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MONITORING WEAR OF SPOOL VALVE IN FLUID POWER CONTROL SYSTEM

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ABSTRACT
Solid particles such as sand and wear particles contaminated in the hydraulic oil are considered the main cause of the wear of moving surfaces like spool valves and internal surface of hydraulic cylinders. The present work aims to specify the relationship between sand particles contaminated in the hydraulic oil and the wear mechanisms by examining wear particles retained by the oil filter disassembled from the hydraulic system. The photomicrographs of wear particles provided specific information about the severity of wear. The visual inspection of the surface of spool by optical microscope described wear mechanism, detected the transfer from one wear mechanism to the other and identified the effect of sand particles on the severity of wear.

It can be concluded that wear particle analysis for fluid power system gives specific information about system condition, where examination of the wear particle morphology will reveal the wear mode such as severe sliding wear and solid contaminants induced wear. During sliding of spool valve, abrasion can be considered the major type of wear. Abrasion leads to scuffing and scoring that may cause high increase in sleeve clearance. Besides, sand particles are critical cause of excessive spool wear. Proper design and maintenance of the filtration system is essential. The mechanisms that largely influence the wear in the spool and sleeve include abrasion, adhesion and scuffing as well as chemical corrosion. Both of these mechanisms can operate independently or together, depending on the operating variables. It was found that during system operation under severe dusty environment, the spool and sleeve are the most intensively worn parts.

KEYWORDS
Wear and sand particles, hydralic oil, spool valve, oil filter.

INTRODUCTION
Spool valve is critical component of the fluid power control system and machinery, [1]. There is increasing demand to study the effect of solid contaminants in the hydraulic oil on wear of the spool valve. It was observed that rapid failure of spool valve was caused by the usage of hydraulic oil contaminated by solid particles. Based on that observation, the relationship between solid contaminants and wear of spool valve was confirmed.

The two major types of wear of hydraulic spool valve are the erosive and abrasive wear, where erosive wear arises from the action of solid particles in the hydraulic oil when pass the control edge of a spool and remove the material. Then, the sharp-edged geometry of the control edge is rounded and the function of the spool valve is influenced significantly. While solid particles enter the gap between spool and sleeve or spool and housing, abrasive wear is prevailed and microgrinding of the surfaces proceeds to introduce expansion of the radial clearance between spool and sleeves.

The particle erosion in hydraulic spool valve was predicted, [2 - 7]. A numerical model was developed to simulate the erosion process and obtain the erosion rate and worn profile. The experimental and field data show good agreement with the model. The influence of particle size, differential pressure, spool opening and flow direction on the erosion rate and worn profile were discussed. As the particle size increases, the erosion rate firstly increases significantly and then reduces slowly. As the spool opening changes, the maximum erosion rate for small particles (10 µm) shows no remarkable change. So, for the spool valve used in the hydraulic servo system (in which almost all the particle diameters are under 15 µm), the influence of the spool opening can be ignored during the rough calculation of erosion rate. Furthermore, the shape of the worn profile is independent of the particle size, differential pressure, and flow direction. When the spool opening is small, the worn profile becomes more even as the opening increases. However, when the opening becomes larger, the shape of the worn profile is almost unchanged.

The mobile hydraulic system was monitored, [8], by a mobile inline particle contamination sensor to diagnose requirements of Condition Based Maintenance. It was concluded detection of metallic particulates, offers a reliable way to measure real time wear of hydraulic components. Solid contaminants affect the performance and life of hydraulic equipment, leading to the types of system failure such as clearance-sized particles interact with both sliding surfaces causing abrasive wear, [9]. Besides, contamination causes temporary resistance on the valve spool from moving. Then the catastrophic failure that happens suddenly when a few large particles or agglomeration of small particles cause complete seizure of moving parts. The main sources of contaminants in hydraulic systems are built-in contaminants, from manufacturing, assembly and testing of hydraulic components. In addition to that ingressed contamination often occurs due to insufficient sealing and filtration of the systems.

Condition monitoring based maintenance is usually applied, [10 - 16], to prevent the failure, hence equipment condition is assessed by inspection and diagnosis, and maintenance actions are performed only when necessary. Previous studies confirm that machine components, data acquisition from sensors, data extraction, transformation and analysis are all key aspects of condition monitoring based maintenance.

