РЕПУБЛИКА СРБИЈА
МИНИСТАРСТВО ОДБРАНЕ

ВОЈНОТЕХНИЧКИ ИНСТИТУТ
1948

OTEH 2024

11TH INTERNATIONAL SCIENTIFIC CONFERENCE ON DEFENSIVE TECHNOLOGIES

PROCEEDINGS

TOPICS

AERODYNAMICS AND FLIGHT DYNAMICS
AIRCRAFT
WEAPON SYSTEMS AND COMBAT VEHICLES
AMMUNITION AND ENERGETIC MATERIALS
INTEGRATED SENSOR SYSTEMS AND ROBOTIC SYSTEMS
TELECOMMUNICATION AND INFORMATION SYSTEMS
MATERIALS AND TECHNOLOGIES
QUALITY, STANDARDIZATION, METROLOGY, MAINTENANCE AND EXPLOITATION

OTEH 2024

11TH INTERNATIONAL SCIENTIFIC CONFERENCE ON DEFENSIVE TECHNOLOGIES

Serbia, Tara, 9-11 October 2024

Pavle Savic
(1909-1994)

Publisher
The Military Technical Institute
Ratka Resanovića 1, 11030 Belgrade

Publisher's Representative
Col Asst. Prof. Ivan Pokrajac, PhD Eng

Editors
Col Aleksandar Kari, PhD Eng
Prof. Ljubica Radović, PhD Eng

Technical Editing
Aida Jeremić
Jelena Petrović

Printed by
The Military Technical Institute
Ratka Resanovića 1, 11030 Belgrade

CIP - Каталогизација у публикацији
Народна библиотека Србије, Београд

NAUČNO-stručni skup iz oblasti odbramenbih tehnologija (11 ; 2024 ; Beograd)
Proceedings [Elektronski izvor] / 11th International Scientific Conference on Defensive Technologies, OTEH 2024, Belgrade, 9-11 October 2024 ; [organized by] Military Technical Institute, Belgrade ; [editors Aleksandar Kari, Ljubica Radović]. - Belgrade : Military Technical Institute, 2024 (Beograd : Military Technical Institute) 1 USB memorija.

Sistemski zahtevi: Nisu navedeni. - Nasl. sa naslovne strane dokumenta. -
Bibliografija uz svaki rad.

ISBN 978-86-81123-94-2

1. Vojnotehnički institut (Beograd)
a) Војна техника - Зборници
b) Технички материјали – Зборници
c) Телекомуникациони системи - Зборници

ORGANIZATIONAL COMMITTEE

Nenad Miloradović, PhD Eng, Assistant Minister of Defense for Materiel Resources, ***President of the Organizational Committee***
Bg Asst. Prof. **Slavko Rakić**, PhD Eng, Head of the Department for Defense Technologies
Col Asst. Prof. **Ivan Pokrajac**, PhD Eng, Acting Director of the Military Technical Institute
Marina Soković, PhD Eng, Assistant Minister for Science - Ministry of Science, Technological Development and Innovations
Vladimir Popović, PhD Eng, Dean of the Faculty of Mechanical Engineering, Belgrade
Bg **Milan Popović**, Head of the Department for Planning and Development GS SAF
Col **Dejan Stojković**, PhD, Head of the Department for Strategic Planning
Bg Prof. **Boban Đorović**, PhD Eng, Rector of the University of Defense
Col Prof. **Srđan Blagojević**, PhD, Head of the Military Academy
Col **Nebojša Svjetlica**, Head of the Department for International Military Cooperation
Col **Saša Veselinović**, PhD Eng, Director of the Technical Test Center
Col Prof. **Slobodan Ilić**, PhD Eng, Director of Directorate for Standardization, Codification and Metrology
Col **Ivica Marjanović**, PhD Eng, Director of Military Quality Control
Col **Dejan Đorđević**, PhD Eng, Director of Military Geographical Institute
Prof. **Jovanka Šaranović**, PhD Eng, Institute for Strategic Research
Vladimir Radovanović, Assistant Minister for Innovation, Transfer of Technology and Technological Development – Ministry of Science, Technological Development and Innovations
Prof. **Dejan Gvozdić**, PhD Eng, Dean of the Faculty of Electrical Engineering, Belgrade
Prof. **Petar Uskoković**, PhD Eng, Dean of the Faculty of Technology and Metallurgy, Belgrade
Boris Dumnić, PhD Eng, Acting Dean of the Faculty of Technical Sciences, Novi Sad
Prof**. Danijela Milošević**, PhD Eng, Dean of the Faculty of Technical Sciences, Čačak, University of Kragujevac
Prof**. Vladimir N. Cvetković**, PhD Eng, Dean of the Faculty of Security Studies, Belgrade,
Prof. **Goran Bošković**, PhD Eng, University of Criminal Investigation and Police Studies, Belgrade
Predrag Ćulibrk, Director, IRITEL, Belgrade
Vladimir Cizelj, PhD Eng, Vlatacom Institute, Belgrade
Nikola Tomašević, PhD Eng, Director, Mihajlo Pupin Institute
Jugoslav Petković, Director, Yugoimport SDPR, Belgrade
Jovanka Andrić, Director, Krušik, Valjevo
Zoran Stefanović, Director, Sloboda, Čačak
Predrag Ilić, Acting Director Milan Blagojević - Namenska A.D. Lučani
Dobrosav Andrić, Director, Prvi Partizan, Užice
Stanoje Biočanin, Director, Prva Iskra - namenska, Barič
Saša Milošević, Director, Zastava - oružje, Kragujevac
Anđelka Atanasković, Director, Prva Petoletka – namenska, Trstenik
Stefan Đurić, Director, Zastava Tervo, Kragujevac
Časlav Kljajić, Director, PPT-TMO A.D., Trstenik

