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LABORATOORSE LOBRIEROSIOONKATSESEADME TÖÖKINDLUSE TÕSTMINE

MAGISTRITÖÖ

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TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Mechanical and Industrial Engineering

IMPROVEMENT OF RELIABILITY OF THE LABORATORY SLURRY EROSION TESTER

MASTER THESIS

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Contents

PREFACE

Bachelor's Degree thesis topic "Improvement of reliability of the laboratory slurry erosion tester" was proposed at the Tallinn University of Technology. The topic was chosen by student because it was providing new opportunity to study design and work of machines which was completely new for her. Research task and information collection was taking place at the university's laboratory.

At Tallinn University of Technology Research Laboratory of Tribology and Materials Testing, it is possible to simulate slurry erosion by using slurry erosion device. The analysis of possible improvement of slurry erosion tester and tests with advanced apparatus were done during work process. While doing analysis process it was needed to find new solutions or components for machines better, more reliable work. The main problematic components were metal channels which were worn out quite fast at high speed and/or with use of hard angular abrasive particles.

Investigation was started with review of the existing slurry erosion tester evolution, for analysis the possible reason of unstable work. All apparatuses reviews were summarized in one table for better understanding of all advantages and disadvantages.

Material tests were done after slurry erosion tester improvement. It was confirmed that machine is now suitable for testing different materials, such as: steels, plastic, ceramics, rubbers and composites. The images of materials were captured by Scanning Electron Microscope and their wear mechanisms were analysed.

Drawings of slurry erosion apparatus model were made in SolidWorks software.

Slurry erosion, hydro-abrasive conditions, slurry tests

1. INTRODUCTION

Significant number of machines (85..90%) fail due to wear of parts. Increased wear of parts in one case violates the geometrical precision of the contacting parts of the machine, in the other - it impairs the normal lubrication mode, in the third - leads to a loss of the kinematic accuracy of the mechanism. Wear and damage to the surface reduces the fatigue resistance of parts and can be a reason for their destruction even under minor stresses [1].

Slurry erosion is defined as the type of wear, or loss of mass, that is experienced by material exposed to a high-velocity stream of slurry, i.e. a mixture of solid particles in a liquid (usually water). The typical simulation method of slurry erosion is done in laboratory in the slurry erosion tester [2].

Slurry erosion testers are used for slurry erosion method research at the laboratory conditions. The slurry erosion machines are easy to manufacture because they usually have quite simple structure. For faster and economical results, all parts are replaceable. Apparatus is easy to operate and provide rapid results of different materials. The results of slurry erosion tester are usually very similar to real pipeline wear. However, it is very difficult to measure and control exact flow speed and angle of the impact of slurry at the tester (or in pipeline). Investigations are complicated because of blunting and crushing of the hitting abrasive particles during the test. Therefore, effect of properties of abrasive particles is high. Abrasive particle's shape and size have very significant influence [3].

Slurry erosion tests are economical and environmentally friendly alternative for better investigation of wear in the laboratory conditions (than in real conditions). Tests are carried out to understand the mechanism of wear and corrosion processes. Slurry erosion apparatus helps us to explore the effect of the different parameters on one material or to compare different materials under same slurry erosion conditions. There are two main slurry erosion tests methods: laboratory simulation tests and pipe wear tests. Laboratory tests methods are more popular because it is low in cost, relatively easy and fast to set up and operate, research results could be obtained quite quickly. There are many different designs of slurry erosion apparatuses with various flow speed, power, abrasive consistence and sample positions [4].

The aim of investigation was to improve slurry erosion tester work and to simulate real life conditions experienced during slurry erosion. Investigation was started with slurry erosion tester evolution review, for finding the possible reason of unstable work. Another aim was to understand the mechanisms of slurry erosion, work of machine and related wear processes. During investigation of apparatus, possible problems due to non-constant intensity of slurry volume ejection were considered. New design of slurry erosion tester was proposed and implemented to provide stable abrasive velocity. Channels material was changed from metal to ceramic to improve its dimensional stability and reliability of testing.

In the work, the behaviour of six steel grades was investigated in abrasive slurry erosion conditions. Improved slurry erosion tester was used since it allows the simulation of various slurry wear conditions with various abrasive particles and liquids. The performance of steel samples was evaluated with conditions similar to real applications. Furthermore, the wear surfaces of the samples were analysed with the help of SEM micrographs obtained with "Hitachi TM 1000 Microscope„ to reveal extent of damage and the types of damage of the materials. Hardness, as main indicator of wear resistance of materials was measured with the help of „INDENTEC" device. The density was measured according to Archimedes technique with the help of the Mettler Tolledo ME204 scale to calculate the volumetric wear of materials required for comparison of their resistance against wear. The conclusions were provided according to obtained data.

Improved slurry erosion apparatus was already used for two client's orders. All intended enhancements were achieved and tests were performed with intended reliable (stable) conditions.

2. WEAR

Wear is mechanical damage to solid surface caused by forcible sliding contact with another solid, liquid or gas [2]. The scientists were investigating this problems and revealed a various wear modes and mechanisms. Due to the performed studies of wear our knowledge about wear has increased and has been made significant progress in this field. Our knowledge of wear has been changed significantly with the help of laboratory tests. As soon as wear studies became more advanced, classifications of wear also have changed, it became more deep and informative. Scientists opened new unknown areas in wear investigation, knowledge of several basic processes like abrasion, adhesion and fatigue is still not sufficient. Chemical industries have influenced significant growth of number of new materials, which are not well studied yet. It is still remaining quite problematic to reduce and/or predict the rate of wear of existing or new materials [5].

Applying surface coating on material allows us to get lower friction and wear. But using of new materials is not always safe for environment and utilization of these materials can be ineffective. For better wear prediction we should know and take into account properties such as: mechanics, physics, chemistry and material science, but something even all this information is not enough. Lubrication helps to reduce wear, but to predict accurately behaviour of all materials in all conditions is still impossible [3].

2.1 Classification of wear

Wear can be found all around the world in everyday things. It can be experienced by earth moving equipment or in our daily life such as knives, stairways or human's joints like a knee. By using tribosystem analysis, various wear mechanisms can be established. Classification of wear can be difficult because it has various approaches. One way of the classifying of wear process is the type of relative motion between two or more bodies in contact with each other. Another is mechanism characterizing the energetic and material interaction between the parts. Nowadays many techniques are applied to research wear-related phenomena. Different wear systems or testing techniques are available around the world and testing procedures are made available by different investigators in various conditions. Laboratory testing conditions should be similar to each other (and/or to real field conditions) as it is possible. The most valuable result can be achieved if testing conditions are as close as possible to real-life (real field) conditions [1].

2.2 Types of wear

There are different classifications of wear processes. The mechanical classification way is based on mechanisms that are operating:

- Abrasion – Wear due to hard abrasive particles, which are located between friction surface and also being in contact with abrasive surrounding. Requires hard, sharp surfaces imposed on softer surfaces. Abrasion categorized by types of contact:
  - Two-body. Abrasive particles are moving freely over a material surface.
  - Three-body. Abrasive particles act as interfacial elements between the solid and counter body.

Abrasion categorized by contact environment:

  - Low-stress abrasion (light rubbing contact of abrasive with metal parts)
  - High-stress abrasion (stress is so high that even abrasive particles are damaged/crushed)
  - Gouging abrasion (repetitive compressive loading of the surface)
  - Polishing wear (material surface is removed without visible scratches) [1].
- Adhesion – wear of material when two surfaces slide across each other under pressure [6]. Requires interaction between conforming surfaces.
- Fretting wear – localized wear of lubricated surface due to reciprocating sliding of extremely low amplitude because of vibration [11].
- Surface fatigue – mechanical wear caused by loading during friction, caused by high local stress between asperities. Requires repetitive compressive stresses.
- Tribochemical reaction – chemical interaction between two solid surfaces that react with the environment [1].
- Erosive wear – see below.

2.2.1 Erosive wear

Erosive wear is caused to solid bodies by the sliding impacting action of solids, liquids, gases [1]. Attack (impingement) angle, particle size, particle velocity is very important characteristics in surface wear. Types of erosion:

- Solid particle
- Droplet
- Liquid
- Cavitation
- Slurry erosion [3].

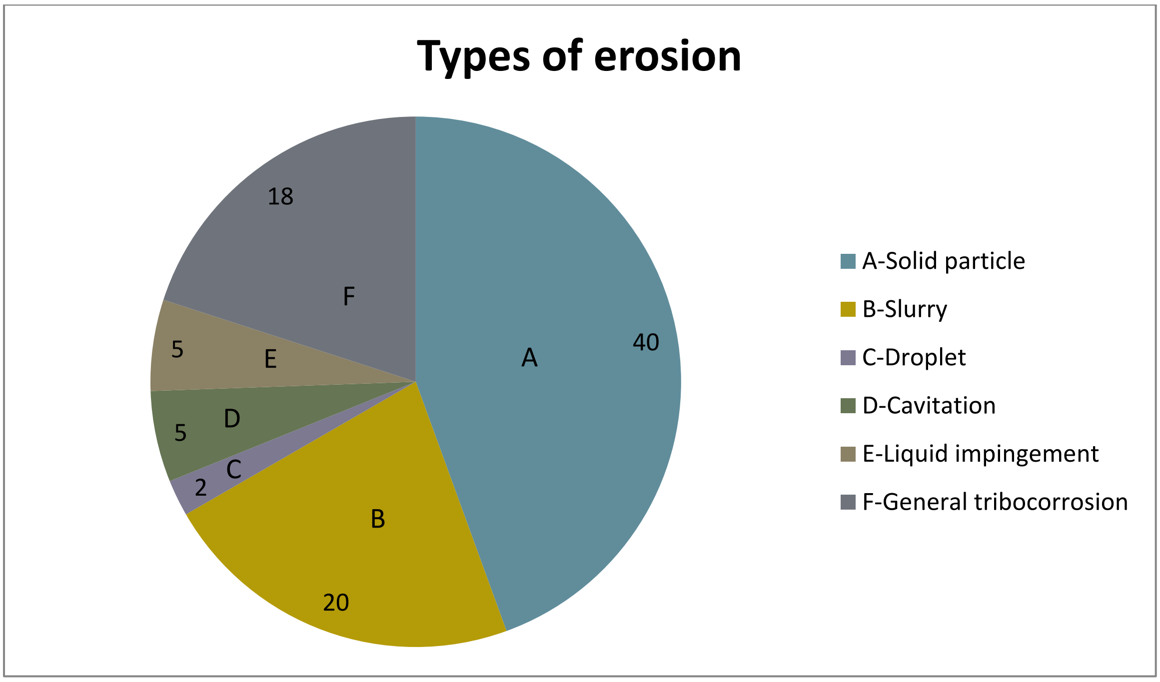


Figure 1. Types of erosion and their occurrence in % [3]

In the work, slurry erosion was studied. Slurry erosion wear is caused by abrasive particles. In this case it is not important, if particles are accelerating in liquid flow or opposite, detail (object of investigation) is moved inside the slurry. Abrasion can be accompanied by tribochemical reaction [3].

2.2.2 Slurry erosion

Slurry erosion is progressive loss of material from a solid surface by the action of a mixture of solid particles in a liquid (slurry) in motion with respect to the solid surface (of object). In this form of erosion, particle size or concentration can be different. Slurry erosion should be reviewed separately from abrasive wear, because slurries can be corrosive [3].

Intensity of slurry erosion depends on attack angle of particles:

$$J = a \cdot V^m \quad (2.1)$$

a - coefficient, depends on material and attack angle

m – depends on material (for example, steel m=2,5: cast iron m=2,8)

V – speed [17].

A slurry is a physical pumpable mixture of solid particles and a liquid. Abrasive particles must be in the liquid. Slurries that are pumped usually contain min 10 % of solids [10]. For example: mixture of "wet" concrete is pumpable and it can be considered as a slurry, even if it have 90 % of solids. On the other hand, we can't consider pure water without suspended minerals in it as a slurry [10].

This slurry erosion can occur in two ways:

- the material moves at a certain velocity through the slurry
- the slurry is bypassing the material at a certain velocity [1].

Concentration of solids (by weight or by volume) in slurry mixture is influencing the wear rate and the mechanism. In addition, the particles size should be significant for producing erosion. Polishing slurry particle for example have 10 % by weight of 1 µm aluminium oxide in water. If some other solids like glass or carbon particles have enough quantity to produce damage on surfaces, then they also could be considered as slurries [2].

For further forecast of pump replacement parts or other equipment, slurries should be tested for "apparent abrasiveness". Abrasiveness without inhibition is known as the Morrison-Miller effect. Material reaction for various slurries can be different. This reaction does not indicate how that new material would respond similarly to another slurry. Slurry Abrasion Response (SAR) test method based on the Miller number method procedure. The aspects of corrosion are different with dissimilar materials and sometimes obscured the effects of true abrasive erosion, or wear [1].

Miller numbers are illustrating the abrasiveness of slurries, they are based on the rate of metal loss during test. If effect of the slurry is aggressive then number will be high [10].

2.2.3 Slurry wear modes

An other slurry wear modes exist as well. The most common wear modes are shown in Figure 2:

- Abrasion-corrosion (the most severe wear mode),
- Scouring wear, abrasive metal-to-metal wear (crushing and grinding),
- High-velocity erosion,
- Low-velocity erosion,
- Saltation wear
- Cavitation [7].