Wear particle analysis for hydraulic oils provides important information regarding system condition where the quantitative change in particle concentration and size distribution from established baseline values signals an abnormal wear mode. The wear of hydraulic system was studied by Ferrography, [17 - 22], in which hydraulic oil tests were developed for the determination of the wear particle generation rate and oil filter

efficiency. Sand particles can enter into the system through intake air, fresh oil and fuel. In addition, presence of big metallic wear and iron oxide particles in sizes up to 300 μm confirmed that load carrying capacity of the lubricant film is not enough and extreme pressure as well as anti-corrosion additives should be developed.

The present work monitors wear of the spool valve and discusses the effect of sand particles on the wear mechanisms by examining wear particles retained by the oil filter disassembled from the hydraulic system. The worn surface of the spool has been examined by optical microscope to describe wear mechanism and identify the effect of sand particles contaminated in the hydraulic oil on the severity of wear.

EXPERIMENTAL

Wear particles contaminated in the hydraulic oil were examined using optical microscope. The oil filter was disassembled from the hydraulic system, Fig. 1. The filter housing was opened. A square piece, 20 × 20 mm, of the pleated papers was cut and ultrasonically scrubbed in 50 ml of normal heptane to redisperse the particles for 30 minutes. Then the wash was filtered by 0.4 μm membrane. The material deposited on the membrane was considered to be the wear and solid contaminant as well as oxidation products. The membrane was washed by 50 ml of benzol to dissolve the oxidation products.

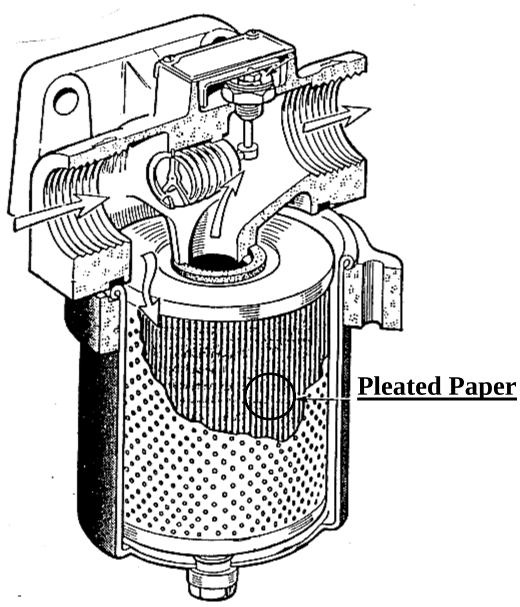

Fig. 1 The tested full flow oil filter.

Ferrography technique was used for the magnetic precipitation of ferromagnetic and paramagnetic wear particles from the hydraulic oil onto a thin glass slide called a Ferrogram substrate for examination by bichromatic light microscope. Ferrographic oil analysis includes an instrument for making Ferrograms and bichromatic optical microscope, Figs. 2 and 3 respectively, for visual inspection of solid particles on the Ferrograms. The oil sample taken from the lubricating oil of the engine was prepared by using three cc's of the oil and one cc of the fixer. The prepared sample is pumped

across the transparent substrate that is mounted at slight incline and affected by highly divergent magnetic field so that the magnetic particles deposit along the length of the substrate, Fig. 4. A wash cycle is used to remove the residual oil and cause the wear particles to adhere permanently to the Ferrogram.