SECRETARIAT

Elida Vasiljević, Military Technical Institute, ***Secretary***
Mirjana Krstović, Military Technical Institute, ***Deputy Secretary***
Jelena Pavlović, Military Technical Institute
Lt Col **Nebojša Grebović**, Military Technical Institute
Asst. Prof. **Tihomir Kovačević,** PhD Eng, Military Technical Institute
Srdjan Živković, PhD Eng, Military Technical Institute
Col **Branko Medan,** Department for Defensive Technologies
Lt Col **Slobodan Malbašić,** Department for Defensive Technologies
Lt Col **Igor Đorić,** Military Technical Institute

Ljiljana Obradović, Military Technical Institute
Suzana Vuković, Military Technical Institute
Dobrivoje Granžan, Military Technical Institute
Irina Ulanova, Military Technical Institute
Aida Jeremić, Military Technical Institute
Jelena Petrović, Military Technical Institute

SCIENTIFIC COMMITTEE

Col **Aleksandar Kari**, PhD Eng, Military Technical Institute, Belgrade, Serbia,
President of the Scientific Committee
Prof. **Ljubica Radović**, PhD Eng, Military Technical Institute, Belgrade, Serbia
Col **Bojan Pavković,** PhD Eng, Military Technical Institute, Belgrade, Serbia
Prof. Emeritus **Taek Lyul Song**, PhD Eng, Hanyang University, South Korea
Evgeny V. Sudov, PhD Eng, R&D Applied Logistic Centre, Moscow, Russia
Prof. **Stevan Berber**, PhD Eng, Auckland University, New Zealand
Srećko Stopić, PhD Eng, RWTH University Aachen, Germany
Zbyšek Korecki, PhD Eng, University of Defense, Brno, Czech Republic
Radi Ganev, PhD Eng, “Lyuben Karavelov” University of Structural Engineering and Architecture, Sofia, Bulgaria
Prof. **Tomaž Vuherer**, PhD Eng, Faculty of Mechanical Engineering, Maribor, Slovenia
Prof. **Biljana Marković**, PhD Eng, Faculty of Mechanical Engineering, East Sarajevo, Republic of Srpska (Bosnia and Herzegovina)
Prof. **Milan Tica**, PhD Eng, Faculty of Mechanical Engineering, Banja Luka University, Republic of Srpska (Bosnia and Herzegovina)
Prof. **Dženana Gačo**, PhD Eng, University in Bihać, Bosnia and Herzegovina
Prof. **Strain Posavljak**, PhD Eng, Faculty of Mechanical Engineering, Banja Luka, Republic of Srpska (Bosnia and Herzegovina)
Prof. **Mersida Manjgo**, PhD Eng, Faculty of Mechanical Engineering Mostar, Bosnia and Herzegovina
Prof. **Kemal Delijić**, PhD Eng, Faculty of Technology and Metallurgy, Podgorica, Montenegro
Col **Predrag Rakonjac**, PhD Eng, University of Defense, Belgrade
Col Prof. **Dragan Trifković**, PhD Eng, Military Academy, Belgrade, Serbia
Col Prof. **Damir Jerković**, PhD Eng, Military Academy, Belgrade, Serbia
Col Prof. **Branimir Krstić**, PhD Eng, Military Academy, Belgrade, Serbia
Col Prof. **Boban Pavlović**, PhD Eng, Military Academy, Belgrade, Serbia
Col Prof. **Boban Bondžulić**, PhD Eng, Military Academy, Belgrade, Serbia
Col Prof. **Milenko Andrić**, PhD Eng, Military Academy, Belgrade, Serbia
Col Prof. **Slobodan Simić**, PhD Eng, Military Academy, Belgrade, Serbia
Col Prof. **Zoran Bajić**, PhD Eng, Military Academy, Belgrade, Serbia
Col Prof. **Radovan Karkalić**, PhD Eng, Military Academy, Belgrade, Serbia
Col **Saša Bakrač**, Military Geographical Institute, Belgrade, Serbia
Jasmina Stevanović, IHTM Belgrade, Belgrade, Serbia
Srećko Manasijević, PhD Eng, LOLA Institute, Belgrade, Serbia
Dragana Perić, PhD Eng, Vlatacom Institute, Belgrade, Serbia
Prof. **Srećko Nijemčević**, PhD Eng, Vlatacom Institute, Belgrade, Serbia
Miroslav Sokić, PhD Eng, Institute for Technology of Nuclear and Other Mineral Raw Materials, Belgrade, Serbia
Prof. **Stevica Graovac**, PhD Eng, Mihajlo Pupin Institute, Belgrade, Serbia
Nikola Zogović, PhD Eng, Mihajlo Pupin Institute, Belgrade, Serbia
Violeta Nikolić, PhD Eng, Vinča – Institute of Nuclear Sciences, Belgrade, Serbia
Prof. **Vladimir Mladenović**, Faculty of Engineering, Čačak, University of Kragujevac, Serbia
Asst. Prof. **Dušan Arsić**, Faculty of Engineering, University of Kragujevac, Serbia
Prof. **Vladimir Arsovski**, PhD Eng, Faculty of Electrical Engineering, Belgrade, Serbia
Prof. **Dragan Milčić**, PhD Eng, Faculty of Mechanical Engineering, University of Niš, Serbia
Prof. **Dragan Šešlija**, Faculty of Technical Sciences, Novi Sad, Serbia