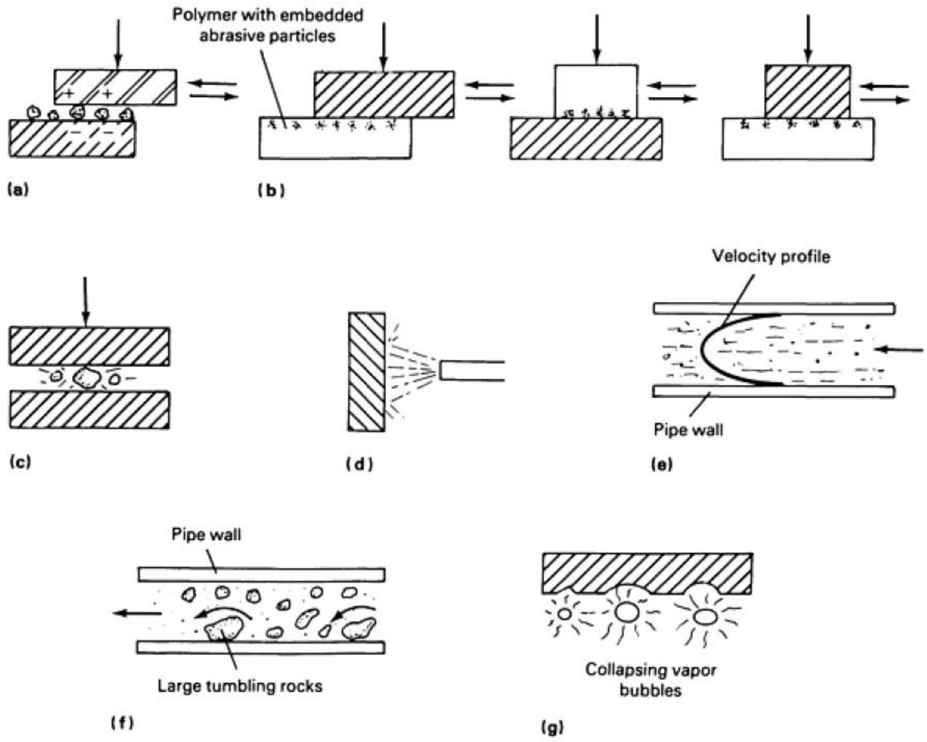


Figure 2. Slurry erosion wear modes: (a) abrasion-corrosion; (b) scouring wear, with wear areas equal (left) and unequal (centre and right); (c) crushing and grinding; (d) high-velocity erosion; (e) low-velocity erosion; (f) saltation erosion; (g) cavitation

Abrasion-corrosion wear – it is usually metal-to-metal scratching in the abrasive solids in a corrosive liquid. Typical parts of reciprocating pumps that are involved are: metal-to-metal valves and seats (upon each closure), metal piston parts that rub on metal liners and plungers, or piston rods that rub against metal stuffing box parts or trim. In different metal parts which are in contact with slurry, electrolytic effects are included in this mode [2].

Scouring wear occur with elastomer-to-metal rubbing. Solid particles of abrasive are scratching elastomeric, or rubber. For example it is present in pistons, packing, and valve inserts [2].

Crushing and grinding is encountered with abrasive metal-to-metal contact [2].

High-velocity erosion can be very destructive. It is usually occurring in reciprocating pumps handling slurry. Erosion have high velocity from 6 to 9 m/s. Sometimes effect of erosion can be catastrophic, when some parts wears to the extent that a slight leak develops and high speed of slurry makes rapid failure of parts. All other parts that are downstream also experience this type of rapid wear [2].

Low-velocity erosion occurs with the regular low velocities flow. Pipelines with laminar flow have velocity profile that near the wall of the pipe speed is nearly zero, what gives us minimal wear. This mode is sometimes used for the impellers and cut-water mechanism of centrifugal pumps [1].

Saltation wear results of movement of a sediment. The particles are bounces from a bottom surface while moving forward. One of examples can be seen in pipelines that transport phosphate rock from slurry pit to the processing plant. For distribution of wear, pipe should have many turnings [10].

Cavitation – it is the process of formation and subsequent collapse of bubbles in the fluid flow, accompanied by noise and hydraulic shocks, the formation of cavities in the liquid (cavitation bubbles, or voids) that may contain rarefied steam. Damage can be microscopic, but intense, liquid pressure blasts against the metal near the cavitation area, following the repeated collapse of the vapour bubbles [2].

2.2.4 Mechanisms of erosion by solid particles

Many parameters are affecting the slurry erosion process; particle characteristics, tested material properties, operating conditions and the different erosion mechanisms. Generally considered, that erosion occurs due to "cutting" and "deformation" mechanisms [9].

The cutting mechanism is associated with particles impacting the eroding surface at an oblique angle with sufficient energy to gouge a fragment loose. The deformation mechanism is associated with particles impacting perpendicular to the eroding surface with enough kinetic energy to cause plastic deformation or subsurface crack formation in the eroding material surface [9].

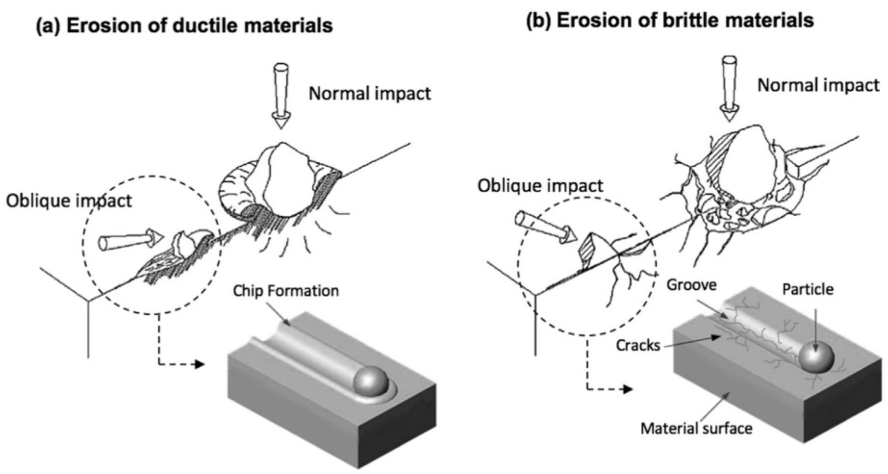


Figure 3. Schematic representation of erosion caused by deformation mechanism at normal impact and cutting mechanism at oblique impact in a) ductile and b) brittle materials [9]

Many slurry erosion processes are of industrial importance while their phenomena are understood just partly. A large number of factors affects the rate of material removal. However, the main mechanism of material remove is usually overlooked as micromachining by particles. The particles are facing at an acute angle the specimen surface with sufficient impulse to scoop out a groove. Leading face of particles can give different effect. If angle would be more positive than the critical angle, then they would remove material. If angles would be less favourable, then particles can't remove the material [8].

The impact angle is very important, but the contribution of each mechanism to the total erosion also depends on the ductility of the target surface. Erosion can be divided into ductile erosion and brittle erosion. In ductile erosion material is removed by cutting/ploughing. Ductile erosion under normal impact involves the formation of a crater with extruded lips and consequent ductile fracture [8].

In low impact angle and low particle velocity ploughing erosion mechanism is the dominant when the particles slide on the surface; they squeeze the metal ahead and to the sides to form ridges. There is difference between ploughing and cutting. In ploughing, the material is not removed from the surface and just moved to the side of the erosion groove. But during cutting process, a debris forms in front of the erosive particle and a volume of material equal to the volume of the erosion groove can be lost from the surface, as it is shown in Figure 4 below [9].

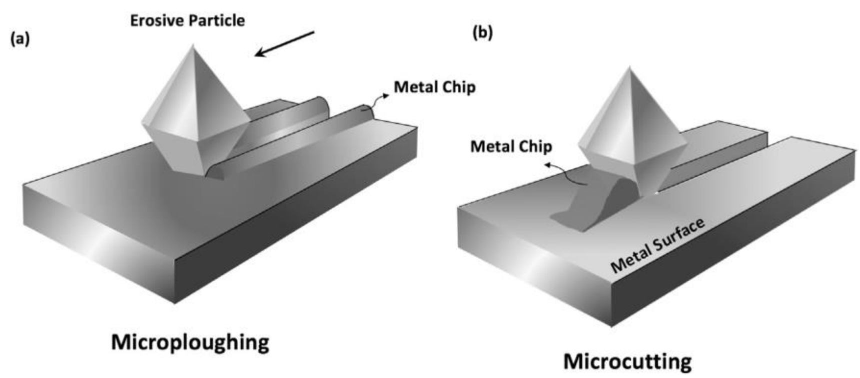


Figure 4. Schematic illustration of a) microploughing and b) microcutting erosion mechanism [9]

Under low impact angle and high particle velocity, cutting is the main mechanism of erosion. Material removal at the later stages of the erosion also occurs by the fracture of ridges. At repeated energetic particle impact, the work-hardened surface is partly brittle and ready to crack and fracture (Figure 5).

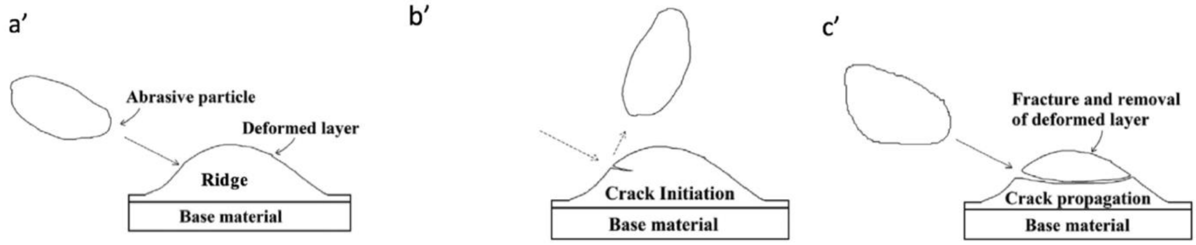


Figure 5. Schematic illustrations of the metal removal steps [9]

Under high impact angle and low particle velocity, plastic deformation and flattening of ridges is the main mechanism (Figure 6). The repeated impact by the abrasive particle causes fracture and removal of vulnerable lips.

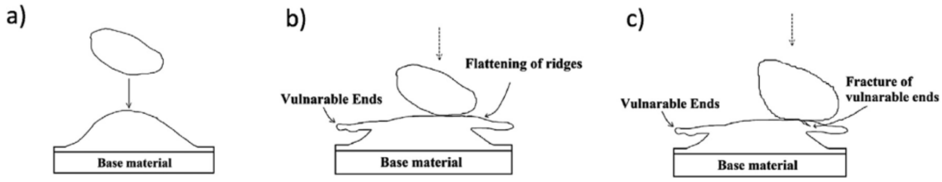


Figure 6. Schematic illustration of the metal removal steps at low velocity and high impact angle [9]

In high impact angle and high particle velocity, particle fracture and secondary metal cutting constitute often occurs. Erosive particles strike and are deflected by previously embedded particles resulting in the removal of a small metal particle (Figure 7).

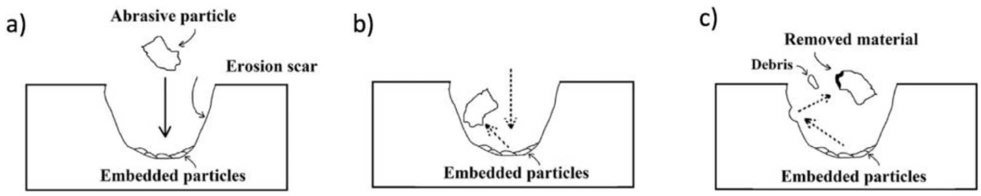


Figure 7. The secondary cutting process steps at high velocity and high impact angle [9]

Only comparatively short grooves are observed to be present on surfaces eroded under industrial conditions, but systems of extended parallel grooves are more commonly found to be present on metallographically polished surfaces [3].

This may be because the contacting fibres (of composite materials) are rubbing extended grooves that obscure those made by the abrasive particles. Extended grooves can be made by abrasive particles which are entangled between or embedded in the fibres. Many of different possibilities were not investigated yet [3].

The erosion concept provides explanation for some feature surfaces polished with abrasive suspensions that are detrimental. The first process considers the difference in level develops between phases with various polishing characteristics than in micromachining process. A second negative effect of polishing by an erosion mechanism takes place when the interface between adjoining phases or constituents is discontinuous [3].

Occasionally, slurry erosion may be considered as a type of abrasion. It can belong to erosion category because it is material removal from a solid surface by mechanical action of liquid. The fluid is used to force to the solids in slurry to create material removal. Hard particles in slurry tests are nocuous for material, without them process of material removal will not happens (or will be very slow). Slowly liquid erosion can be caused, unless made energetic by high velocity. For rubbing slurries can be used pads, while the force with which the particle is pushed against the surface is a function of the stiffness of the pad [2].

Another important aspect is size of particles. It could be thought that very small particles can be innocuous, but industrial experience shown opposite. Laboratory tests have shown that slurry particles with size from 5 to 10 nm can produce a corrosion synergy. That is why even nanometer-sized particles can be significantly effective [2].

Volume fraction of particles should also be considered, but it is not giving so significant effect on extent of erosion damage. Usually, it is required at least >10 % of the nano-particles by weight to create an aggressive erosive slurry [10].

The slurry erosion mechanism is caused by particles that remove protective layer from the surface together with particle rubbing (scratching + adhesive wear). If material would not have passive film, then only abrasion component will take place and synergy of tribocorrosion will not have any effect. One of the main factors is the force that imposes the slurry particles on sliding along the surface. Slurry velocity is important to exponent of more than 2, since it influence the particle force [2].