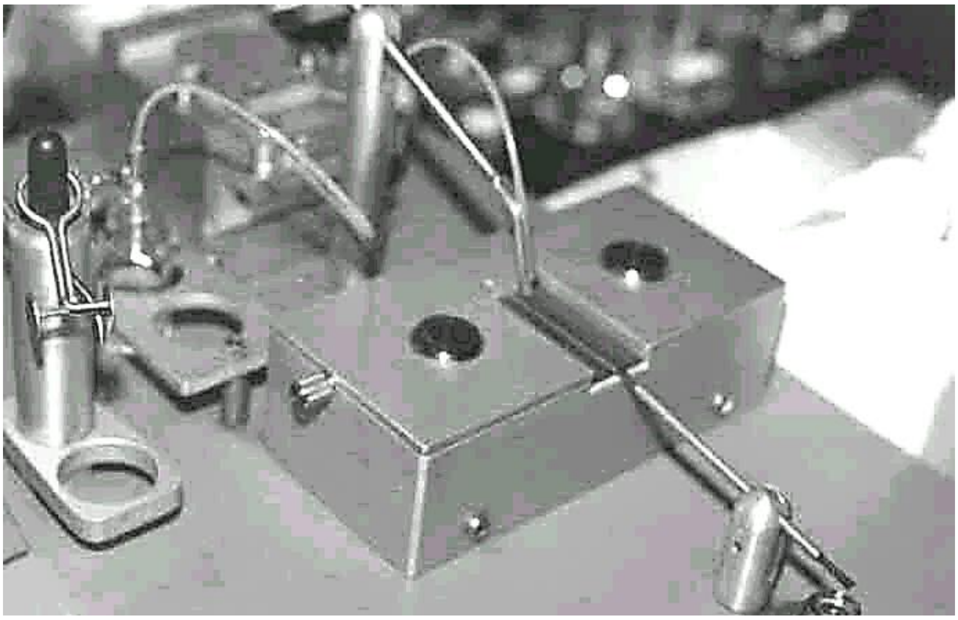

Fig. 2 Magnet of the Ferrography.

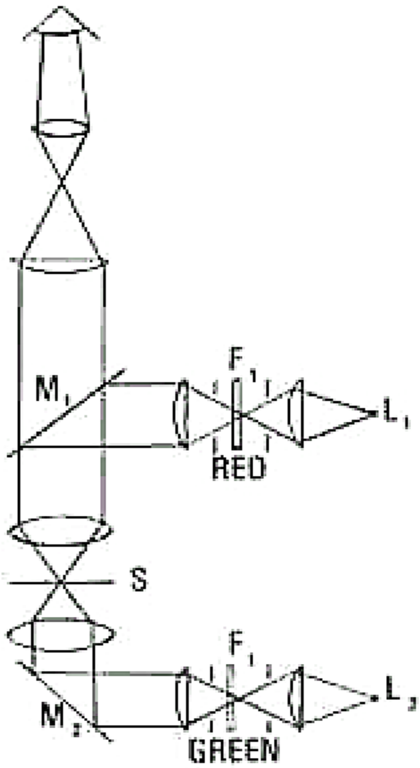

Fig. 3 Bichromatic optical microscope.

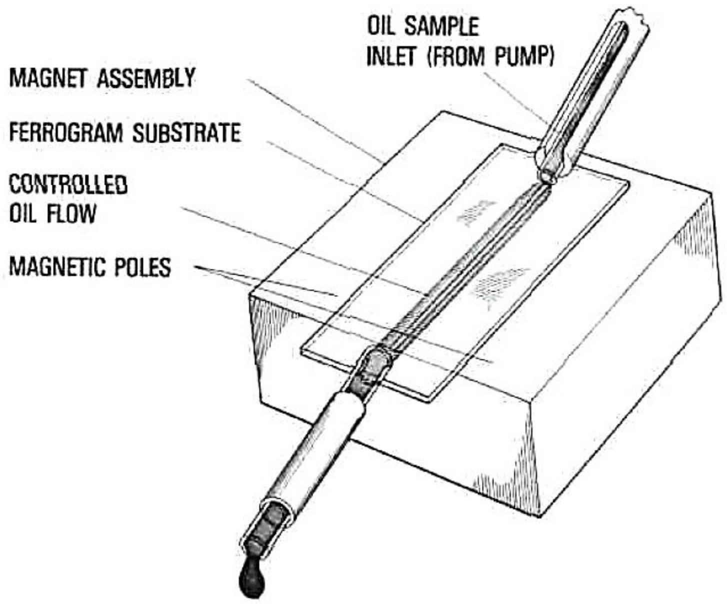

Fig. 4 Preparation of Ferrogram.

The worn surface of the spool valve, Fig. 5, was examined by optical microscope to inspect the growth of surface initiated cracks and their development in the deformed surface layer where the average thickness of the wear particles depends on the deformed layer. The acceleration of the wear may be from the abrasion action of sand particles into the sliding surface as result of the breakdown of the oil film or the inefficiency of the filtration system that could not withstand the severe dusty working conditions.

