mechanisms.

3. RESULTS AND DISCUSSION

3.1. Metallographic examination

Surfaces treated either under an argon/nitrogen mixture or in a pure nitrogen gas shield showed three distinct regions: the resolidified region, the heat affected zone and the unaffected base alloy (Fig.1.).

The resolidified region, consisted of a well developed dendritic structure (Fig.2.) which was shown by X-ray diffraction analysis to be rich in titanium nitride (TiN), see spectrum in Fig.3a.

Titanium has a strong affinity for nitrogen, and the formation of titanium nitrides is due to direct chemical reactions between titanium in the molten state and the nitrogen from the gas shield. The X-ray diffraction analysis taken from surfaces treated by the argon/nitrogen mixture shows weaker peak intensities for TiN (Fig.3b) and this could be attributed to the lower concentration of nitrogen (only 20% by volume) in the argon/nitrogen mixture corresponding to a lower level of nitrides formation in the resolidified region.

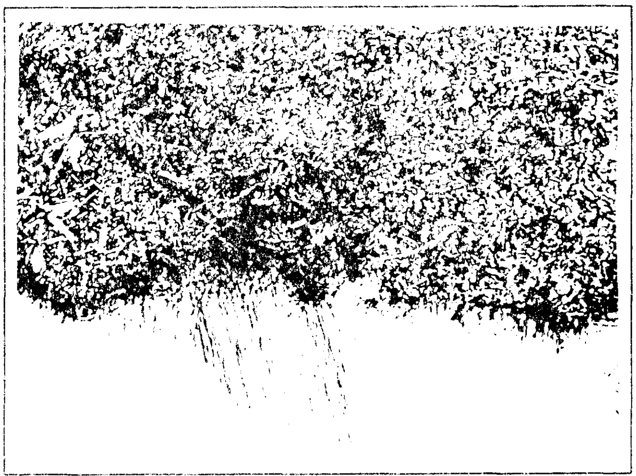


Figure 1. Micrographs showing Ti-6Al-4V alloy surface treated under an argon/nitrogen mixture

The heat affected zone consists primarily of α' martensite (Fig.4.), which resembles α' martensite produced by conventional quenching. The $\alpha+\beta$ microstructure of the unaffected base alloy is shown in Fig.5.

The shielding gases were also successful in preventing the formation of oxides in the surface melted zone, the presence of which could have been detrimental to surface wear properties. In addition, the treated surfaces were free from cracks and pores associated with gaseous entrapment.

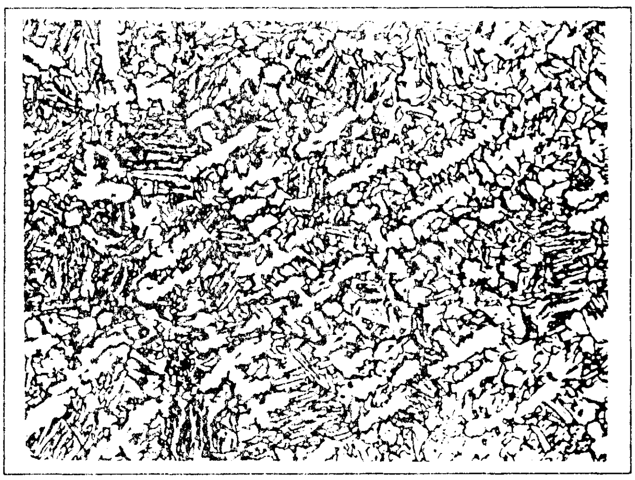


Figure 2. Surface morphology of resolidified region produced under a pure nitrogen gas shield