2.3 Slurry abrasive

In study of slurry abrasivity (abrasiveness), particle hardness is also an important aspect. Harder particles can scratch a substance more effectively. The Mohs harness scale of abrasives shows materials ability to scratch each other. For example the diamond is hardest material in the list and it can scratch all other materials [12].

In the Unites States, the test for classification of water slurries of minerals was developed in the 1980s. This test is guidance for suitable pipeline material for conveying coal and other minerals long distances in pipelines [12].

2.4 Slurry erosion tester

There are tests which can identify “corrosion” and “abrasion” components of the erosion [6]. In the literature, we can find many slurry erosion test machines and devices. Many of these pumps provide high velocity at the surface of a test sample. One of the basic tests is described in ASTM G75-07(2013)” Standard Test Method for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number)”. The relative effect of slurry abrasivity is defined by measuring the mass loss of a block of plastic elastomer after it has been driven in a reciprocating motion in a trough containing the slurry [14].

The trough has a “V” shape or flat bottomed inside shape, because it helps to forces the slurry particles to the reciprocating path taken by test sample. The slurry may be of any material, for example sand in water [14].

One of the testers is the Miller number machine. Main strategy of this test is to lift a little bit the test block and delays momentarily at the end of each stroke, what allows to give time for fresh slurry material to flow back into the wear path. The test is measuring the mass loss of a part per unit time [14].

There are other slurry erosion tests available. They are schematically illustrated in Figure 8. The Miller number test is used for evaluating the abrasivity of slurries and classifies materials for their ability to survive pumping different slurries. The tested sample is moving back and forth on a rubber lap inside the slurry. The Miller number is measured with the help of standard high-carbon sample or high-chromium white iron. The Miller number shows abrasive is slurry; higher number means more abrasive particles. This test was intended to simulate reciprocating pumps, while continuous pumps can also be tested by this method [17].

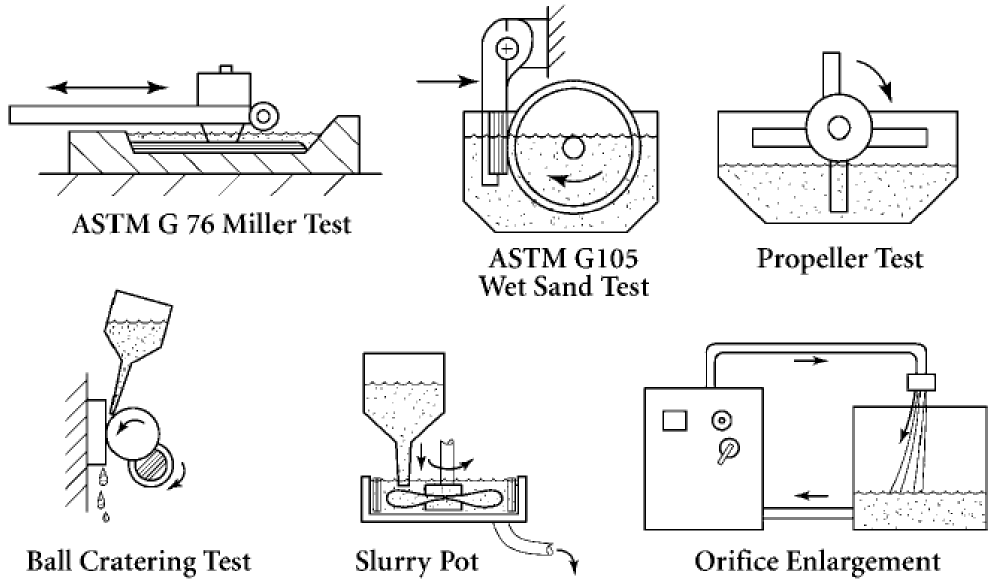


Figure 8. Slurry erosion tests [6]

2.5 Running-in phenomena

Running-in was studied for more than seventy years ago by E. J. Abbott and F. A. Firestone [15], whose signal work in 1933 led to the useful concept of the bearing area curve. Their statement for reporting bearing area as a function of distance below the highest peaks of the surface are still used in the bearings and gears industry. They stated: *When two newly machined surfaces are placed together, they touch only on the peaks of the highest irregularities, and the actual contact area is very small. If surfaces are 'runin' under load, or otherwise fitted, the projecting irregularities are gradually removed and the actual area of contact is increased. At first the wear is quite rapid, but it decreases as the contact area increases*.

Undoubtedly, these statements by Abbott and Firestone have set the general tone for understanding the early stages of bearing contact, but their focus on the changes in microtopography falls short of highlighting the broader aspects of running-in, like the changes that occur in the materials immediately adjacent to the surfaces. Clearly, in order for the engineering surfaces to fit together, elastic and usually irreversible plastic deformation of asperities is required. During that deformation process, changes in crystallographic orientation and the state of work hardening (especially in metals) can occur. Debris can accumulate and interfacial transfer can occur. Therefore, not only do the shape, texture, and roughness of the surface features change, but their substructure and micro-mechanical properties do as well [15].

2.6 Slurry pot

One of the slurry erosion standard tests is the ASTM G 119. This test is performed in Slurry-pot machine. In ASTM G119 have a horizontal propeller and complete immersion of the impeller. This test standard is illustrated in Figure 9 and rotating paddle (impeller) is used to provide fluid velocity and assess effects on corrosion rate. It is very popular among members of the US National Association of Corrosion Engineers (NACE) [16].

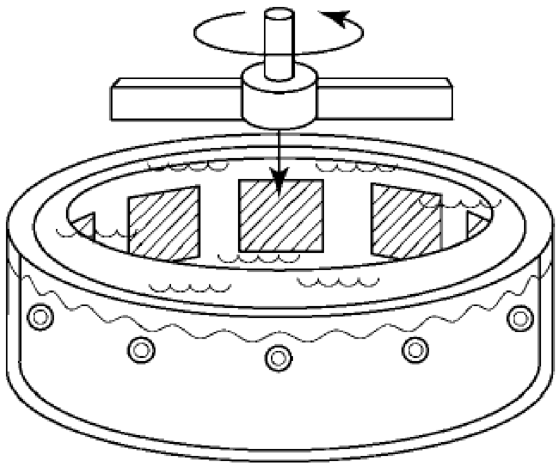


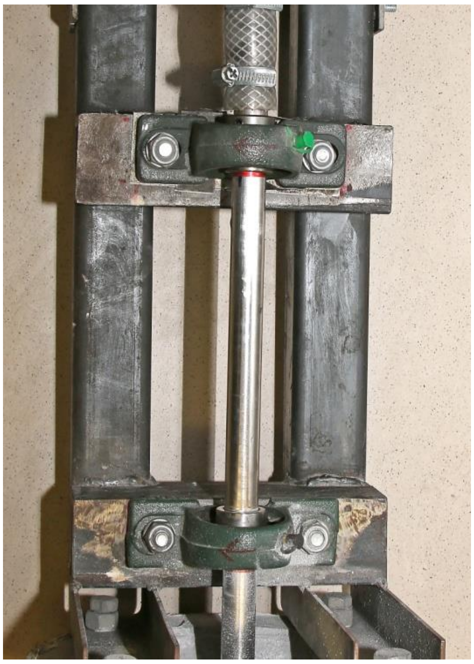
Figure 9. Schematic of NACE liquid erosion test [14]

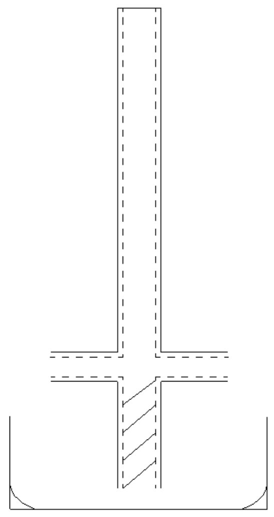
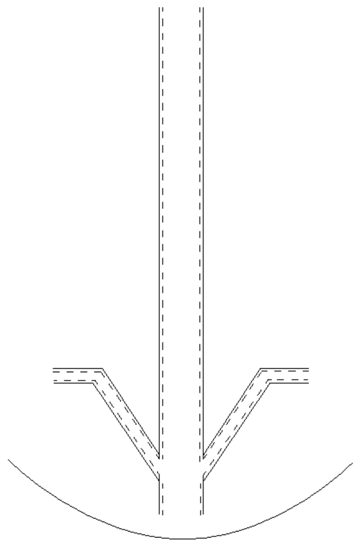
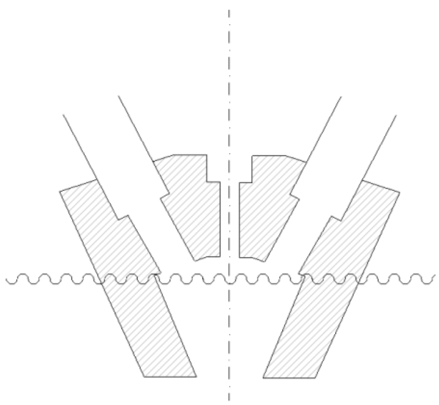
The impeller can create a different speed of abrasive. The effect of speed can be determined by mass change measurements on the samples that are electrically isolated from each other. The samples are embedding in a non-conductive ring. The samples holder had been incorporated in slurry pot tests. In the pot is slurry. One of the problems of this test is that the abrasivity of particles can change with time. To avoid this problem, should have a large supply of slurry and make it one pass through the pot and be discarded. This is one of most effective ways of testing the slurry erosion [14].

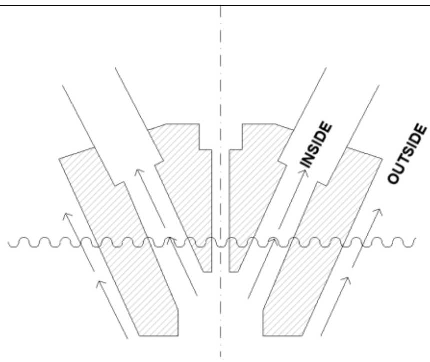
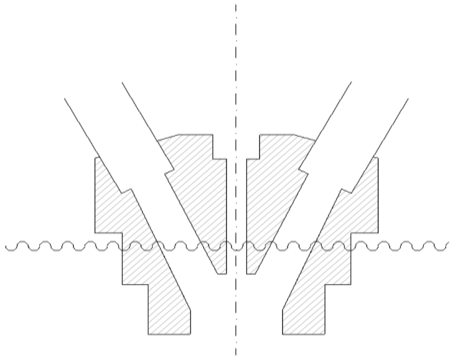
2.7 Slurry machines historical evolution at Tallinn University of Technology

The Tallinn University of Technology have own historical evolution of slurry erosion testers. While using the machines, some issues have occurred. From time to time machine design was improved. Important components were added or replaced by other parts to improve reliability. Main features of the evolution of slurry erosion tester are shown below in Table 1.

Table 1. Hydro-abrasive slurry test device evolution

Model No.	Advantages	Disadvantages	Illustration
1	- Stable work only with low concentration of slurries	- Only one speed -Motor bearings were quickly destroyed -Bucket bottom is flat ⟶large heavy particles tend to escape from centre of slurry bucket and concentration of abrasive particles in slurry that participate in wear process could be reduced - Accelerator disk was fixed to motor shaft	
2	-Additional shaft and bearings for supporting of accelerator disk were added to reduce damage of motor bearings	- Hard to do balancing - Bucket bottom is flat ⟶ large heavy particles tend to escape from centre of slurry bucket and concentration of abrasive particles in slurry that participate in wear process could be reduced	

Model No.	Advantages	Disadvantages	Illustration
3	- No need of balancing due to low weight of accelerator and concentric design	- Get clogged due to small size of spiral - Extreme corrosion of spiral (made of high-speed steel) in corrosive slurries - Accelerator elements are welded together and parts cannot be replaced - Bucket bottom is flat → large heavy particles tend to escape from centre of slurry bucket and concentration of abrasive particles in slurry that participate in wear process could be reduced	
4	- All parts are made from stainless steel to reduce corrosion - Working good - Ribs were added into bucket to minimize rotation of slurry - Bucket bottom shape was changed to spherical to provide stable particle concentration during test - Method of initial acceleration is changed from spiral-driven to centrifugal-type	- Parts had thin walls and were quite quickly worn - Very hard to repair the details after wear - Static balancing was required	
5	- New design with replaceable channels that were technologically very easy to manufacture - Bucket have ribs - Bucket have rounded bottom - Parts were made exchangeable and with thick walls to provide longer lifetime	- Was not working stable (because the input holes of accelerating device were located too high above the bottom of the bucket (were immersed insufficiently into slurry)	

Model No.	Advantages	Disadvantages	Illustration
6	- Stable pumping through internal channels - Bucket have ribbing - Bucket have rounded bottom	- Slurry is additionally (uncontrollably) accelerated by outside surface of device's bottom part (not intended)	
7	- Device was working very well - Bucket have ribbing - Bucket have rounded bottom (stable slurry concentration)	-Metallic exit channels (where slurry is moving with highest speed) had fast wear resulting in unstable work at high speed with high concentration of abrasive particles and during long tests	
Current work improvement	-Working stable even at high concentration and long tests - Bucket have ribbing - Part of channel experiencing wear is made of exchangeable ceramic (Alumina) - Bucket have rounded bottom - Additional elements to provide balancing are installed on shaft and are easy to access and adjust.	- Not yet observed	

In Table 1 of review it can be seen that design of slurry erosion tested have been changes 8 times. Each improvement was giving better quality of tests and longer parts lifetime. During evolution, two main parts were improved:

- Bucket
- Accelerator

Two changes were done in the bucket. Before the first modification, bucket bottom was flat. For improvement it was changed to rounded-shape bottom. Previously, the problem was caused by the fact that heavy large particles were tending to escape from centre of slurry bucket and concentration of abrasive particles in slurry in the centre of bucket was reduced.