Prof. **Predrag Elek**, PhD Eng, Faculty of Mechanical Engineering, Belgrade, Serbia
Prof. **Aleksandar Simonović**, PhD Eng, Faculty of Mechanical Engineering, Belgrade, Serbia
Prof. **Jelena Svorcan**, PhD Eng, Faculty of Mechanical Engineering, Belgrade, Serbia
Vencislav Grabulov, PhD Eng, IMS Institute, Belgrade, Serbia
Prof. **Ivan Kostić**, PhD Eng, Faculty of Mechanical Engineering, Belgrade, Serbia
Prof. **Slađana Vujičić**, PhD, Faculty of Business Economy and Entrepreneurship, Belgrade, Serbia
Prof. **Aleksandar Marinković**, PhD Eng, Faculty of Technology and Metallurgy, Belgrade, Serbia
Prof. **Melina Kalagasidis Krušić**, PhD Eng, Faculty of Technology and Metallurgy, Belgrade, Serbia
Asst. Prof. **Marija Samardžić**, PhD Eng, Military Technical Institute, Belgrade, Serbia
Dijana Damljanović, PhD Eng, Military Technical Institute, Belgrade, Serbia
Asst. Prof. **Jelena Gržetić,** PhD Eng, Military Technical Institute, Belgrade, Serbia
Prof. **Maja Vitorović-Todorović**, PhD Eng, Military Technical Institute, Belgrade, Serbia
Željko Bulatović, PhD Eng, Military Technical Institute, Belgrade, Serbia
Miloš Pavić, PhD Eng, Military Technical Institute, Belgrade, Serbia
Lt Col Asst. Prof. **Saša Brzić**, PhD Eng, Military Technical Institute, Belgrade, Serbia
Asst. Prof. **Danica Bajić**, PhD Eng, Military Technical Institute, Belgrade, Serbia
Col **Rade Pavlović**, PhD Eng, Military Technical Institute, Belgrade, Serbia
Col Asst. Prof. **Mihajlo Ranisavljević** PhD, Military Technical Institute, Belgrade, Serbia

11TH INTERNATIONAL SCIENTIFIC CONFERENCE
ON DEFENSIVE TECHNOLOGIES
OTEH 2024
Serbia, Tara, 9-11 October 2024

THE INFLUENCE OF DESIGN CONDITIONS ON THE FAILURE OF THE UNIVERSAL CROSS JOINT (UCJ) OF THE CARDAN COUPLING

SAŠA SPASENIĆ
Kontrol Inspekt D.O.O., Belgrade, spasenic_sale@yahoo.com

MILETA RISTIVOJEVIĆ
Kontrol Inspekt D.O.O., Belgrade, miletaristivojevic@gmail.com

VLADIMIR MILOVANOVIĆ
Faculty of Engineering University of Kragujevac, Kragujevac, vladicka@kg.ac.rs

ALEKSANDAR DIMIĆ
University of Belgrade Faculty of Mechanical Engineering, Belgrade, adimic@mas.bg.ac.rs

STEFAN DIKIĆ
University of Belgrade Faculty of Technology and Metallurgy, Belgrade, sdikic@tmf.bg.ac.rs

SRETEN SPASENIĆ
Kontrol Cert D.O.O., Belgrade, sreten.spasenic@yahoo.com

Abstract: *In the system of power transmission from the driving to the operating machine, cardan couplings are components of vital importance. Due to the ability to transmit power over long distances, as well as insensitivity to the coaxiality of the connecting shafts, they have found wide application in all branches of mechanical engineering. In the plant for the production of profiled semi-finished steel products, a volumetric failure of the sleeve on the universal cross joint (UCJ) of the cardan coupling occured. This type of failure occurs very rarely with cardan couplings. In order to understand the real reason for the failure of the sleeve, analytical and numerical models were formed, and tests of materials and fracture surfaces were carried out. The influence of the line load distribution at the mating surfaces and the geometric stress concentration on the load capacity of the UCJ was analyzed using the developed models. With the increase in the unevenness of the line load distribution, the influence of tangential stresses on the stress state in the critical cross-section significantly increases. It is concluded that the simultaneous influence of the uneven line load distribution and the geometric stress concentration led to the failure of the UCJ sleeve.*

Keywords: *Universal cross joint, cardan coupling, sleeve failure, strees concentration, load distribution*.