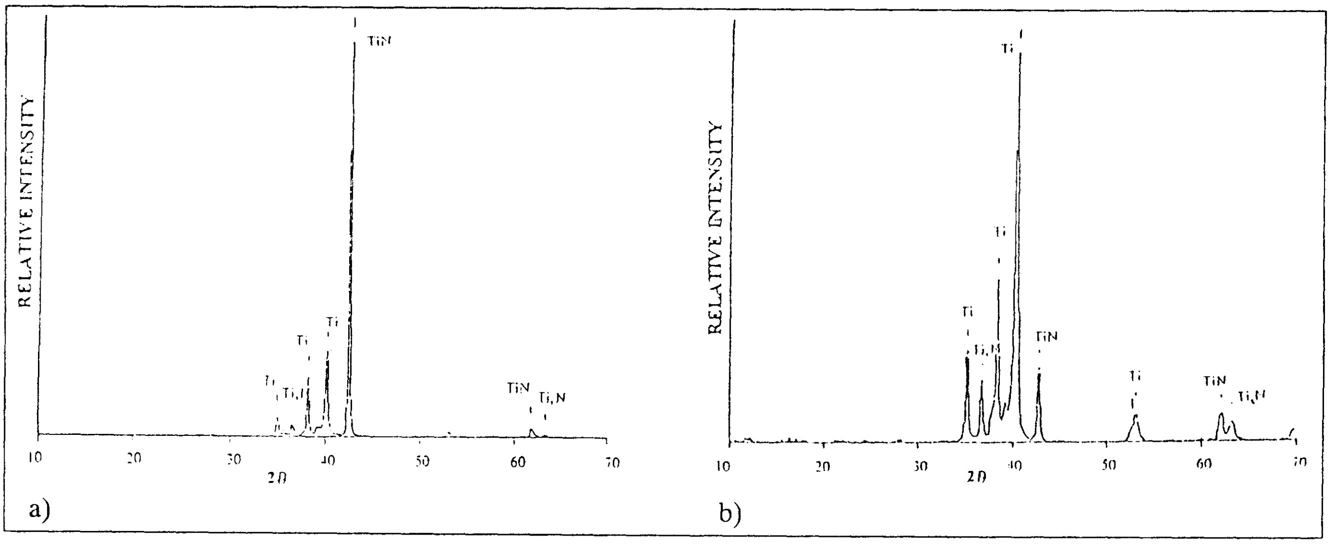


Figure 3. X-ray diffraction spectra taken from surfaces melted under: (a) a pure nitrogen gas shield; and (b) an argon/nitrogen mixture

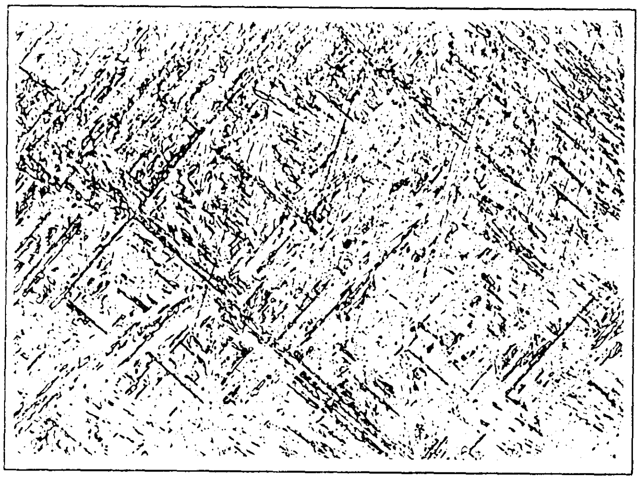


Figure 4. Microstructure of heat affected zone of the surface treated under a pure nitrogen gas shield