At the second change, bucket was updated with ribbing for stopping rotation of slurry. Ribbings are immersed into the slurry, slurry cannot easily rotate and that helps accelerator to pump.

The accelerator also had significant changes in design: from simple shape with two pipes into CNC machined accelerating disk manufactured with thick walls for longer lifetime and stable work.

During the last modification (topic of the current thesis), the ceramic exit channels (contacting with slurry flowing at highest speed) were incorporated to improve reliability of testing.

3 TEST METHODS

3.1 Equations

$$G_W = \frac{V_W}{t} \quad (3.1)$$

Where: G_W – throughput (water or slurry) [l/s]

V_w – volume of pumped water or slurry [l]

t – testing time [s]

$$V = \frac{\pi dn}{sin\beta} \quad (3.2)$$

Where: V – jet exit speed [m/s]

d – diameter of disk accelerator [m]

n – rotation frequency

β – slurry abrasive output [β=55°]

$$m_t = m_W + m_a \quad (3.3)$$

Where: m_t – hydro-abrasive mass [kg]

m_W – water mass [kg]

m_a – abrasive mass [kg]

$$V_a = \frac{m_a}{\rho_a} \quad (3.4)$$

Where: V_a – abrasive volume [l]

m_a – abrasive mass [kg]

ρ_a – 2.6 – density of abrasive [kg/l]

$$V_t = V_W + V_a \quad (3.5)$$

Where: V_t – hydro-abrasive volume [l]

V_W – water volume [l]

V_a – abrasive volume [l]

$$C_{va} = \frac{V_a}{V_t} \cdot 100 \quad (3.6)$$

Where: C_{vw} – percentage of abrasive by volume [%]

V_a – abrasive volume [l]

V_t – hydro-abrasive volume [l]

$$G_s = \frac{V_s}{t} \quad (3.7)$$

Where: G_s - the capacity of the device when working with hydro-abrasive [l/s]

V_s – pumped hydro-abrasive volume abrasive [l]

t – test time [s]

3.2 Calculations

Abrasive concentration: 4 kg of water + 1 kg of silica (SiO_2) sand

Test time: 3 h = 10800 s

Diameter of disk accelerator: 150 mm = 0,15 m

Hydro-abrasive speed: V = 20 m/s

1. Concentration of abrasive by weight with circulation [%]

Table 2. Concentration of abrasive by weight

Water [%]	Sand [%]
80	20

2. Throughput capacity (water or slurry) [l/s] – determined in work of I.Pirk [33] for 20 m/s.

$$G_W = \frac{V_W}{t} = \frac{837,49}{10800} = 0,078\ [l/s]$$

3. Rotation frequency n [sek^{-1}]

$$V = \frac{\pi d n}{\sin\beta}, =>$$

$$n = \frac{\sin\beta \pi d \cdot V}{\pi d} = \frac{\sin 55 \cdot 20}{\pi \cdot 0,15} = 34,8\ s^{-1}$$

4. Weight of hydro-abrasive mass required for test with circulation [kg]

$$m_t = m_W + m_a = 4\text{ kg} + 1\text{ kg} = 5\text{ kg}$$

5. Calculation of abrasive concentration by volume

6. Pumped hydro-abrasive volume if the circulation is absent (with single pass of slurry) [L]

$$G_s = \frac{V_s}{t}$$

$$V_s = G_s \cdot t$$

$$V_s = 0,085 \cdot 10800 = 918\ [L] = 0,918\ [m^3]$$

7. Density of hydro-abrasive mixture (slurry) with 20 % of silica sand [kg/m^3]

$$\rho_w = \frac{100}{\frac{20\%}{2600} + \frac{80\%}{1000}} = 1140{,}4\ kg/m^3$$

8. Weight of hydro-abrasive mixture required for device without circulation [kg]

$$W_t = 0{,}918\ m^3 \cdot 1140{,}35\ \ kg/m^3\ = 1046{,}9\ kg$$

9. Content of components in hydro-abrasive mixture required for device without circulation

$W_t = 1046{,}8\ kg$ =>

Table 3. Concentration of abrasive without circulation

Abrasive mixture component	Percentage [%, wt]	Weigh [kg]	Volume [L]
Water	80	837,5	837,5
Sand	20	209,4	80,5
Total:	100	1046,9	918

Table 4. Comparison of consumption of abrasive and water in case of device with or without circulation of slurry

With circulation of slurry	No circulation (single pass of slurry)
Sand + Water 1 kg + 4 kg	Sand + Water 209,4 kg + 837,5 kg

3.3 Conclusion

The slurry erosion tester was used during the tests. It is of interest to check how Eco-friendly this apparatus is. Calculations were done to show how much water and sand were saved. This method helps to test materials at the laboratory conditions with less cost and consumption of resources. According to calculations, the saving of the resources during one test with circulating slurry type of device can be summarized as following:

- Silica sand 209,4 – 1,0 = 208,4 kg
- Water: 837,5 - 4,0 = 833,5 kg

Slurry erosion device have circulation of abrasive media inside the apparatus. This method helps to save water, sand or other used particles during the tests. The consumption of resources is reduced more than 200 times. With such advantage, the applied testing method of slurry erosion may be considered as the Eco-friendly device.

4 ANALYSIS OF HYDRO-ABRASIVE (SLURRY) DEVICE

4.1 Research aim

Slurry erosion is complex phenomenon that is not completely understood. As it was written before, the degradation of materials depend on impact angle of particle with material, slurry velocity and concentration of solid particles in the liquid. The development of slurry erosion devices can affect these parameters. Unfortunately, many of parameters are not easy to control (adjust). The aim of my work is to assist in further development of hydro-abrasive (slurry) apparatus at Tallinn University of Technology.

The apparatus was designed by previous researcher's team in Tallinn University of Technology, Research Laboratory of Tribology and Materials Testing and now it is needs to be improved due to requirement of stable work even with high velocities, high abrasive particle concentration, high hardness of abrasive particles and longer duration of tests. After testing and analysing, the necessary changes were made in design of tester. For better understanding of working process, several tests with commonly available steel grades were done.

4.2 Analysis of hydro-abrasive tester before improvement

Hydro-abrasive tester from Tallinn University of Technology has stationary fixed sample position. In this case, samples are continuously exposed to a slurry jet. Similar device is described in the ASTM G-75 and G73 standard, with fixed sample. The tester has velocity from 3 m/s to 35 m/s [33]. Abrasive concentration could be from 0 up to 60 % vol. Slurry abrasive is pumped and directed to the samples though nozzle. Thus, the main risk was in metal exit channels, because they had fastest wear due to highest speed.

Slurry erosion tester contains a drive mechanism in the form of an electric motor. Motor is connected to the shaft of the test pumping setup. Inside the tank, the following parts/substances are present: slurry abrasive mixture, nozzle for abrasive supply, rotor with channels for abrasive exit, sample holder. The device is positioned on floor and additionally fixed to the table to avoid falling.

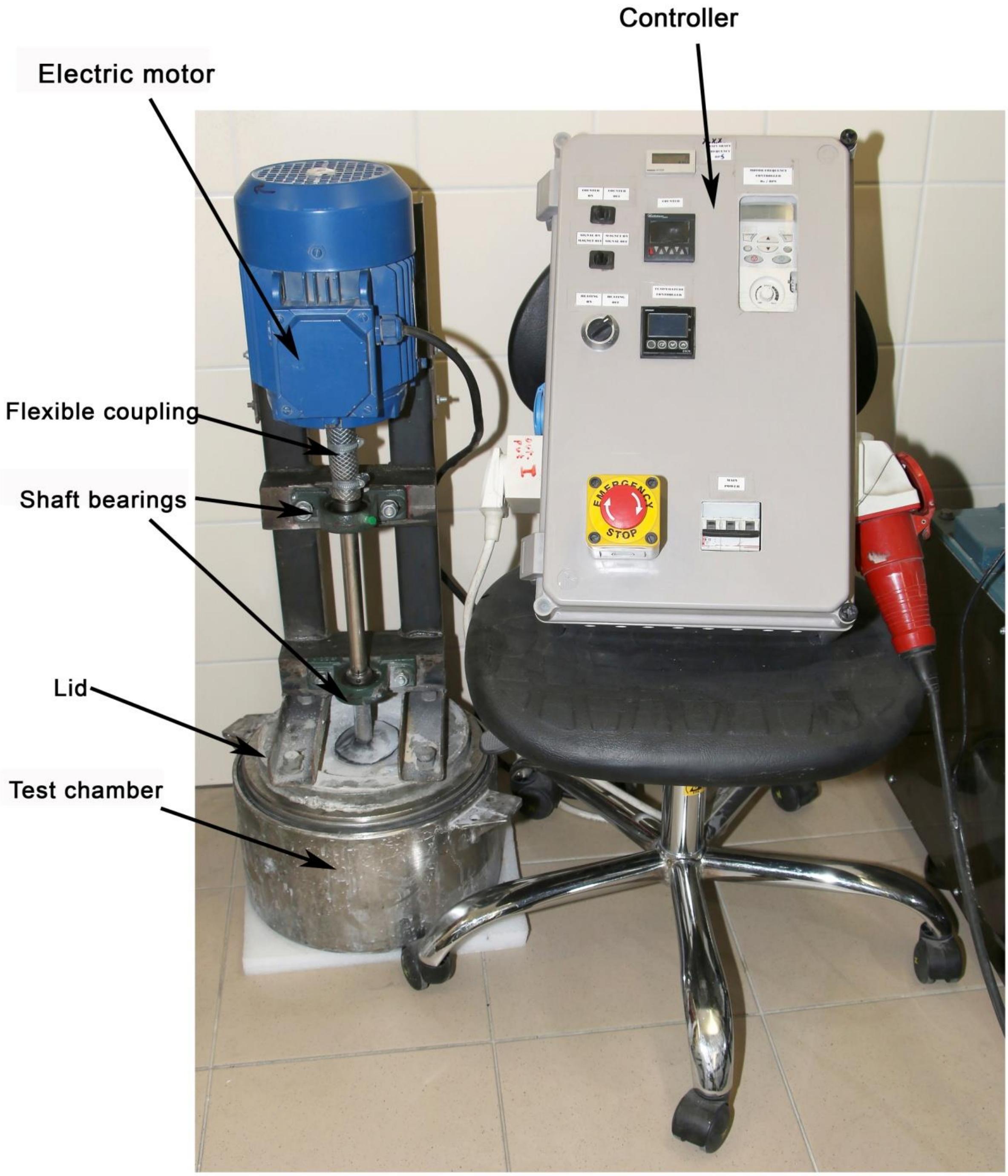


Figure 10. The side view of current hydro-abrasive (slurry) tester. The channels that were modified as part of the current thesis are inside the test chamber and are not visible

Testing method contain following aspects. The tank is filled with abrasive and liquid with correct proportions. Up to 38 samples (with size 5*15*25 mm) can be installed in the removable holder. Next step is to place device in working position by lowering the tip for supplying slurry into the bottom container with spherical buttom. After that, the rotation speed and the test duration parameters are set. All these parameters are set at the controller. Next step is to start the machine.

Futher, rotor with radially located channels is starting rotation with respect to a vertical axis. The slurry is entering the lower channels, is rised up by centrifugal force and is ejected through the exit channels onto the samples fixed around it. After this, abrasive mixture continue for some time the flow along the samples and then flows back into the container and the process is repeated again and again (slurry is circulating).

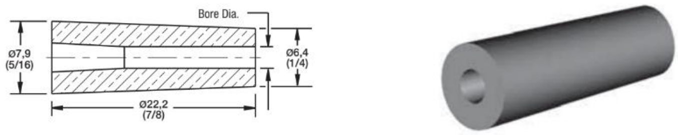
Figure 11. 3D model of improved hydro-abrasive (slurry) tester

4.3 Channels

The main factor related to unstable work was found. Metal channels had wear and mainly due to this problem, tester's work wasn't stable. If new metallic channels are used for each test, then stability is acceptable but exchange of channels is quite complicated and the device has to be balanced after that. During test, the wear is causing the inner diameter of exit channel to increase and volume of pumped slurry can increase as well. It was required to reduce wear of channels and to improve reliability of testing. In order to provide lower wear of channels, the best suitable solution was to use channels with higher resistance against wear – channels made of alumina (wear resistant ceramic material). It was expected that this would help to make more high quality research to understand the wear mechanisms and assess the performance of existing and new materials.

Considering all the aforementioned it was decided to use standard ceramic channels for ease of replacement. New channels internal diameter (bore) is 2,3 mm. Component was ordered from Kennametal catalogue, that is shown below in Figure 12.

- 5/16" O.D., tapered to 1/4" O.D.



C3 Series

order number	catalog number	model number	bore diameter mm	bore diameter in	length mm	length in
2940299	B1214515	C3-1-1/2	2,4	3/32	22,2	7/8

Figure 12. Ceramic channel from Kennametal catalogue [35]

The length of ceramic channel was slightly longer than it was required for our tester and it was necessary to remove part of it by diamond disk.