1. INTRODUCTION

In mechanical systems, the power from the driving machine to the working machine is delivered through a gearbox, which transforms that power - adapts it to the needs of the working machine in terms of the number of revolutions and torque. Couplings play a very important role in this power transmission process. They connect driving and working machines and gearboxes into one functional unit. Their failure interrupts the chain of transmission of power from the driving machine to the working machine, which also means the interruption of the functioning of the machine system. That is why it is very important that the couplings perform their function reliably and safely.

According to the working conditions regarding the required co-axiality of the connected shafts and the mutual distance of the driving and working machine from the gearbox, a large number of different types of couplings have been developed. Couplings that are not sensitive to the coaxiality of the connected shafts and can connect shafts at greater distances are cardan couplings. They are widely used in agricultural machinery, rail, cargo and combat vehicles, as well as in heavy industry [1-3]. In the vehicle industry, the universal joint is one of the most critical parts of both the engine and the transmission system of a vehicle [4].

In a rolling mill for the production of rod profiles, the power from the driving machine (electric motor) to the working machine is transmitted and transformed by means of a multi-stage gearbox. The gearbox has one input and two output shafts. The output shafts of the power transmission are connected to the roller shafts by a telescopic shaft by means of cardan couplings.

Corresponding author: S.Spasenić;
E-mail: spasenic_sale@yahoo.com
DOI: 10.5937/OTEH24084S

On one sleve of the universal cross joint (UCJ) of the cardan coupling, which connects the telescopic shaft and the roller shaft, there was a volumetric destruction - breakage of the driven sleeve. The load from the sleeve to the coupling fork is transferred by means of two needle bearings, placed on the sleeve. By inspecting the contact surfaces of the sleeve, a markedly uneven load distribution was observed in the needle bearings, that is, the bearing located on the upper half of the sleeve had a negligibly small part in transmitting the working load. The conducted analysis showed that this was one of the main reasons for the breakage of the shaft sleeve. It is an important aspect of these bearings that while in action they never go through complete cycles. In other words, each of these bearings revolves only a few degrees around its axis before returning to its original position. Therefore, there are only a group of rolling bodies in these bearings that take the bearing load [5].

Bearings are very important machine elements because they have a significant influence on the correct functioning of the components of the machine assemblies. At the same time, they can be very sensitive if the installation and maintenance conditions deviate from the prescribed ones. There are a large number of accidents, serious and less serious, caused by the failure of rolling bearings. One failure is described in the paper [6]. In the gearbox, at one support of the intermediate shaft, the outer ring of the conical roller bearing, is installed in the housing with a loose fit. As a result, the outer ring rotated and thus generated thermal energy, which eventually led to the volumetric destruction of the gear teeth and parts of the bearing. By the analysis of information and data obtained in many researches related to this area referred the fact that exploitation reliability of Cardan shaft in working machines are directly determined primary by reliability of needle bearing and cross shafts [2].

In this paper, the generated damage to the UCJ is reviewed in detail. An ultrasonic and magnetic method was applied in order to see possible defects in the material. In addition, an analytical and numerical analysis of the stress state was performed. On the basis of the conducted analyses, it was concluded that the uneven engagement of the needle bearings in load transmission and the design conditions of the UCJ generated large local stresses that led to the formation of the initial crack. It spread over time and led to the volumetric destruction, i.e. brekage of the sleeve of the UCJ.

2. DAMAGE ANALYSIS OF THE UCJ SLEEVE OF THE CARDAN COUPLING

Surface and volumetric damage were generated on the sleeve of the UCJ of the cardan coupling which connects the shaft of the working machine and the telescopic shaft. Destruction in the form of local plastic deformations appeared on the contact surface of the sleeve in question, Figure 2.1a. It is common that after long-term usage, unilateral wear occurs at a joint’s shaft journal; this eventually leads to grooves forming on the contact surface of the universal joint, which in turn causes looseness and noise [7]. In addition to the surface destructions, volumetric destruction in the form of breakage were also generated on the sleeve, Figure 2.1b. The surface damage is located in the load zone of the needle bearing, i.e. in the zone where the load is transferred between the sleeve and the bearing.

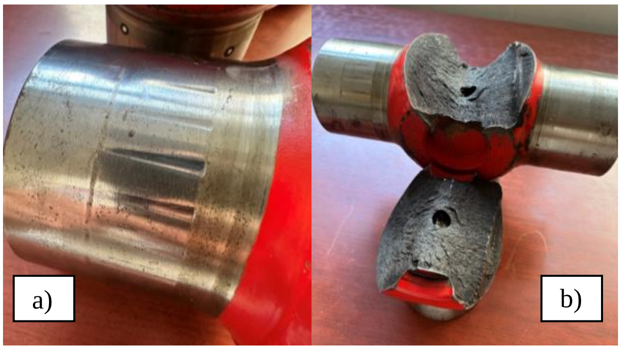

Figure 2.1. a) Surface damage of the sleeve in the form of local plastic deformations, b) volumetric damage of the sleeve in the form of breakage

Formed damage is manifested by the appearance of grooves due to plastic deformation of the surface layers of the contacting surfaces of the sleeve and rolling elements -- needles. The direction of the grooves coincides with the direction of the longitudinal axis of the sleeve. Grooves are not present along the entire length of the sleeve's contact surface. They extend from the beginning of the contact surface, which is located near the root of the sleeve, to approximately the middle of the length of the sleeve, Figure 2.1a.