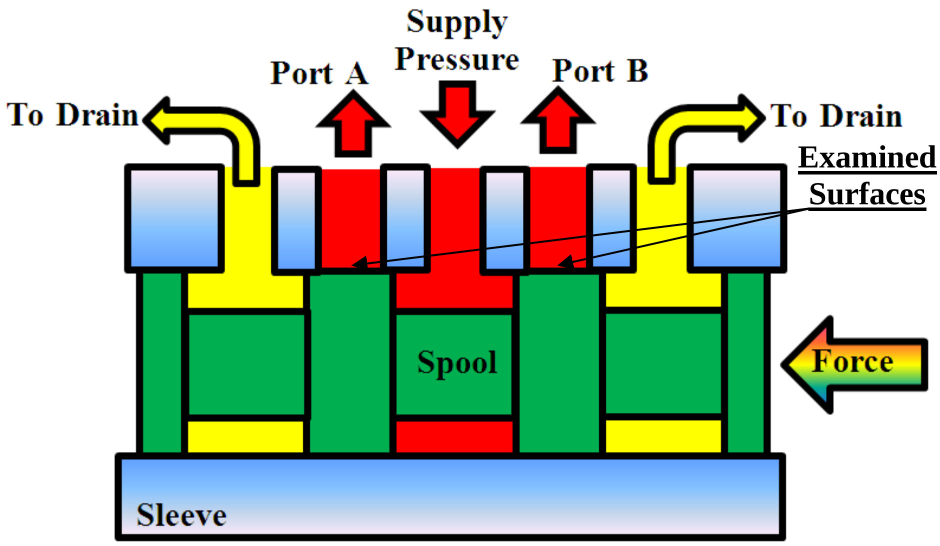

Fig. 5 Spool valve.

RESULTS AND DISCUSSION

Inspection of wear particles retained by the oil filter showed complete surface failure detected by very big wear particles. Wear particles were of surface striation indicating severe sliding. This would be occurred due to the fatigue wear of spool and sleeve surfaces as result of the repeated severe action of sand particles. Examples of different types of wear particles collected from the tested hydraulic oil are illustrated in Fig. 6. These types are steel wear particles resulted from excessive spool wear and bronze wear particles from sleeve surface failure. A low alloy steel wear particle is shown with striation marks. This particle was removed from alloy steel spool surface. Presence of surface striations describes the severe abrasive wear mechanism prevailed before the removal of such particle. A relatively big wear particle of cast iron might be removed from the casing of the gear pump. The brittle behaviour of the worn material is clearly shown. Presence of such particles indicates the scuffing wear of the sliding surface. Besides, dark colour wear particles are shown indicating their oxidation that was accelerated by the presence of water in the hydraulic oil. A big flat wear particle removed from polymeric components is shown. This particle is characterized by the presence of dark spots distributed on the surface. It might be removed from oil, air filter and/or seals. The size of the particle indicated the early failure of the polymeric components. Those observations recommend inspection of wear particles retained by the oil filter because it contains the most significant wear particles and solid contaminants, which characterize the mode of engine wear. Besides, oil filter removes and stores important information about particles generated from the rubbing surfaces.

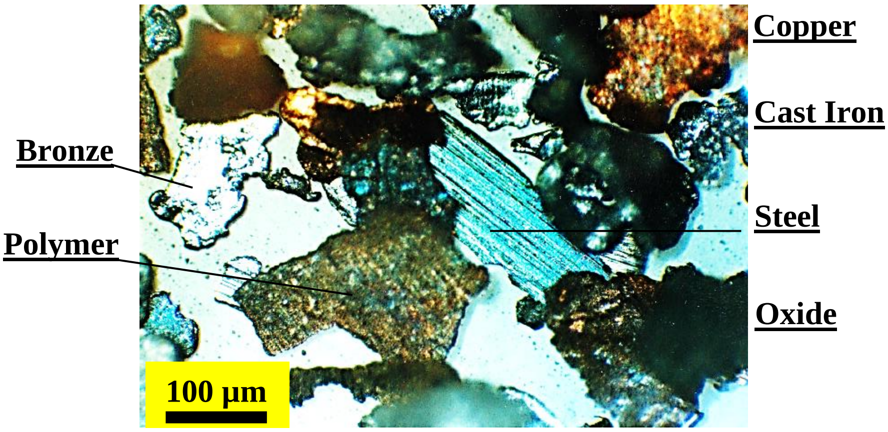

Fig. 6 Wear particles retained by the oil filter of the tested hydraulic system.