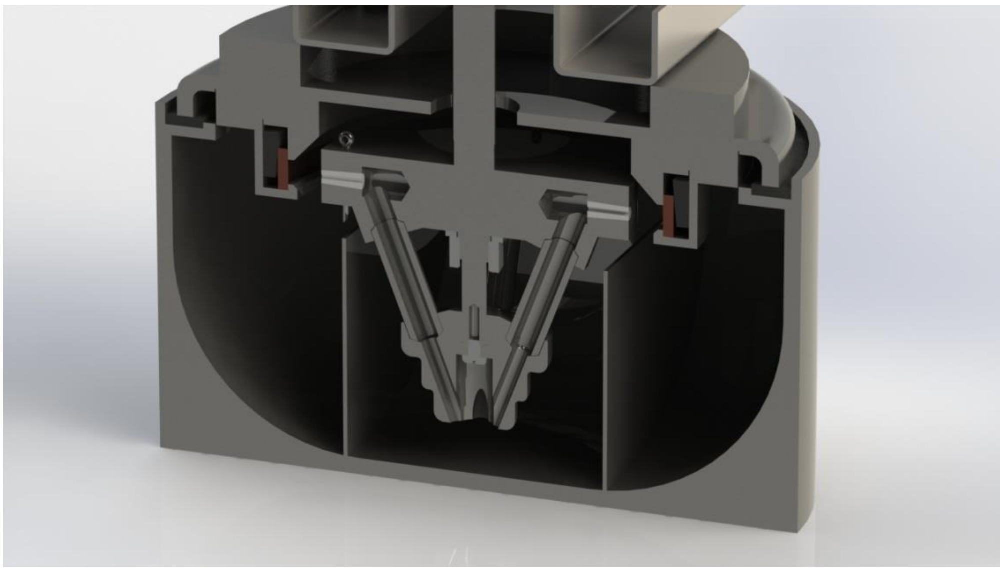


Figure 13. 3D model section view of improved hydro-abrasive (slurry) tester with installed ceramic (white) channels

5 ASSESSMENT OF THE WORK OF SLURRY EROSION TESTER

5.1 Preparation for testing

Before testing, samples were labelled, so that after the test it was possible to determine which sample we are dealing with. Samples were cleaned with compressed air, washed in ultrasonic bath and dried with blower at 50° C for 1 hours. The weight was determined and the results were written into the protocol. Then, the test samples were installed into the hydro-abrasive accelerator. The installation of the sample into the holder should ensure that the certain area of the working surface of the sample is exposed to hydro-abrasive. Hydro-abrasive mixture is prepared in accordance with the environment that must be simulated during testing.

According to the results of sample weighing before and after testing, the average loss of the tested samples was determined according to the equation. The density was measured to calculate the volumetric wear of samples.

5.2 Testing of samples

The current design of hydro-abrasive tester allows doing slurry erosion tests at the Tallinn University of Technology. Machine has horizontal fixed position of samples. They are fixed inside the holder. During testing it is possible to test at the same time up to 38 pc of metal samples with dimensions 5 mm x 15 mm x 25 mm.

The samples are manufactured in the form of plates, without sharp edges. This is done to avoid breaking of sharp edges during preparation or testing, that would reduce precision of wear rate measurments and would influence the reliability of testing.

The rotor speed and test time are set. While using different abrasives, the speed of rotation, as well as the concentration of the abrasive, is set experimentally. During testing, it is necessary to provide a continuous supply of hydro-abrasive to the rotor. The mixture in the chamber must be enough to provide stable work for accelerator and less than the level, that may lead to excessive turbulence. For better results, the required quantity of hydro-abrasive is supplied, after that device is turned on. When test is over, the samples are removed, washed under water, dried in a heater at 50 ° C for 1 hour and weighed. The results before and after are recorded in the table (protocol). During set up and while removing the samples damage to the surfaces are not allowed.

5.3 Description of steel specimens

Six metal material grades were chosen for checking the work of the hydro-abrasive (slurry) tester (Table 5). The composition, maximum service temperature (in dry conditions), type of steel and additional comments are presented in Table 6.

Table 5. Specimen materials

Specimen No.	Material grade
C-1, C-2, C-3	Cr_3C_2-Ni commercial hardfacing. Ni content is approx. 40 %
2-1, 2-2, 2-3	P265GH
4-1, 4-2, 4-3	AISI 304 L
5-1, 5-2, 5-3	253MA
6-1, 6-2, 6-3	16Mo3
9-1, 9-2, 9-3	T91

Table 6. Description of steels tested [34]

Material designation and grade	Composition (wt %)	Maximum service temperature in dry air (°C)	Type	Comments	Relative price level
C (Cr_3C_2-Ni)	-	-	Ceramic-metal composite coating	Have high resistance against wear and corrosion	≈ 20.0
2 (P265GH)	0.2C, 0.012N, 0.3Cr, 0.3Ni, 0.4Si, 1Mn, 0.015S, 0.08Mo, 0.02V, 0.3Cu, 0.02Nb, 0.03Ti, 0.025P, 0.02Al, Fe	450	Ferritic-pearlitic	High-quality structural carbon steel for pressure lines and vessels suitable for elevated working temperatures	1.0
4 (AISI 304L)	0.026C, 0.037N, 18.2Cr, 8.1Ni, 0.4Si, 1.62Mn, 0.032P, 0.001S, 71.584Fe	850	Austenitic	High temperature stainless grade. Low carbon content results in improved lower susceptibility to intergranular corrosion in heat affected zones.	3.5
5 (253MA)	0.088C, 0.173N, 20.93Cr, 10.92Ni, 1.63Si, 0.51Mn, 0.021P, 0.001S, 0.11Cu, 0.001Nb, 0.1Co, 0.04Ce, 65.476Fe	1100	Austenitic	Heat and creep resistant stainless steel with improved oxidation resistance due to increased silicon content and addition of very small quantities (micro-alloying, MA) of rare earth metal (Ce). Creep strength is achieved by increased contents of nitrogen.	7.0

Material designation and grade	Composition (wt %)	Maximum service temperature in dry air (°C)	Type	Comments	Relative price level
6 (16Mo3)	0.16C, 0.005N, 0.04Cr, 0.06Ni, 0.22Si, 0.63Mn, 0.011P, 0.007S, 0.045Al, 0.02Cu, 030Mo, 98.502Fe	480	Ferritic-pearlitic	Heatproof boiler steel for pressurised service	1.5
9 (T91)	0.10C, 0.046N, 8.66Cr, 0.2Ni, 0.31Si, 0.41Mn, 0.01P, 0.003S, 0.018Al, 0.95Mo, 0.07Nb, 0.23V, 88.993Fe	600	Tempered martensitic	Creep resistant tube boiler steel. Vanadium and niobium additions decreased susceptibility to weld cracking comparing to conventional bainitic T9 steel and also provide high creep resistance.	1.0

5.4 Testing

The experiments were done in modified (improved) centrifugal type slurry erosion tester built at the Tallinn University of Technology. Samples may experience conditions similar to ASTM G75-07. Tester parameters were described before in Chapter 3. The slurry mixture was accelerated by motor to have an impact velocity of 20 m/s. Testing time was 3 hours. Then each sample were cleaned by compressed air and dried at + 50 °C for 1 h. Each test was made three times with 3 samples of each material.

Summary of slurry erosion wear test parameters:

- Hydro-abrasive speed: V = 20 m/s
- Ratio of water and abrasive is: 4kg water + 1kg of silica sand Euroquarz Microsil M4, Germany (average size is 50 um)
- Rotation frequency: 34,8 s^{-1}
- Amount of samples: 18 pcs.
- Temperature: 20 °C
- Time: 3 h

Totally 9 tests of each material grade were made while 3 tests were done by using the same samples. To qualify the weight loss, the samples were weight after each test. For weight measurements, Mettler Toledo ME204 balance was used. First test were made to exclude the effect of running-in phenomenon, what is described in Chapter 2. The results of second and third tests are introduced in Table 7.

Table 7. Specimen weight change during slurry erosion testing

Sample	Mass after 1st test (mg)	Mass after 2nd test (mg)	Mass after 3rd test (mg)
2-1 (P265GH)	11,8149	11,7739	11,7284
2-2 (P265GH)	12,5993	12,5621	12,5213
2-3 (P265GH)	12,0138	11,9793	11,9467
4-1 (AISI 304L)	10,4528	10,4156	10,3759
4-2 (AISI 304L)	10,3783	10,3428	10,3049
4-3 (AISI 304L)	10,4358	10,4033	10,3666
5-1 (253MA)	14,7156	14,6785	14,6377
5-2 (253MA)	14,8601	14,8162	14,7672
5-3 (253MA)	13,2281	13,1944	13,1577
6-1 (16Mo3)	11,287	11,2433	11,1967
6-2 (16Mo3)	10,7397	10,6971	10,6508
6-3 (16Mo3)	10,3666	10,3233	10,2776
9-1 (T91)	10,7627	10,7204	10,6785
9-2 (T91)	10,8237	10,7813	10,736
9-3 (T91)	10,6666	10,6267	10,5788
C-1 (Cr_3C_2-Ni commercial)	13,9793	13,9677	13,9553
C-2 (Cr_3C_2-Ni commercial)	14,0917	14,0822	14,0694
C-3 (Cr_3C_2-Ni commercial)	13,9479	13,907	13,8642

Table 8. Average mass change (loss) after hydro-abrasive (slurry) tests

Specimen	Mass loss after 2nd test (mg)	Mass loss after 3rd test (mg)	Average mass loss (mg)
2 (P265GH)	37,57	39,63	38,6
4 (AISI 304L)	35,07	38,10	36,59
5 (253MA)	38,23	42,17	40,2
6 (16Mo3)	43,20	46,20	44,7
9 (T91)	41,53	45,03	43,28
C (Cr_3C_2-Ni)	20,67	22,67	21,67

All grades were characterized with tabletop Scanning Electron Microscope (SEM) “Hitachi TM 1000” and obtained images are provided later.

Figure 14. Hitachi TM 1000 SEM Tabletop microscope

According to Tables 7 and 8 it is possible to conclude that even 3-hour test was causing measurable loss of material.

5.4.1 Measurement of materials hardness

Erosion of component is usually strongly influenced by material hardness. Scratches and ploughing marks appear easier on the soft materials. Hardness tests were done with the help of the „INDENTEC" apparatus at the TalTech Laboratory of Mechanical Testing and Metrology. Test force – 10 HV and loading and holding time - 10 sec. Test results are shown in the Table 9.

Figure 15. Hardness tester „INDENTEC"

Table 9. Material's hardness

Specimen No.	First test, [HV10, kg/mm²]	Second test, [HV10, kg/mm²]	Third test, [HV10, kg/mm²]	Average, [HV10, kg/mm²]
C (Cr_3C_2-Ni)	706,7	727,2	705,0	712,9
2 (P265GH)	153,7	156,8	152,9	154,5
4 (AISI 304L)	221,7	222,7	217,3	220,6
5 (253MA)	268,1	253,6	245,0	255,5
6 (16Mo3)	166,8	156,2	155,6	159,5
9 (T91)	236,5	232,0	219,1	229,2

5.4.2 Density test

Density of the various specimen was checked with the help of the „Mettler Toledo ME204" apparatus. All results are listed in the Table 10.

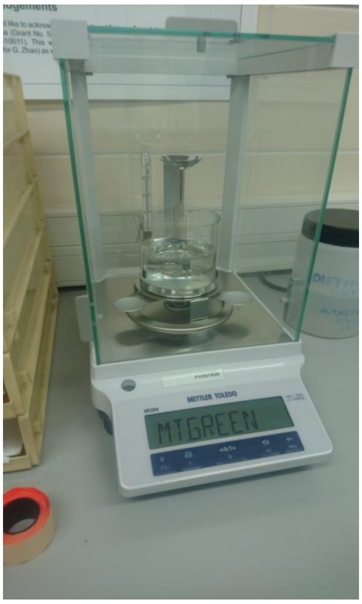


Figure 16. Density measurement setup with the Mettler Tolledo ME204 scale

Table 10. Average density of the specimens

Specimen No.	Density, [g/cm³]
C (Cr_3C_2-Ni)	7,500 [35]
2 (P265GH)	7,757
4 (AISI 304L)	7,837
5 (253MA)	7,709
6 (16Mo3)	7,750
9 (T91)	7,715

All specimens have similar density, because almost all of them are steels. Density of composite coating was taken from literature [35].

6 RESULTS AND DISCUSSION

6.1 Graphical representations

Figure 17 presents the loss of material after 2nd and 3rd tests. First test results were not considered because of running-in phenomena.