On the basis of the generated surface damage on the sleeve, Figure 2.1a, it can be concluded that the depth of the formed grooves changes along the sleeve. It is the largest at the beginning of the contact surface, which is located near the root of the sleeve. Then it gradually decreases, and in the middle of the length of the sleeve it is negligibly small. On the basis of these damages, it can be concluded that the load distribution along the length of the contact of the contacting parts, the sleeve and the rolling bodies (needles), was uneven. Due to such distribution of the line load, the contact surface on the upper part of the sleeve's length participated minimally in the transmission of the working load.

Figure 2.2. Fracture of the sleeve of the UCJ

In the case of the considered UCJ of the cardan coupling, which connects the telescopic intermediate shaft and the shaft of the working machine (rollers of the rolling mill), there was a volumetric destruction of the sleeve, Figure 2.2a and 2.2b. The fracture occurred on the sleeve of the UCJ, which is connected to the fork of the intermediate shaft. On the surface of the fracture, two zones are clearly visible, the zone of dynamic and the zone of static destruction, Figure 2.1b. The size of the fatigue failure zone is approximately 30% of the static failure zone. On the basis of this fact, it can be concluded that the process of dynamic destruction gradually expanded and progressed. The fracture surface does not lie in one plane, but in two planes that form an angle of 90°. This means that, in addition to normal stresses, tangential stresses also had a strong influence on the destruction process.

3. LOAD DISTRIBUTION AND STRESS STATE OF THE UCJ SLEEVE

3.1. The influence of the geometric characteristics of the UCJ on the load distribution

The nominal load in the form of tangential force caused by torque is not evenly distributed along the line of contact of the meshed parts of the universal joint. The highest intensity of the nominal load is in the points belonging to the root of the sleeve, diagram in Figure 3.1. The lowest intensity of the nominal load is in the points belonging to the top of the sleeve. The difference between these limit values of the nominal loads depends on the geometric dimensions of the sleeve. In order to analyze the influence of the geometric dimensions of the sleeve on the uniformity of the distribution of the nominal load along the sleeve, a corresponding analytical expression was formed.

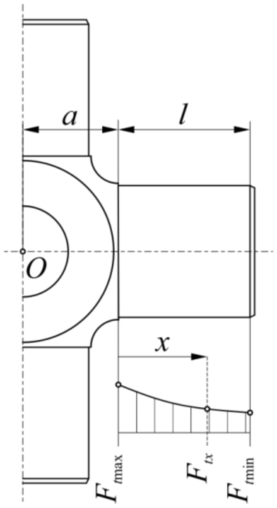

Figure 3.1. Distribution of the nominal load along the sleeve of the UCJ

The ratio of the nominal load in the form of a tangential force at an arbitrary point (*x*) on the slant height of the sleeve, to its maximum value, was observed:

$$\psi = \frac{F_{tx}}{F_{tx\max}} = \frac{1}{1+k\cdot\dfrac{l}{a}}, \qquad (1)$$

wherein:

k =*x* / *l*,

l – sleeve length,

a – the distance of the root of the sleeve from the axis of rotation of the cross.

The correlation between the nominal load and the geometric characteristics of the sleeve is shown by the diagram in Figure 3.2. Higher values of the geometric parameter *k* and ratio *l*/*a* correspond to higher unevenness of the nominal load distribution. Small values of the ratio *l*/*a* correspond to a smaller gradient of change in the nominal load from the root to the top of the sleeve of the UCJ. This means that the degree of uneven distribution of the nominal load on the sleeve will be smaller if the sleeve is further away from the axis of rotation.

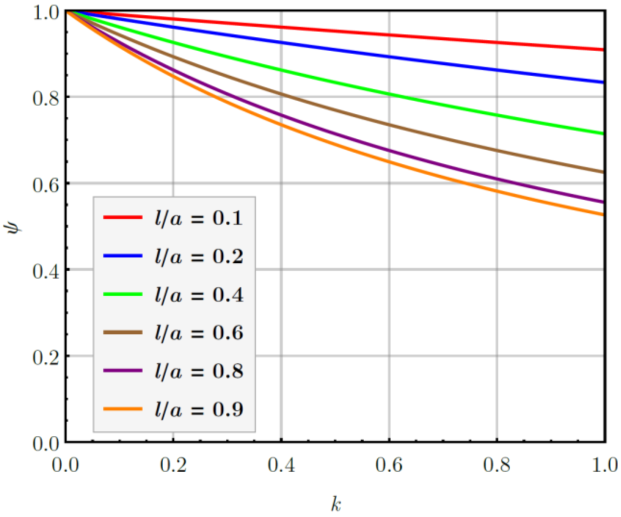

Figure 3.2. The influence of the geometry of the UCJ on the distribution of the nominal load along the sleeve

4. EXPERIMENTAL ANALYSIS

4.1. Ultrasonic testing

Ultrasonic testing (UT) was performed in order to examine subsurface and internal defects in material. The method is based on sending a high frequency sound through the metallic product and analyzing its reflections. Examination was performed in accordance with standard SRPS EN ISO 16810, using both longitudinal and transversal waves. The impulse-echo, ultrasonic method, was performed.