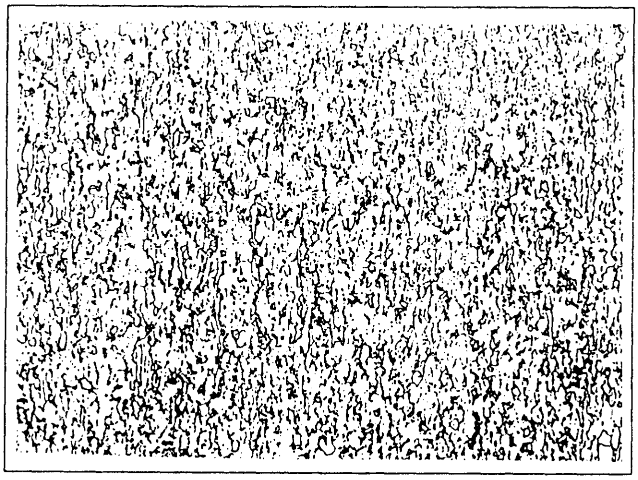


Figure 5. Microstructure of Ti-6Al-4V alloy unaffected by surface treatment

3.2. Micro-hardness measurements

The surface micro-hardness of the titanium alloy was found to increase when pure nitrogen or argon/nitrogen mixture of gases was used, see profiles in Fig.6. An increase in hardness from *360* $HV_{0.5}$ for the untreated alloy, to a value of *1070* $HV_{0.5}$ was possible when using pure nitrogen as the shielding gas. A uniform hardness was achieved to a depth of *0.9 mm* after which a gradual drop in hardness was recorded for the heat affected zone. In general, the hardness values were lower for surfaces treated using the argon/nitrogen mixture (typically *610* $HV_{0.5}$), which can be associated to a lower concentration of nitride phases produced at the surface. The interstitial solid-solution strengthening of the α-phase of titanium alloy will also be expected to contribute to any increase in hardness in the heat affected zone of the treated surfaces [4]. When these results are compared with laser treated titanium surfaces as shown by the superimposed hardness profile in Fig.6, it is clear that the hardness values for the laser melted surface decrease rapidly with increasing distance from the surface. In comparison, the tungsten arc produces not only a much wider melted zone (which is determined by the diameter of the electrode used), but a more uniform surface hardness is maintained to a greater depth.

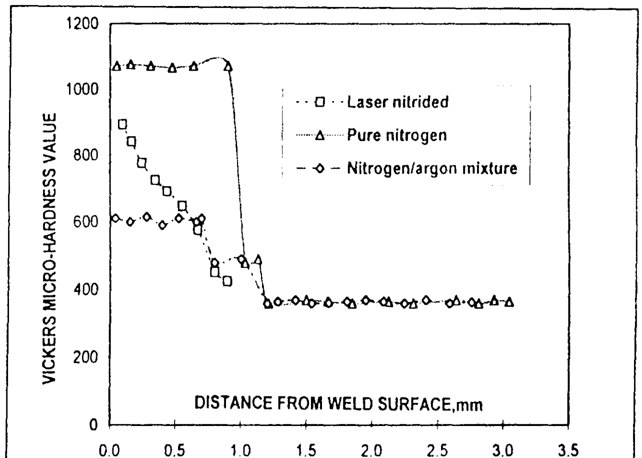


Figure 6. A comparison of micro-hardness depth profiles for surfaces treated Ti-6Al-4V alloy

3.3. Ageing treatments

Micro-hardness depth profiles of a titanium alloy which is treated under an argon/nitrogen mixture, aged at *450 °C*, and for different ageing times is shown in Fig.7. Ageing after *3h* increased surface hardness by 20%. This might be due to the precipitation of Ti_2N, because excess nitrogen is present. However, with increasing distance from the surface, hardness begins to drop rapidly, which is attributed to the increased diffusivity of nitrogen, from the surface to the interior, that leads to a reduction of the solid-solution hardening effect of nitrogen (interstitial solid-solution strengthening of the a phase of titanium alloy) [3].

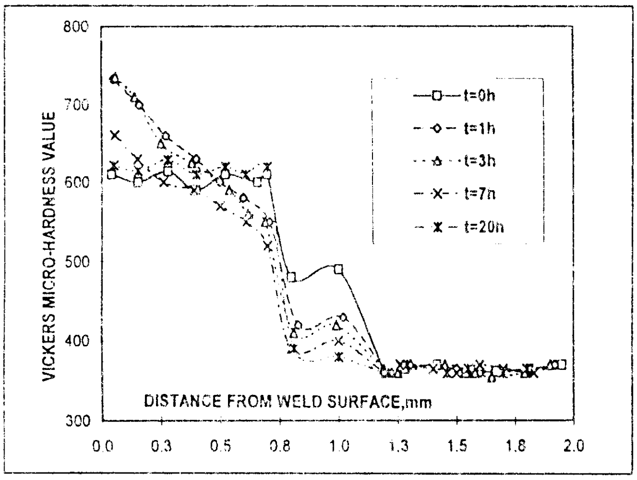


Figure 7. Micro-hardness depth profiles of Ti-6Al-4V alloy treated under an nitrogen/argon mixture, aged at 450 °C

Hardness in the heat affected zone decreased by *15%*, reaching a constant value of about *420* $HV_{0.5}$. The decrease in hardness in the heat affected zone is an indication of hard α' martensite decomposition to relatively soft $\alpha+\beta$ mixture, as shown in Fig.8. Further ageing decreased the hardness slowly, and at the end of *20h* ageing, the hardness in the heat affected zone was about *370* $HV_{0.5}$. This is consistent with the fact that upon decomposition of α' martensite, a stable $\alpha+\beta$ microstructure is produced.