Solid particles contaminated in hydraulic oil and deposited on the Ferrogram are shown in Fig. 7. It is cleary seen that the photomicrograph containes excessive amount of sand particles. This observation confirmed that the system is suffering from abrasion, where abrasive wear particles are generated when the relatively harder materials (sand particles) abrade the softer one. The embedment of relatively hard particles such as sand and oxide wear particles in the softer surface (sleeve) produces very fine machining swarf, removed from the spool sliding surface. The common example of this mechanism is the embedment of abrasive particles in the surface of the sleeve then starts to abrade the spool. The size of those particles is ranging from 2 to

100 μm. They are considered as abnormal wear particles since detection of their massive generation signals the early failure of the component.

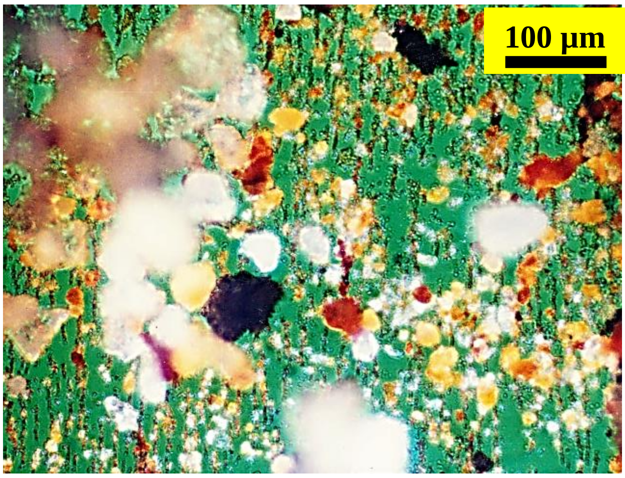

Fig. 7 Solid particles contaminated in hydraulic oil and deposited on the Ferrogram.

The worn surface of the spool valve showed region of heavily deformed cavities of different sizes caused by the indentation experienced by sand particles, Fig. 8. However, size of plastic deformation from sand particles indicated that the precise performance of spool valve cannot be achieved, due to the observed depth of deformation of the surface. It is shown that sand particles had been pushed along the surface, leaving a distinct wear groove in the spool surface. Presence of pits within the surface also suggests that sand particles damaged the surface.

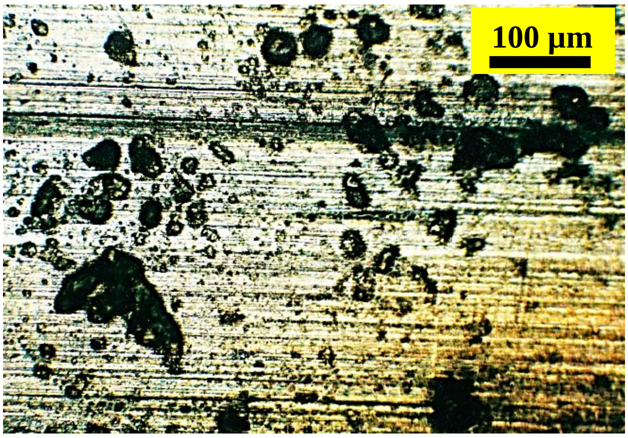

Fig. 8 Worn surface of spool valve influenced by scuffing and pitting.

The deformation of spool surface by hard asperity or abrasive particle can be described by rubbing, where the surface is plastically deformed forming two lateral ridges and front one that are pushed away by sand particles. When rubbing becomes more severe, the plastically deformed material is removed producing wear particles. The combined action of adhesion and abrasion between sand and sliding spool causes severe plastic deformation, Fig. 9. Ploughing of the matrix is displayed in the photomicrograph.

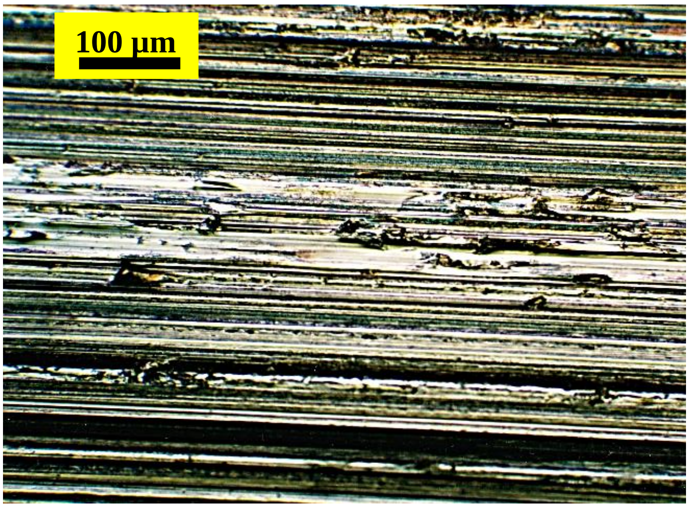

Fig. 9 Severe action of sand particles in the spool surface.