Testing with longitudinal waves was performed by dual crystal straight probes as well as with single crystal probes, while testing with transversal waves was performed only by single crystal probes.

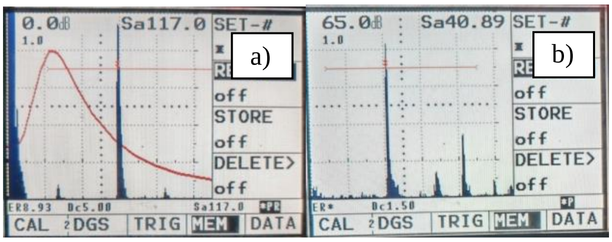

Figure 4.1. Diagrams of material testing using the ultrasonic method

Figures 4.1a and 4.1b show diagrams of material testing using the ultrasonic method. On the basis of these diagrams, it is clearly seen that there are no defects in the material of the sleeve of the universal joint cross.

4.2. Chemical composition

In order to determine the type of material of the cardan cross, tests of the chemical composition were carried out. The chemical composition of the material was determined by two different methods. The first method is Optical Emission Spectrometry, and the second method used is X-ray fluorescence (XRF). The test conditions are given in the Table 4.1.

Table 4.1. Test conditions for determining chemical composition

Standard-method:	Optical Emission Spectrometry (SRPS C.A1.011:2004)
Equipment used:	Belec Compact Port
Type of probe:	Argon probe (Belec)
Surface condition:	60 grit sandpaper
Test instruction:	Manufacturer's instructions
Calibration blocks:	Belec 101, 102, 108, 110
Temperature of the object:	20˚C
Testing according to:	KT KI - UP 002/14

Individual results of testing according to the mentioned method are given in Table 4.2.

Table 4.2. Chemical composition in mass % – OES method

C	Si	Mn	Cu	Al
0,297	0,234	0,86	0,012	0,031
Cr	**Mo**	**Ni**	**V**	**Ti**
1,026	0,004	0,009	0,015	0,053
Nb	**Co**	**W**	**Sn**	**Pb**
0,008	<0,01	<0,01	0,021	<0,003

Based on the obtained chemical composition, it was determined that the material of the UCJ corresponds to the material 34Cr4 (1.7033) according to Belec database. Grade 34Cr4 belongs to quenched and tempered steels.

5. ANALYSIS OF LOAD CAPACITY OF THE SLEEVE

In the considered sleeve of the UCJ, there is a pronounced uneven distribution of the line load on the contact surface of the joint and the rolling elements - needles, Figure 2.1. It has a great influence on the stress state in the critical cross-section of the sleeve. In order to analyze the influence of the distribution of the line load on the load carrying capacity of the critical cross-section of the sleeve, appropriate analytical models were formed.

The influence of line load distribution on the stress state and safety factor in the critical cross-section of the sleeve was analyzed. In the case of uniform-theoretical distribution of the line load, each point on the contact line of the contacting surfaces equally participates in the transmission of the working load, Figure 5.1a. The actual distribution of the line load in real working conditions is uneven. With this distribution, each point on the contact line participates differently in the load transfer, figure 5.1b. One characteristic case occurs when only one point does not participate in load transfer, Figure 5.1c. Another characteristic case occurs when one part of the contact line does not participate in load transfer, Figure 5.1d.

In the considered UCJ, two needle bearings are placed between the sleeves of the cross and the fork. After dismantling the coupling, an uneven distribution of the line load was registered by visual control. Figure 2.1.a, that is, one needle bearing, placed closer to the root of the sleeve, was significantly more involved in transferring the load. The engagement of the second bearing, placed closer to the top of the sleeve, is less than the first bearing.

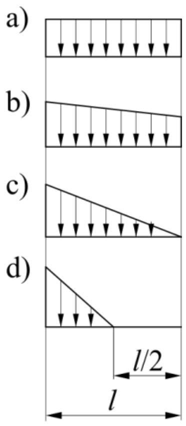

Figure 5.1. Line load distribution along the line of contact between the sleeve and the needle bearing

The mechanical model of the UCJ sleeve represents a cantilever that is loaded with a transverse force. Due to the action of this force, normal stresses due to bending and tangential stress due to shearing are generated in the critical cross-section of the cantilever-sleeve. By observing the ratio of tangential and normal stress, an analytical model was formed for the analysis of the influence of the line load distribution on the stress state at the root of the sleeve:

$$\varphi = \frac{\tau}{\sigma} = \frac{5}{18} \cdot \frac{1}{\frac{1}{6} + \left(1 - \frac{x}{l}\right)}. \tag{1}$$

For the analysis of the influence of the distribution of the line load on the load capacity of the sleeve root, the ratio of the safety factor against volume destruction due to tangential stresses - shearing and due to normal stresses - bending was observed:

$$\lambda = \frac{S_\tau}{S_\sigma} = \frac{3}{10} + \frac{9}{5}\left(1 - \frac{x}{l}\right) \tag{2}$$

Based on the analytical expressions (1) and (2), the corresponding dependencies shown in Figure 5.2 were formed.