The lowering of hardness due to the reduction of solid-solution hardening effect of nitrogen becomes much more effective after 7h ageing. This is unlikely, since the diffusivity of nitrogen, in the α-phase of titanium alloy at *450 °C* is calculated to be very low ($3\cdot10^{-15}$ cm^2s^{-1}) [3]. Therefore, the decrease of hardness after *7h* ageing by *10%*, in comparison with the as-treated surface, must be attributed to changes in both precipitation and solid solution strengthening.

After *20h* ageing, the surface hardness decreased by *15%* in comparison with the as-treated surface. However, the hardness distribution in the resolidified region became almost uniform. The observation of uniform hardness distribution can be attributed to the leveling out of nitrogen concentration by diffusion, and to the precipitation of Ti-N (TiN, Ti_2N) compounds in the previously low hardness region. A Ti-N compounds precipitation is seen to start at the surface in relatively short ageing times (i.e.*1-3h*) because of the high nitrogen concentration there. However, this precipitation in the rest of the melted zone starts after the *20h* ageing treatment, as indicated by the increased hardness in these areas.

The effect of ageing treatments on the hardness of the surfaces treated with pure nitrogen is shown in Fig.9. As the ageing time at *450 °C* is increased the change in hardness becomes noticeable after ageing for more than *7* hours. Although a gradual decrease in hardness is observed at the surface, the depth of hardness also increases. The ageing treatment appears to not only reduce the number of dendrites at the surface, see Fig.10, but would be expected to reduce the solid-solution hardening effect of nitrogen due to the increase in diffusion kinetics of nitrogen (in the solid-state) away from the

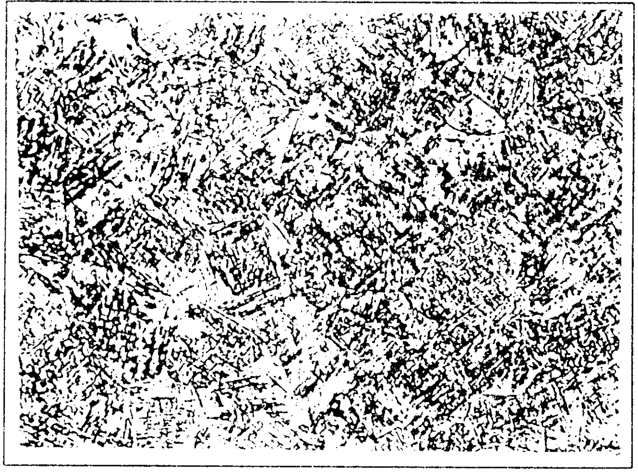


Figure 8. Microstructure of heat affected zone of the surface treated under an argon/nitrogen mixture, and aged for 3h

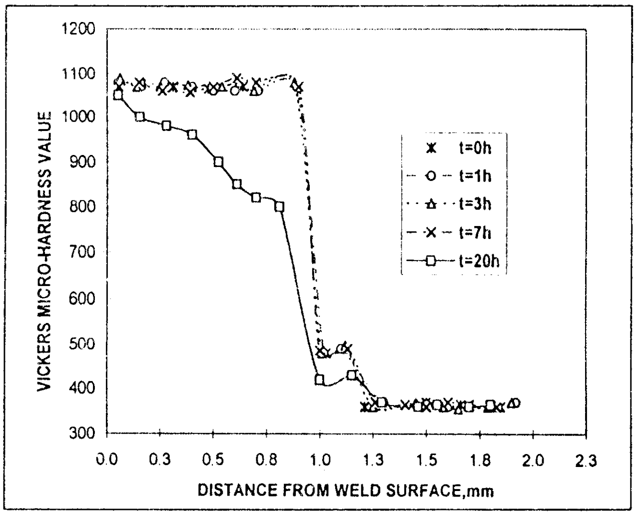


Figure 9. Micro-hardness depth profiles of Ti-6Al-4V alloy treated under an nitrogen/argon mixture, aged at 450 °C