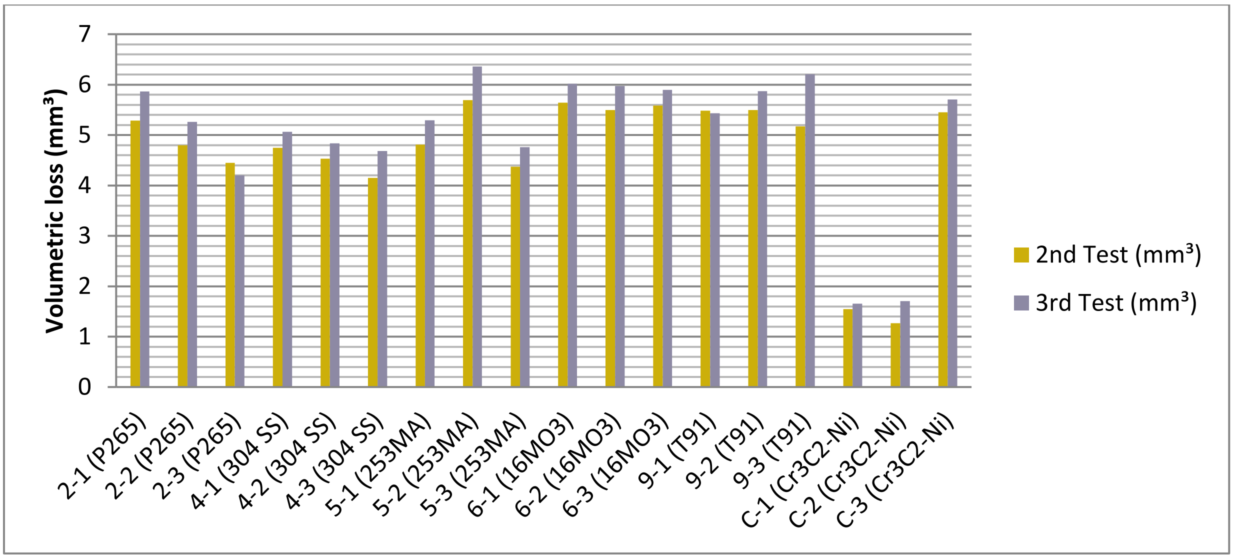


Figure 17. Volumetric loss during hydro-abrasive tests

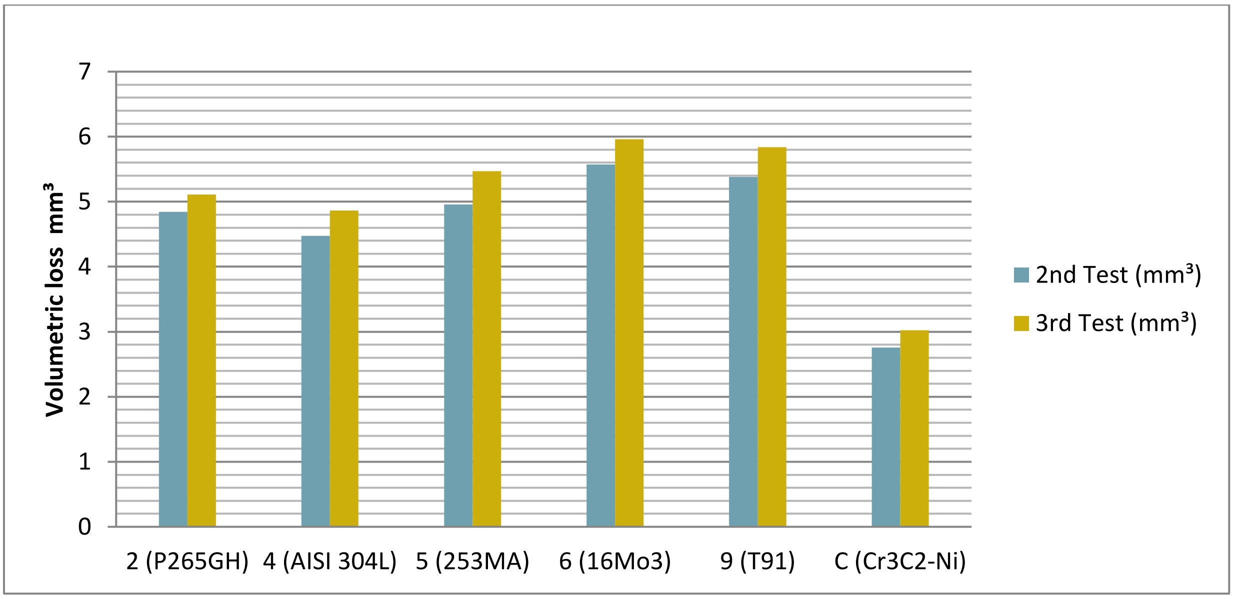


Figure 18. Volumetric average loss during hydro-abrasive tests

Hardness and density test results are shown in the Figure 19 and 20. The hardness HV 10 of materials varies between approx. 150 – 250 and hardness of hardfacing (ceramic-metal coating) was approx. 700.

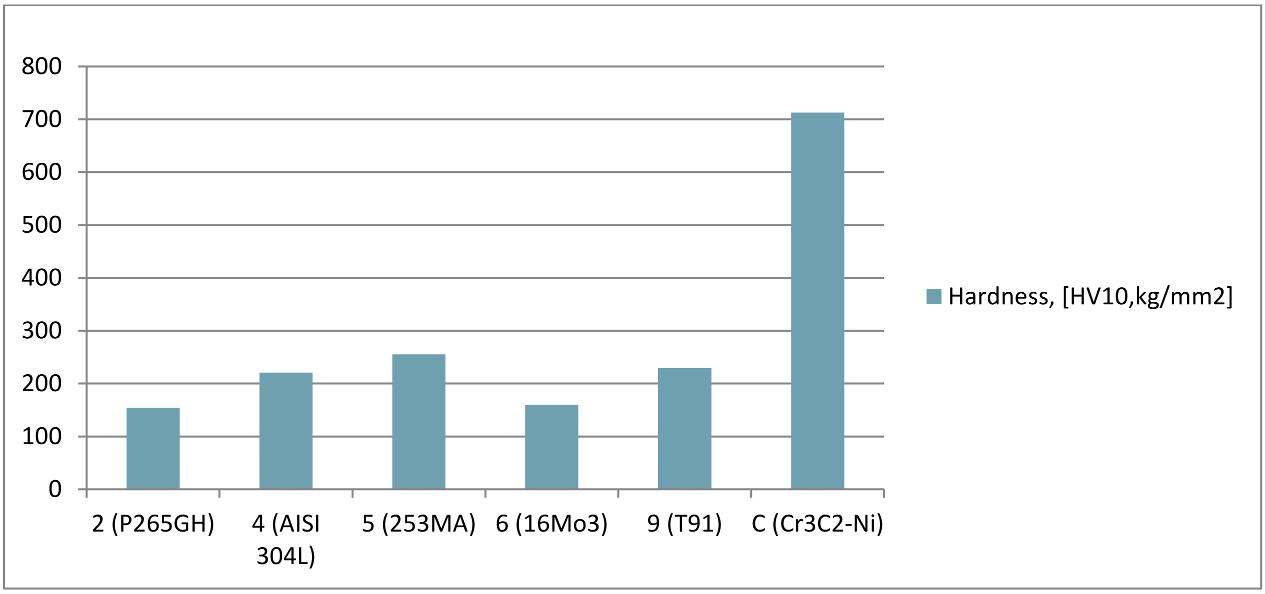


Figure 19. Hardness test results, [HV10, kg/mm^2]

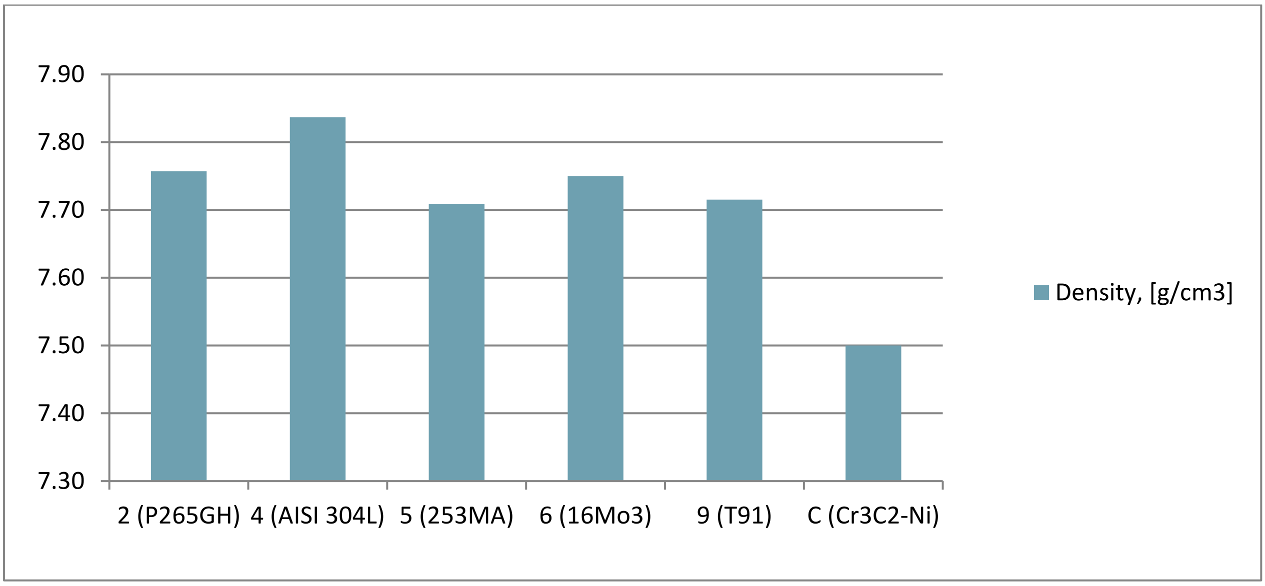


Figure 20. Density test results, [g/cm^3]

6.2 Analysis of worn surfaces

6.2.1 Analysis of specimen 2 (P265GH)

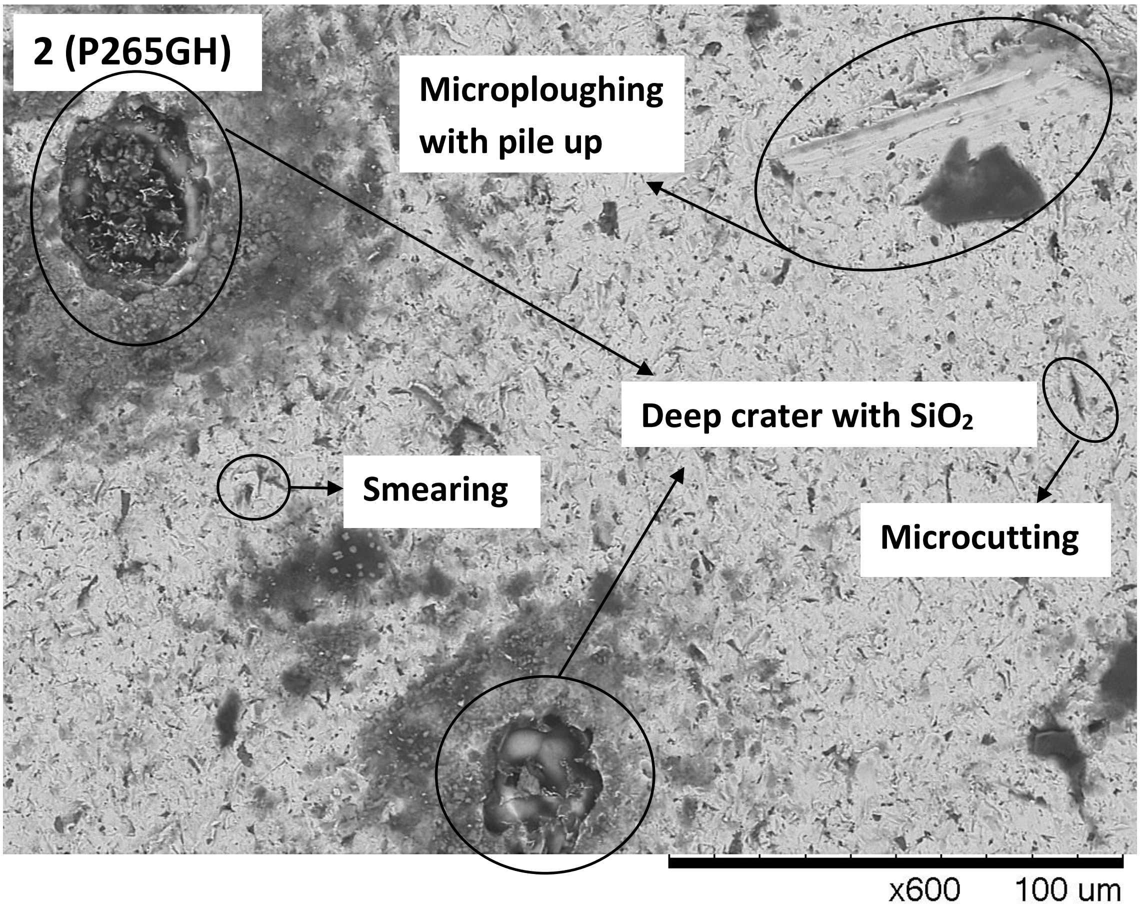


Figure 21. Surface of specimen 2 (P265GH) after slurry test

SEM image (Figure 21) is showing the appearance of material after slurry wear test. The sample middle part was the most suffered from wear since the other parts were protected by holders. In the sample 2 (P265GH), wear causes plastic deformations, the stage of which depends on the hardness and deformability of the steel. However, at the end of the tests there were no polishing marks or marks from remaining after production in either of the materials, obviously because they had been cut away by the turbulent flow of slurry abrasive.

Individual impact-erosion wear features, such as microcutting, smearing, micro plough and short scratch marks, were found all over the surfaces. Deep grooves with sand particles inside also were found. As we can see in Table 9, this steel have the lowest hardness, and it is expected that it should have more extensive deformation and the better visible scratches.

In Figure 21 we can see big micro plough with pile up. The reason for this could be some big sand particle impact on the surface.