Based on the dependencies shown in Figure 5.2, the following conclusions can be drawn:

- In case of uniform distribution of line load, Figure 5.1a, when *x*/*l*= 0.5 the normal stress is 2.5 times higher than the tangential stress. At the same time, the safety factor against failure due to the effect of tangential stresses is 20% higher than the safety factor due to the effect of normal stresses.
- In the case of uneven load distribution, when all points on the contact line do not participate equally in the load transfer, Figure 5.1b, and when *x*/*l*= 0.6, the normal stress is 2.0 times higher than the tangential stress. At the same time, the safety factors against failure due to the action of tangential and normal stresses are mutually equal.
- In the case of uneven load distribution, when one part of the contact line does not participate in the load transfer, Figure 5.1d, and when *x*/*l*= 0.8, the normal stress is 25% higher than the tangential stress. At the same time, the safety factor against failure due to the effects of normal stress is 40% higher than the safety factor due to the effects of tangential stress.

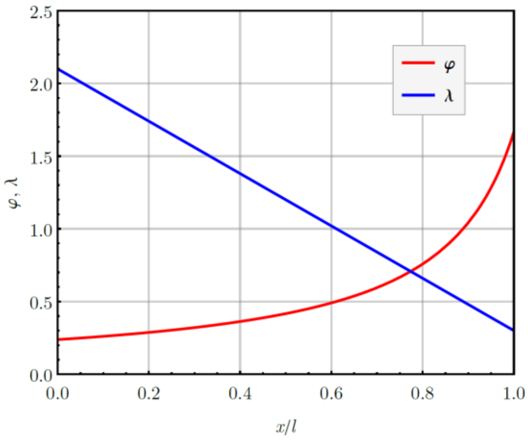

Figure 5.2. The influence of line load distribution on the stress state and load capacity of the UCJ sleeve root

A numerical model was created for the analysis of the stress state at the root of the sleeve, at the source of the stress concentration of the UCJ. The stress concentration is caused by the geometrical characteristic of the section, i.e. the transition from a large to a small sleeve diameter. In addition to this stress concentration, there is an untreated surface step on the UCJ sleeve root which is a consequence of the manufacturing technology. It is marked with a white arrows in Figure 2.2a. In the [1], stress concentration at the point of support due to inadequate finishing, caused the occurrence of an initial crack. In the [8], it was shown that by optimizing the geometrical shape of the cardan joint cross, operating stress can be reduced by up to 40%. The optimization mainly related to the cross-section with stress concentration in the form of a transition radius at the root of the sleeve. In [9] the results of numerical simulation of stress-strain state at critical zones of Cardan joint elements implicate that small modification of design solution can resulted in significant reduction of maximal stress levels. However, one should be careful with this type of optimization, because the increase of fillet, to some limit, induced reduction of stress concentration level. The further increase of fillet over the limit induced increase of maximal stresses [4].

In the case of uniform load distribution, Figure 5.1a, the stress state is shown in Figure 5.3.

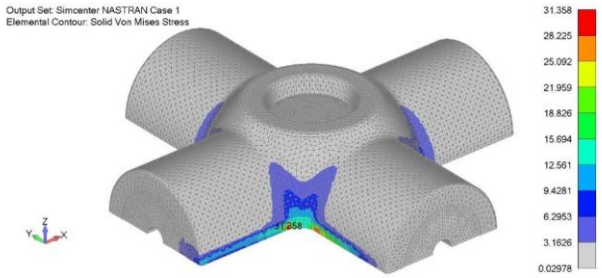

Figure 5.3. Stress state of UCJ in MPa

Figure 5.4 shows the stress state at the root of the sleeve for the case of uneven load distribution, Figure 5.1c and Figure 5.1b.

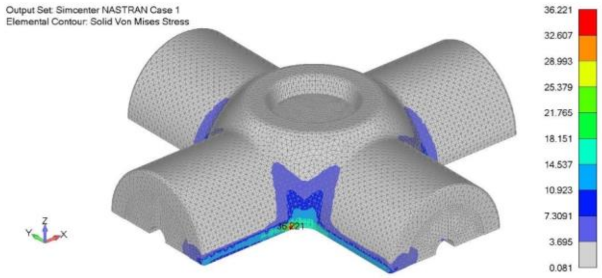

Figure 5.4. Stress state of UCJ in MPa

The stress state at the root of the sleeve in the case of extremely uneven load distribution, when one part of the contact line does not participate in load transmission, Figure 5.1d, is shown in Figure 5.5.