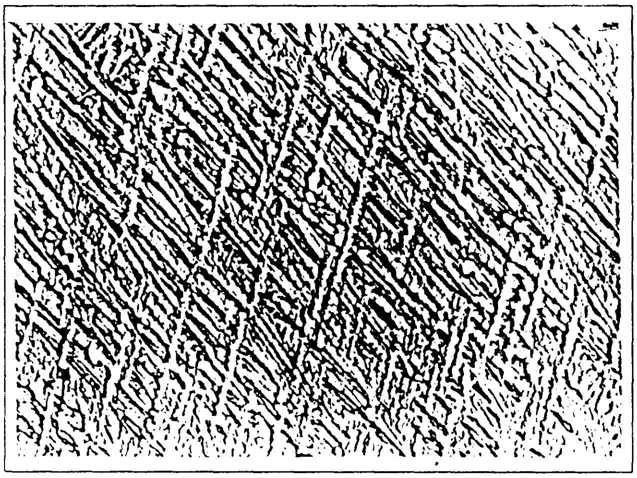


Figure 10. Microstructure of Ti-6Al-4V alloy surface treated under a pure nitrogen gas shield, and aged for 20h

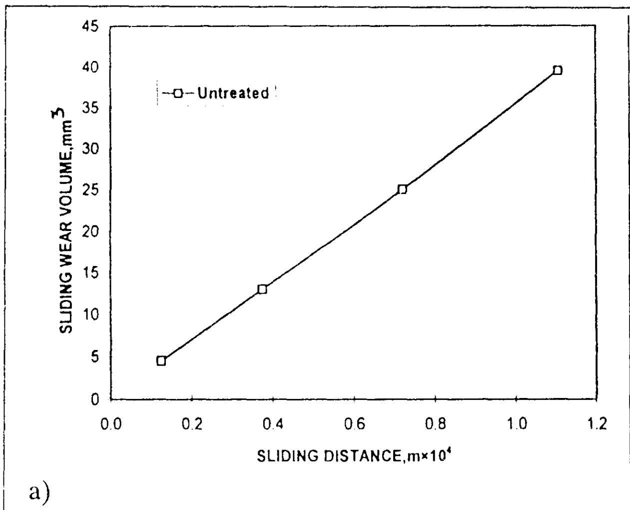
surface. The decrease in hardness in the heat affected zone to a value of *370* $HV_{0.5}$ can be associated with the decomposition of the α' martensite to form the softer but stable $\alpha+\beta$ phases.

3.3. Wear measurements

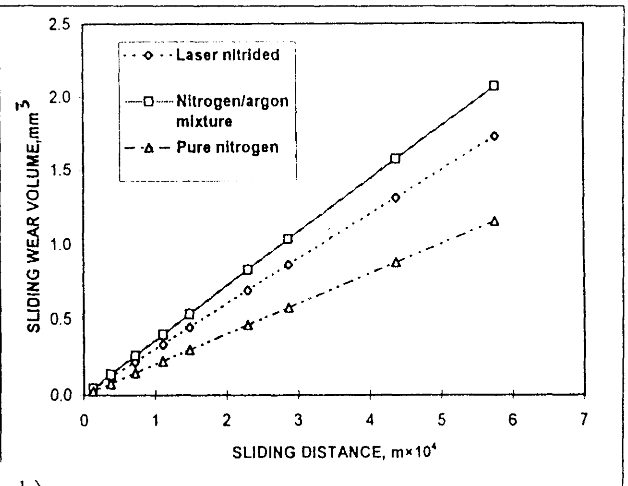
The resistance to surface wear was assessed by monitoring variations in the wear volume and frictional force, with increasing sliding distance, and making a direct comparison with the untreated (reference) titanium alloy. Early work by Lebedeva and Presnyakova showed that the wear behaviour of titanium alloys in air could be classified as severe over a wide range of sliding speeds [9]. The results in this study also confirm that the untreated surface suffers high wear, which increases in severity with increasing sliding distance (Fig.11a.). However, surfaces treated by melting in pure nitrogen or argon/nitrogen mixture show better wear resistance than the untreated titanium alloy surface (Fig.11b.). For comparison the variation in the wear volume with increasing sliding distance for a laser nitrided surface has been superimposed in Fig.11b.[3]. It can be seen that the changes in wear volume of surfaces which are treated by the use of a tungsten arc under a pure nitrogen or argon/nitrogen gas shield are lower than those for laser nitrided surfaces. Furthermore, these results are consistent with the microhardness values, showing that the greater concentration of nitrides formed in the surface improves the surface wear properties of the titanium alloy.

Fig.12. shows a reduction in the frictional force for the treated surfaces, which correlates with micro-hardness changes mentioned above. In comparison with coefficient of friction of laser nitrided surfaces of 0.43 [3], the use of a tungsten metal arc under the pure nitrogen gas shield resulted in lower coefficient of friction of 0.37. The coefficient of friction of surfaces treated using a nitrogen/argon mixture is 0.51, and the coefficient of friction of the untreated titanium alloy surface is 0.62.