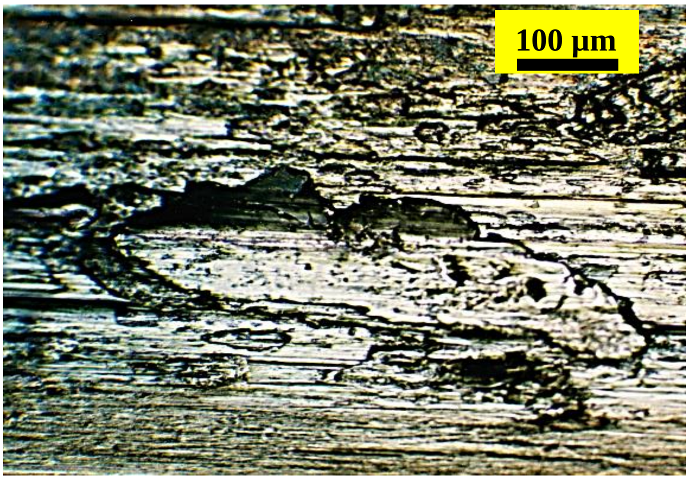

Fig. 10 Scuffing of the spool surface.

Sliding combines shear stress to the normal stresses and consequently increases the probability of plastic flow and fracture of materials in the contact region. Material in the softer asperity deforms to a certain limit then a crack extends across the asperity producing loose wear particle, Fig. 10. Scuffing of the surface revealed the flow of the material around the scuffed area. The mechanism of the generation of wear particles is explained on the basis of the growth of surface initiated cracks when the sliding planes

of weakness in the material become distributed parallel to the surface by repeated deformation process. Also, it was concluded that fatigue wear during sliding is caused by the crack development in the deformed surface layer where the average thickness of the wear particles depends on the thickness of the deformed layer. The acceleration of such wear may be from the presence of sand particles as well as inefficient filtration of the hydraulic system that could not withstand the severe dusty working conditions.

During sliding of spool valve, scuffing can be considered the major type of wear caused by the fatigue failure of the sliding surfaces. This leads to metal to metal contact, causing local welding between the spool and the sleeve. Scuffing of spool surface may occur due to sudden increase in load and speed. It can also occur when the lubrication conditions deteriorate. Scuffing may cause spool seizure or high increase in sleeve clearance. The main factors that influence wear of spool valve and sleeve are speed, temperature, load, sand contaminants, corrosion, surface finish and quality of the hydraulic oil. High temperature causes wear by deteriorating the lubrication of spool surfaces. Lower temperatures, too, cause significant increase in the wear of spool and sleeve due to the corrosion caused by condensate that carries corrosive products. Sand particles are critical cause of excessive spool wear. Proper design and maintenance of filter equipment is essential. The surface finish of spool and sleeve is remarkably affecting scuffing wear. The mechanisms which largely influence the wear in the spool and sleeve include adhesion, scuffing and abrasion as well as chemical corrosion. Both of these mechanisms can operate independently or together, depending on the operating variables. It was found that during system operation under severe dusty environment, the spool and sleeve are the most intensively worn parts.

CONCLUSIONS

- **Inspection of wear particles retained by the oil filter showed complete surface failure detected by very big wear particles. Wear particles were of surface striation indicating severe sliding. This would be occurred due to the fatigue wear of spool and sleeve surfaces as result of the severe abrasion of sand particles.**
- **The tested hydraulic oil contains excessive amount of sand particles. This observation confirmed that the system is suffering from abrasion. The size of those particles is ranging from 2 to 100 μm. They are considered as intiative of the abnormal wear particles since detection of their massive generation signals the early failure of the component.**
- **The worn surface of the spool valve showed region of heavily deformed cavities of different sizes caused by the action of sand particles. However, size of plastic deformation from sand particles indicated that the precise performance of spool valve cannot be achieved, due to the observed depth of deformation of the surface. Presence of pits within the surface also suggests that sand particles damaged the surface.**

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