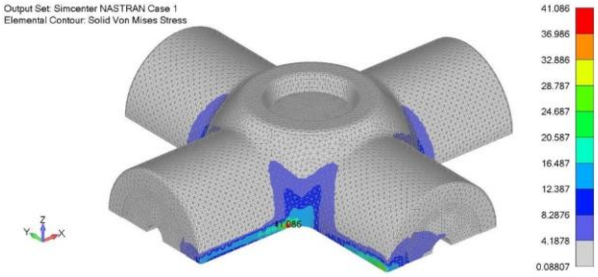

Figure 5.5. Stress state of UCJ in MPa

The stress at the root of the sleeve, at the source of the stress concentration in case of extremely uneven load distribution (Fig. 5.5) is 32% higher than the stress generated in the case of uniform load distribution (Fig. 5.3). Compared to uneven load distribution (Fig. 5.4), the stress is 14% higher with extremely uneven load distribution.

Based on the conducted analysis, it follows that with an increase in the unevenness of the load distribution, the influence of the tangential stress on the volume load capacity of the sleeve increases. It is known that the dynamic strength due to bending is significantly higher than the dynamic strength due to tangential shear stresses. This means that the sleeve of the UCJ in the critical cross-section has a significantly lower ability to resist volumetric destruction due to the effect of tangential stresses compared to normal stresses due to bending. Accordingly, the fracture surface of the UCJ does not lie in a plane that is perpendicular to the longitudinal axis of the sleeve, but in planes that form an angle of 45° with this axis, Figure 2.2b. Large tangential stresses in combination with geometric stress concentration participated in the formation of the initial crack and its propagation until the final destruction - dynamic fracture of the sleeve.

6. CONCLUSIONS

Conducted theoretical and experimental research showed that volumetric destruction - dynamic fracture of the joint of the UCJ of the cardan coupling did not occur due to the existence of defects in the material of the joint, the quality (chemical composition) of the material of the joint and/or the occurrence of an overload - heavy workload. Large stresses at the root of the sleeve in the cross section of the stress concentration are generated due to the extremely uneven distribution of the load along the line of contact of the sleeve and the bearing needles. The geometric stress concentration is present at the root of the sleeve and at the rounding radius of the holes formed on the front surfaces of the UCJ. Tangential stresses in combination with geometric stress concentration led to the fracture of the UCJ. Based on the large zone of fatigue destruction, which is approximately 30% of the static destruction zone, it can be stated that the process of dynamic destruction gradually expanded and progressed under the influence of the workload.

Aknowledgment

The presented paper is a result of the research supported by MPNTR RS according to the Contract No. 451-03-65/2024-03/200105 and Contract No. 451-03-65/2024-03/200135. The authors wish to acknowledge and thank the company Kontrol Inspekt D.O.O. in Belgrade for support and for encouragement in the research realization.

References

[1] SAVKOVIĆ M., GAŠIĆ M., PETROVIĆ D., ZDRAVKOVIĆ N., PLJAKIĆ R.: *Analysis of the drive shaft fracture of the bucket wheel excavator*, Engineering Failure Analysis 20 (2012) 105–117.

[2] IVANOVIĆ L., JOSIFOVIĆ D., RAKIĆ B., STOJANOVIĆ B., ILIĆ A.: *The influence of variation in position of output shaft to load on the cardan joint cross shaft*, International Congress Motor Vehicles & Motors 2012, MVM2012-045.

[3] STRUZ J., HRUZIK L., HAVLIK J.: *Cardan Shaft Load and Its Variation with Length*, ICMD 2020, AHE 17, pp. 343–355, 2023.

[4] IVANOVIĆ L., JOSIFOVIĆ D., RAKIĆ B., STOJANOVIĆ B., ILIĆ A.: *Shape variations influence on load capacity of cardan joint cross shaft*, The 7th International Symposium KOD 2012, 24-26 May, Balatonfured, Hungary.

[5] VESALI F., REZVANI M. A., KASHFI M.: *Dynamics of universal joints, its failures and some propositions for practically improving its performance and life expectancy*, Journal of Mechanical Science and Technology 26 (8) (2012) 2439~2449

[6] RISTIVOJEVIĆ M., LUČANIN V., DIMIĆ A., MIŠKOVIĆ Ž., BURZIĆ Z., STAMENIĆ Z., RACKOV M.: *Investigation of the heavy duty truck gear drive failure*, Engineering Failure Analysis 144 (2023) 106995.

[7] AN K., WANG W.: *Transmission performance and fault analysis of a vehicle universal joint*, Advances in Mechanical Engineering 2017, Vol. 9(5) 1–10.

[8] IVANOVIĆ L., JOSIFOVIĆ D., ŽIVKOVIĆ K., STOJANOVIĆ B.: *Cross Shaft Design From the Aspect of Capacity*, Scientific Technical Review, 2011,Vol.61, No.1.

[9] IVANOVIĆ L., JOSIFOVIĆ D., ILIĆ A., STOJANOVIĆ B., ŽIVKOVIĆ K.: *Optimization of cardan joint design from load capacity aspect*, International Congress Motor Vehicles & Motors 2014, MVM2014-011.