The scanning electron micrograph of dry sliding wear surfaces of the untreated titanium alloy (Fig.13.), shows adhesive wear dominated by plastic deformation involving the ploughing of material and surface delamination. The removal of material by ploughing occurred because the hardness of the tool steel ring of 547 HV0.5 is adequate to abrade the softer titanium alloy surface (360 HV0.5). However, when the titanium alloy surfaces were treated by the use of a tungsten metal arc, their hardness value increased to *610-1070* $HV_{0.5}$. As a result, the ring surface was no longer able to abrade the treated surfaces so that the mechanism of wear changes from abrasion to adhesion. This may be clearly seen on micrograph in Fig.14., showing a distinct change in surface wear mechanisms. In both cases, in which the surface was shielded by pure nitrogen or argon/nitrogen mixture, severe adhesive wear was absent, and smooth regions were visible within the wear scar. These regions appear to have worn far less than other surface areas. The dry sliding wear tests were carried out in air, and the formation of surface oxides was



a)



b)

Figure 11. A dry sliding wear graph showing variation in the wear volume with sliding distance: (a) for the untreated Ti-6Al-4V alloy; and (b) for surface treated Ti-6Al-4V alloy

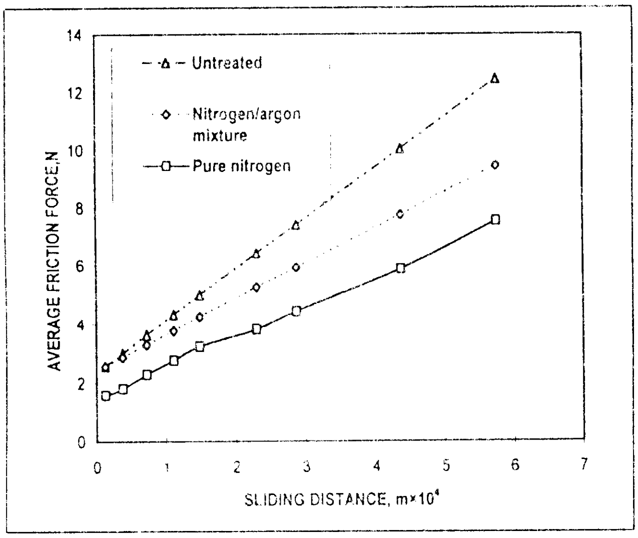


Figure 12. A dry sliding wear graph showing variation in the frictional force with sliding distance for Ti-6Al-4V alloy before and after surface treatments

discounted by EDS analysis of sliding wear surfaces, showing prominent peaks for TiN and the absence of peaks for titanium oxides (Fig.15.).

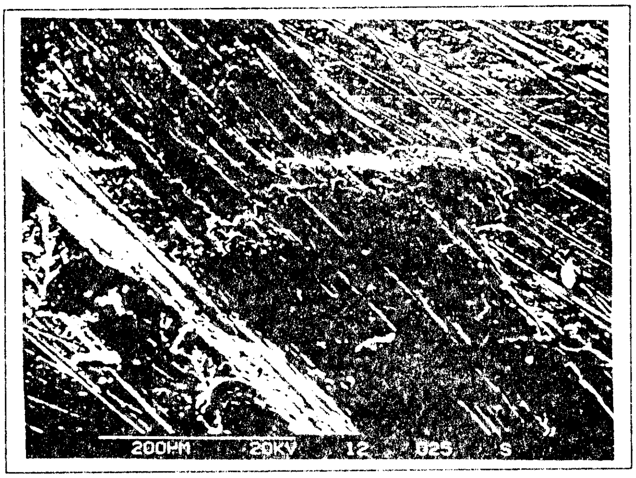


Figure 13. S canning electron micrograph of dry sliding wear surfaces of the untreated Ti-6Al-4V alloy