6.2.2 Analysis of specimen 4 (304 SS)

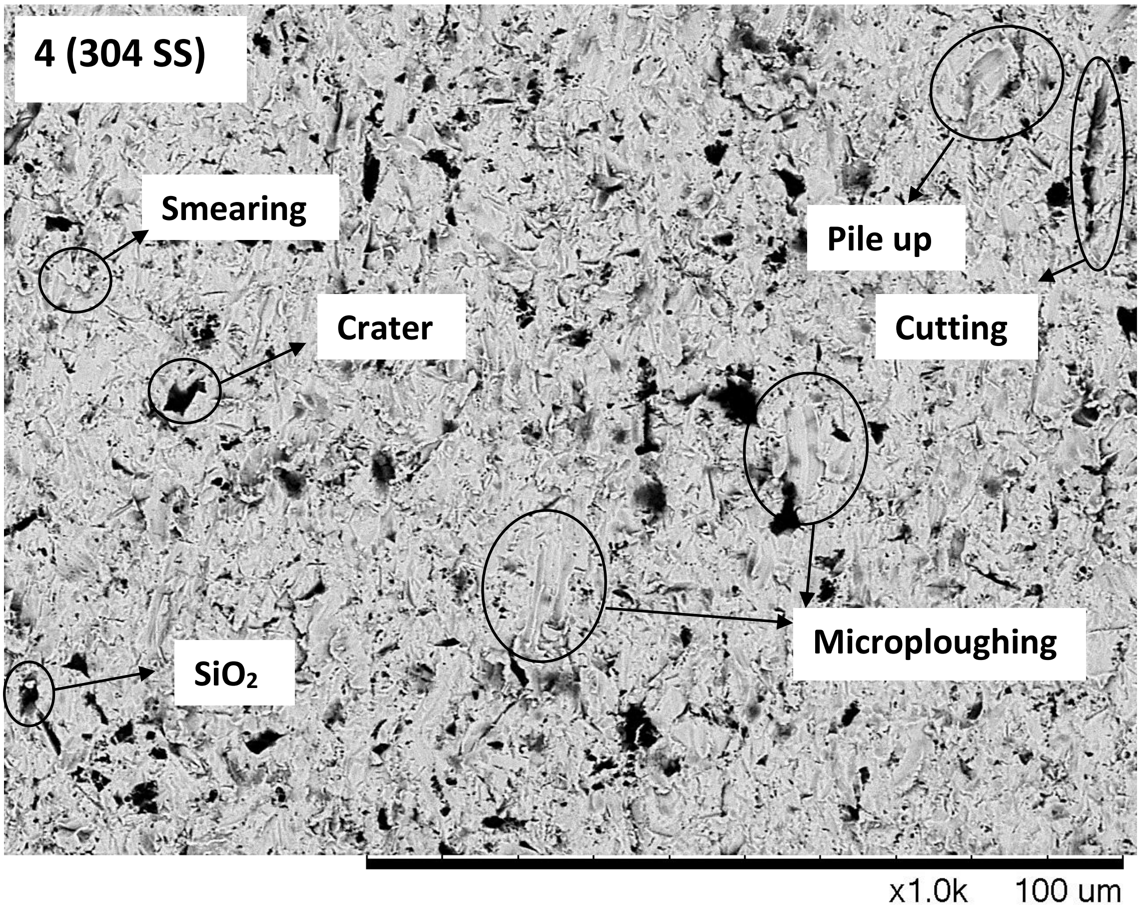


Figure 22. Surface of specimen 4 (304 SS) after slurry test

The nature of fracture of the 4 (304 SS) specimen was evaluated by images obtained by using the SEM (Figure 22). As erosion wear deforms the surface for a long period of time (3 hours), long or wide scratches are rare (they are removed by following particles). The wear surfaces are damaged with scratches and some indents or attached abrasive particles.

Specimen has a lot of micro ploughs, small craters and scratches. The surfaces show extensive plastic deformation. All of those are typical mechanisms of abrasive erosion wear for steels. Further, indentation marks and surface protrusions in the form of lips can be observed.

High quantity of material loss can be caused by material hardness.

6.2.3 Analysis of specimen 5 (253MA)

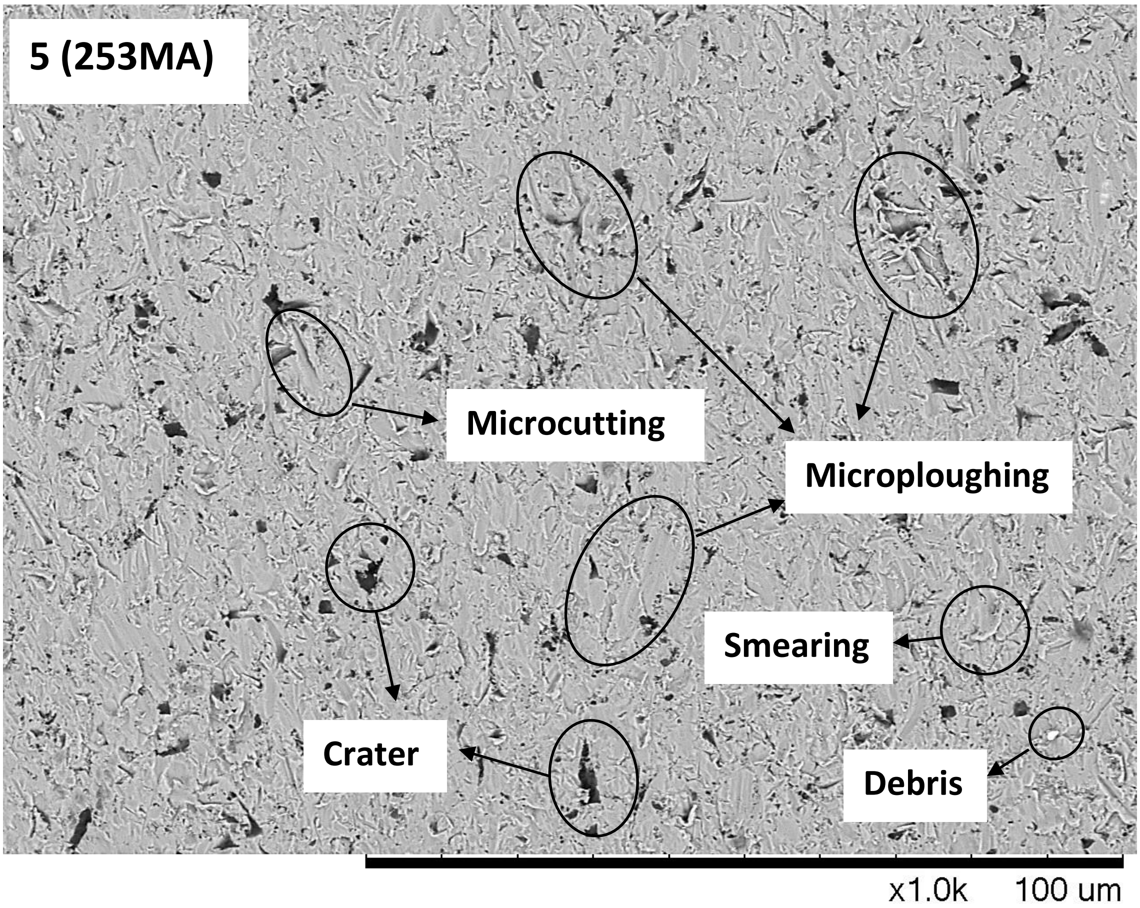


Figure 23. Surface of specimen 5 (253MA) after slurry test

The image of 5 (253MA) material specimen, obtained after the slurry erosion test, is shown in Figure 23. Only small differences could be noted between materials 4 and 5. The reason for this could be the similarity of the steels, as they are similar in the chemical composition and their hardness.

In the specimen 5 (253MA) can be seen a lot of small scratches, microcuttings and craters.

6.2.4 Analysis of specimen 6 (16Mo3)

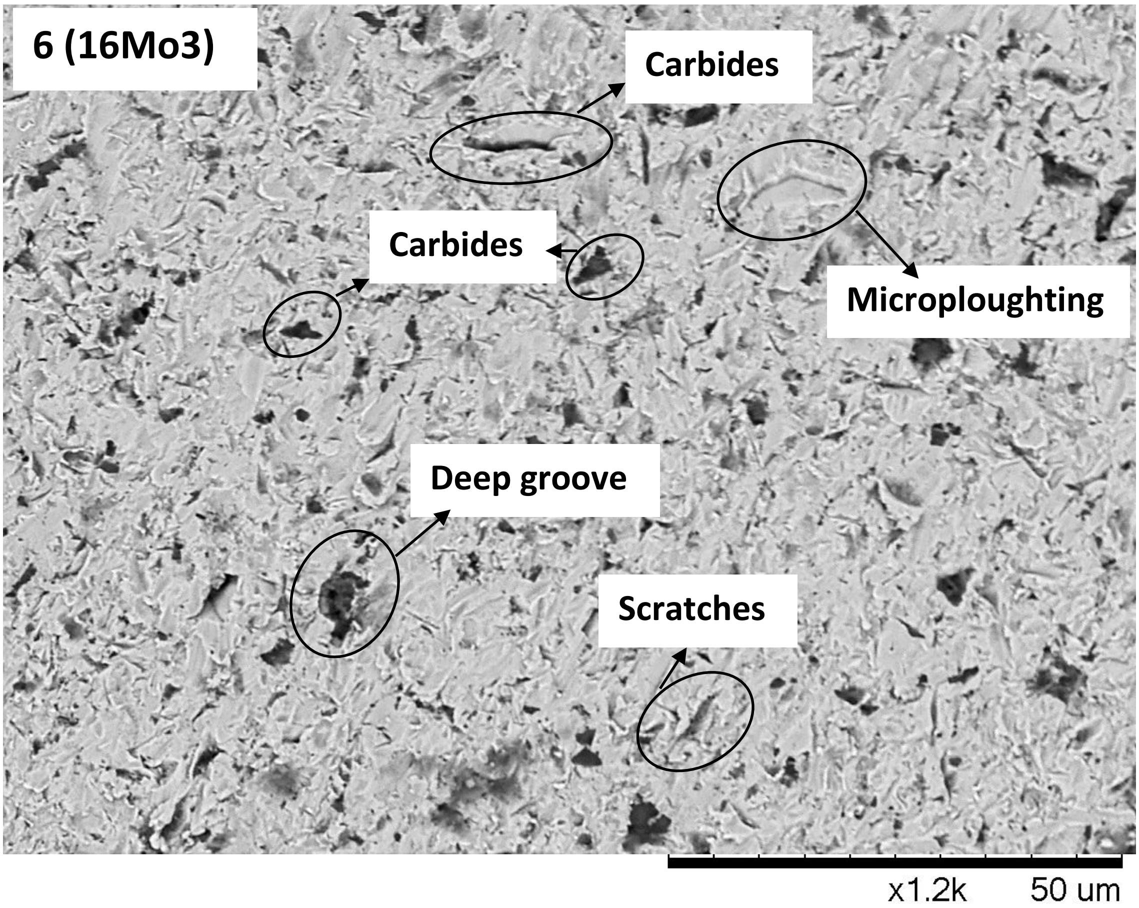


Figure 24. Surface of specimen 6 (16MO3) after slurry test

SEM micrograph of the specimen’s surface after slurry erosion is shown in Figure 24. Sample 6(16Mo3) had the highest amount of sand particles on its wear surface. These particles were also the largest, the surfaces was severely deformed.

With all test parameters, the surface of specimen 6 was clearly the roughest, having many large scratches, dents and embedded that are visible on surface. In abrasive conditions, the most visible difference between the steels was that while all of them showed similar deformed surface layers with white layers and shear bands, their size and quantity varied according to the hardness of the steel. The deformation was found to extend deeper into the material surface.

Because of smaller hardness of material, SiO_2 particles were embedded deeply to the surface. The specimen 6(16Mo3) had the highest erosion loss and damage of the material.

6.2.5 Analysis of specimen 9 (T91)

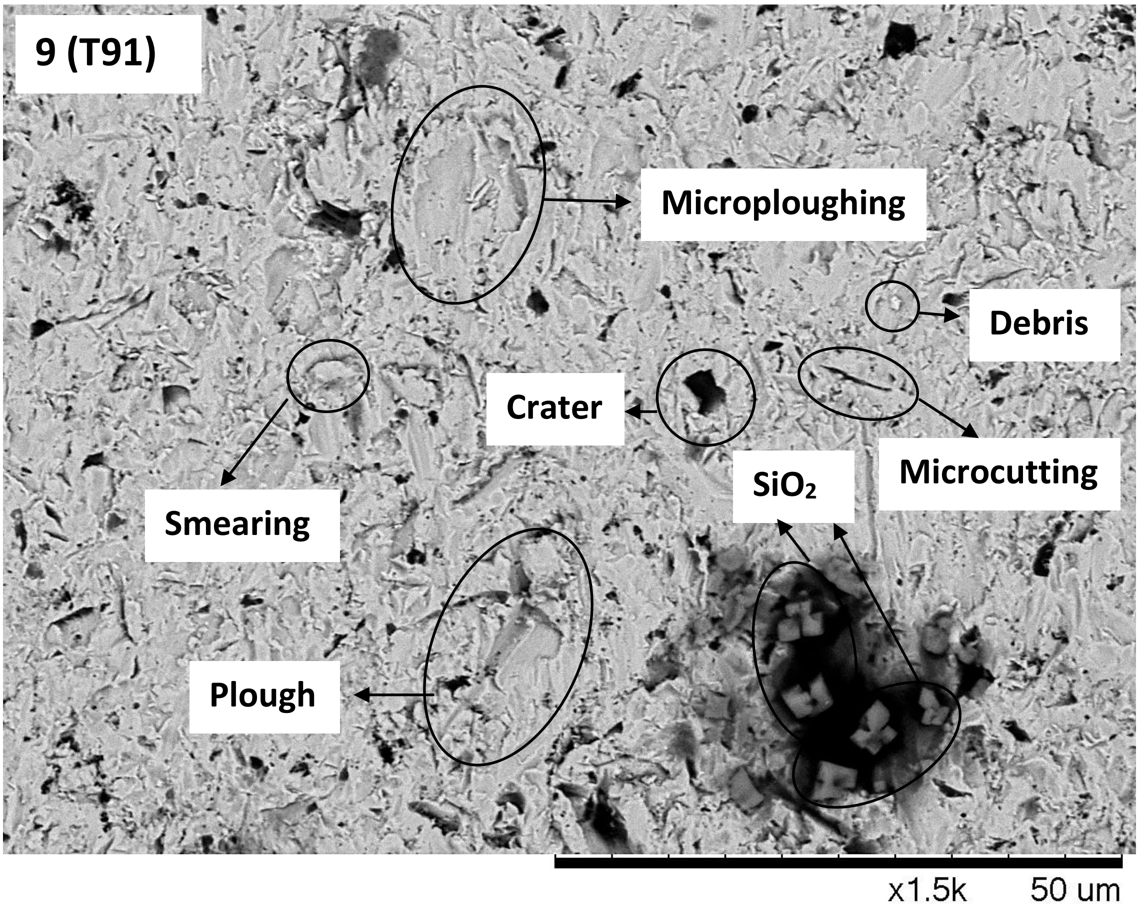


Figure 25. Surface of specimen 9 (T91) after slurry test

The surface state of specimen 9 (T91) after slurry wear is shown in Figure 25.