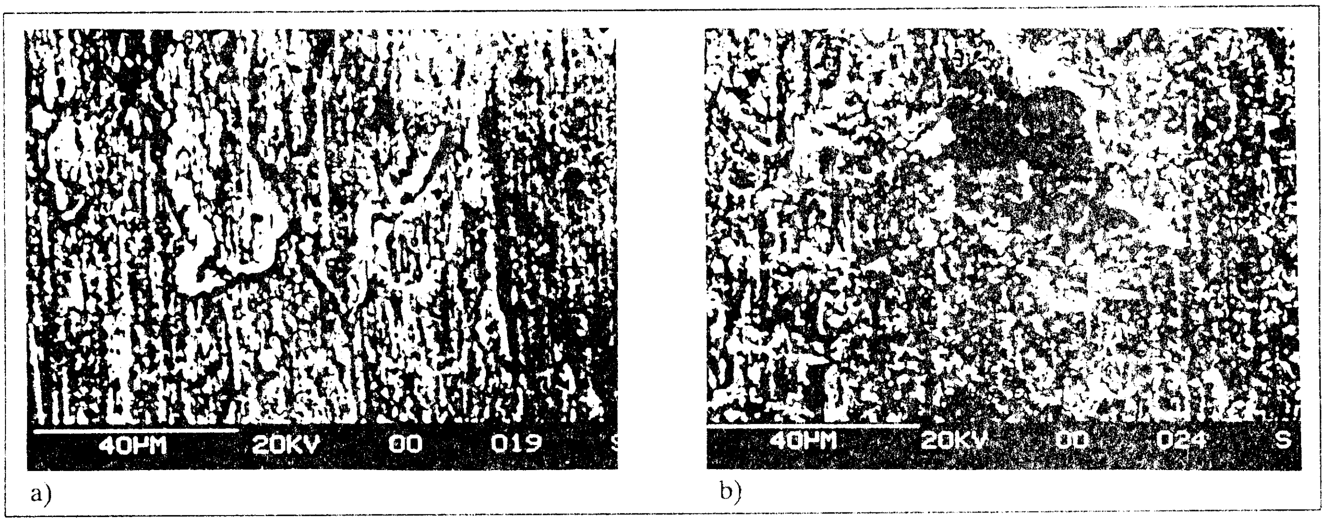


Figure 14. Scanning electron micrographs of dry sliding wear surfaces treated under: (a) a shield of pure nitrogen; and (b) a mixture of argon and nitrogen

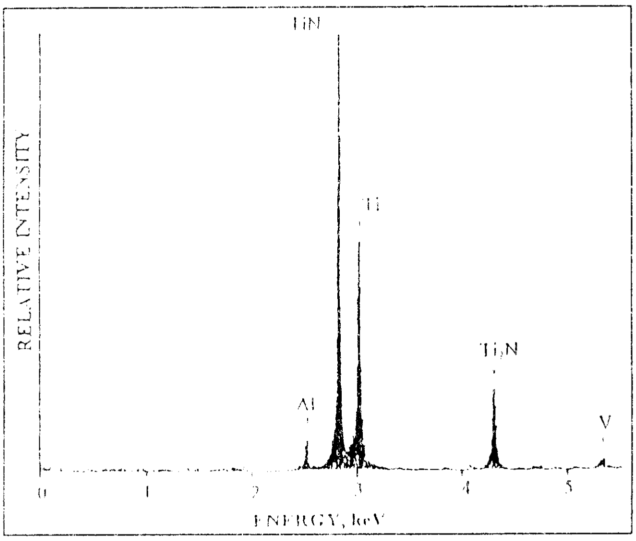


Figure 15. EDS spectrum of dry sliding wear Ti-6Al-4V alloy surface treated under a pure nitrogen gas shield

4. CONCLUSION

In this study, it is shown that by using a tungsten metal arc heat source, surface nitriding of Ti-6Al-4V alloy can be performed in a controlled atmosphere of pure nitrogen or in a mixture of argon and nitrogen to produce a wear resistant surfaces. The metallographic and X-ray analysis together with ageing treatments attribute this to the resolidified surface consisting of a dendritic microstructure rich in titanium nitrides. As a result, the surface hardness increases to values greater than $1000\ HV_{0.5}$ for surfaces treated in a pure nitrogen gas shield, compared to $360\ HV_{0.5}$ for the untreated titanium alloy. The microhardness measurements were found to correlate well with the wear data, and scanning electron microscopy showed that changes in the frictional force, wear rate, and coefficient of friction were lower for surfaces treated by the use of a tungsten metal arc in a shielding atmosphere of pure nitrogen when compared with laser nitrided surfaces. It was found that the presence of titanium nitrides altered the mechanism of surface wear from abrasion to adhesion.

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