In specimen 9 (T91) many different wear mechanisms can be seen: microcutting, craters, smearing, microploughing, deep groove with sand particles and scratches. All this mechanisms are showing that surface has suffered significantly from the effect of slurry jet.

Not big difference can be noted between specimen 6 and 9. It can be explained because of similar materials hardness.

6.2.6 Analysis of specimen C (Cr_3C_2-Ni)

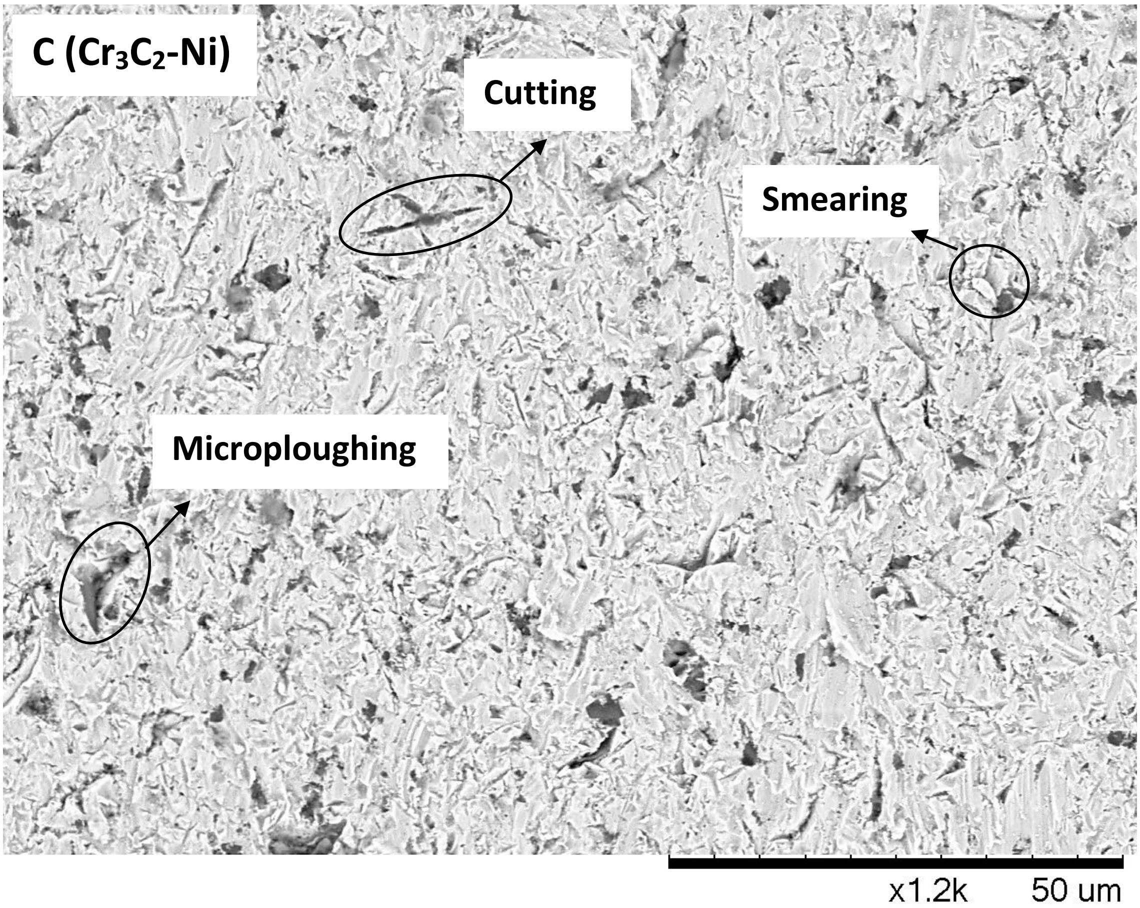


Figure 26. Surface of specimen C (Cr_3C_2-Ni) after slurry test

The specimen C (Cr_3C_2-Ni) exhibits better erosion resistance as compared to the previous specimens. On a detail level, the clearest differences are in the amount of plastic deformation and sharp scratches. The wear surfaces are almost intact except for small scratches and some intended or attached abrasive particles.

6.3 Conclusion

In the beginning (during Test 1), all the specimens showed higher rate of weight loss because of running-in phenomenon. The rate of weight loss gradually decreased with test duration. Materials with higher hardness were having lower wear rate.

From microstructural point of view, same wear mechanisms can be seen on all tested specimens. The most commonly occurring mechanisms are: microcutting, micro ploughing and scratches. Smearing phenomenon can be seen quite rare because slurry abrasive particles are removing them by following impacts of the abrasive particles during the tests.

The best tested material is specimen C (Cr_3C_2-Ni). This sample have highest hardness and lowest weight loss during the tests. All other specimens had similar results after slurry erosion tests.

SUMMARY

Nowadays, the economic importance of slurry erosion, because of high exploitation, has led to many investigations in this research area. These cover the design and improvement of slurry erosion testers and understanding of basic wear mechanisms. The presented overview of laboratory slurry erosion tester evolution enables to track process of improvement of device reliability. The majority of these works have been conducted to study the effect of different designs of slurry erosion testers on their stable work conditions.

The slurry erosion tester was further improved during the current thesis work, due to high demand toward more aggressive tests. Metallic channels were worn quite fast that was resulting in unstable work at high speed, high concentration of abrasive particles and during long tests. For improvement of wear resistance, ceramic channels were implemented to provide required additional significant improvement of reliability.

The design of current device is Eco-friendly and allows saving resources (water, sand). Slurry erosion tester is using same circulating abrasive mixture during the whole duration of single tests. After calculations of possible consumption of water and sand during tests with circulation or non-circulating slurries, the following results of savings for tests with circulation were obtained:

- Silica sand: 208,4 kg (while just 1 kg is required for device with circulation)
- Water: 833,5 kg (while just 4 kg is required for device with circulation)

The consumption of resources is reduced more than 200 times.

Material tests were performed after improvement to assess the work of slurry erosion device. The high speed tester proved consistent and reproducible wear test results with metallic and ceramic-metal composite materials.

Experiments were conducted to investigate the effect of grade (having specific hardness), some studies have been made to address what is occurring microstructurally during erosion by using scanning electron microscope (SEM), but there is still a lack of systematic work on microstructure evaluation during the erosion process by using other methods such as TEM (transmission electron microscopy). These microscopes are able to provide more information on microstructural features like: the disintegration of martensite boundaries, low-angle grain boundaries, dislocation structure, and misorientation analysis of plastic deformation. The observation with SEM of worn surface morphologies has shown that microcutting, scratching and microploughing processes are the main mechanisms of wear during slurry erosion tests.

Recent experiments were performed on different steels at room temperature, in exactly the same experimental conditions, with recording of mass-loss measurement obtained with a microbalance after the test. The studied steel specimens were behaving almost similarly, with exception of composite with higher hardness value. The erosion resistance was higher for materials with higher hardness. Based on the present investigation, the following conclusions could be written as following:

- The material C (Cr_3C_2-Ni) had highest resistance in slurry conditions than other tested steels.
- The specimen 6 (16Mo3) had lowest resistance in slurry conditions among all tested materials.

It could be supposed that design of the slurry erosion tester will require new improvements in the future since the demand toward testing in more aggressive conditions is growing and probably it will be required to test samples with other geometries (than currently used) as well. Nowadays technologies are developing rapidly and new solutions for improvement of slurry device are already available or emerging. Now, the improved device is satisfying all the demands of concurrent industry and significant disadvantages of developed devise are not yet observed.

One of the main observations of this study is that slurry erosion tester work is stable and work of device is more reliable than previously. The improvement of reliability of slurry erosion tester can be considered successful, because devise was working stable with 20 % concentration of silica sand slurry at 20 m/s during 3 - hour tests. Improved slurry erosion apparatus already was successfully used for two other customer’s orders as well. All expected enhancements were achieved and tests were performed with requested conditions.

KOKKUVÕTTE

Tänapäeval hüdroabrasiiverosiooni (lobrierosiooni) majanduslik tähtsus, tänu suurema kasutusele, on toonud kaasa palju uurimusi selles valdkonnas. Uuringud toovad kaasa hüdroabrasiivseadme disaini parendamise ja uuritava materjali kulumise põhimehhanismi arusaamise. Esitatud laboratoorse hüdroabrasiiverosiooni seadme arendamisprotsessi ülevaade aitab märgata masina töökindluse tõstmise protsessi. Enamik uuringutest on läbi viidud hüdroabrasiiverosioonitesti erinevate konstruktsioonide mõju uurimiseks.

Käesoleva magistritöö eesmärgiks oli TalTech-i laboratoorse lobrierosioonkatseseadme töökindluse tõstmine, sest katseseadme töö oli mõnikord ebastabiilne. Metallikanalid kulusid kiiresti, mis oli ebastabiilse töö põhjuseks kõrge kiiruse, abrasiivi osakese kõrge kontsentratsiooni ja pikaajalise testimise tõttu. Keraamilised kanalid olid integreeritud nende kulumise vähendamiseks. See täiendavalt suurendas usaldusväärsust, mida oli vaja agressiivseteks katseteks.

Uuendanud seade on loodussõbralik ja võimaldab säästa ressursse (vesi, liiv). Lobrierosioonkatseseade kasutab terve katse ajal sama abrasiivainet mis tsirkuleerib masina sees. Arvutused näitasid et ühe 3 h katse jooksul (tsirkuleeriva lobri seguga) on võimalik säästa (võrreldes ühekordse lobri kasutamisega):

- Liiva – 208,4 kg (tsirkuleeriva lobri seguga tarbitakse ainult 1 kg)
- Vett – 833,5 kg (tsirkuleeriva lobri seguga tarbitakse ainult 4 kg)

Ehk töötav lobri masin, tsirkuleeriva seguga, tarbib umbes 200 korda vähem liiva ja vett.

Pärast lobrierosioonkatseseadme arendamist viidi läbi proovimaterjalide testid, et hinnata masina käitumist. Läbiviidud katsed, 20 m/s kiirusega, 20 % liiva sisaldusega lobris ja 3 h kestvusega, näitasid et masin töötab nii nagu oli nõutud ja stabiilselt, ehk töökindluse tõstmine sai saavutatud.

Uuriti ka pinnase topograafia muutmist tekitatud lobri katse käigus. Uurimise jaoks kasutati skaneerivat elektroonmikroskoopi (SEM), kuid taseme tõstmiseks on soovitatav tulevikus uurida ka transmissioonelektronmikroskoobiga (TEM). TEM-mikroskoopi kasutatakse rohkem mikrostruktuuride detailsemaks uurimiseks näiteks: martensiidi piiride lagunemine, madala nurga tera piirid, dislokatsiooni struktuur ja plastilise deformatsiooni desorientatsiooni analüüs. Kulunud pindade uurimine SEM-is näitas, et hüdroabrasiiv erosioonkatsete ajal, peamised kulumismehhanismid on mikrolõikamised, kriimustused ja mikrodeformeerimine.

Katsed, mis viidi läbi erinevate katsematerjalidega toatemperatuuril samades katsetingimuses, võimaldasid registreerida massikadu laboratoorsete kaalude abil. Uuritud terase ja metall-keraamiliste komposiitmaterjalide tihedused olid peaaegu sarnased, aga kõvadus oli komposiitmaterjali puhul palju kõrgem. Erosioonikindlus on suurem kõvema materjali puhul. Katsetuste järeldusteks on:

- Materjalil C (Cr_3C_2-Ni) on kõrgeim kulumiskindlus lobri tingimustes kui teistel terastel.
- Materjali proovil 6 (16Mo3) on väikseim kulumiskindlus lobri tingimustes kui teistel materjalidel.

Lobrierosioonkatseseadme disaini saaks ka edasi tulevikus arendada. See on seotud sellega, et tavaliselt tootjatel kasvavad nõudlused, et materjal töötaks rohkem agressiivsetes keskkondades. Tänapäeval tehnoloogiad arenevad kiiresti ja on eeldatav, et uued seadme parandused toimuvad ka edaspidi, aga töös läbiviidud paranduste abil masin töötab nii nagu oli plaanitud ja puudused ei ole veel avastatud. Selle uuringu üks peamisi tulemusi on see, et hüdroabrasiiv (lobri) erosiooniseadme töö on stabiilne. Kokkuvõttes saab öelda, et eesmärk on saavutatud – lobrierosioonkatseseadme töötab stabiilselt ning töökindlus on tõstetud vajalike agressiivsete katsete tingimuste jaoks. Parandatud erosiooniseade on juba kasutatud kahe kliendi tellimisel. Arendatud masin töötas õigesti ja kliendid olid rahul katsetulemustega.

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