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THE USE OF MAGNETIC COERCIVITY METHOD TO DIAGNOSE CRANE METALWARE

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Abstract. The recent problem of estimating the residual life of metal structures for handling equipment is actual, since more than 90% exhausted its regulatory resources. The current paper proposes an approach to solve this problem by using the coercive force. It is shown that in order to determinate damage of dangerous element of crane it is needed to know not only a coercive force but also a stress. Mathematical model is proposed to determine the damage of metal ware.

Keywords: residual life, handling machines, coercive force, fatigue damage of metal.

1. Introduction

The exploitation of handling machines with expired service is the most urgent problem for operators and their organizations (Gąska, Pypno 2011; Moskvin 2007; Vernon *et al.* 2004; Gartsman *et al.* 1998, etc.). Park handling equipment is hopelessly aging and purchase of new machines are making with single samples. Such situation exists in almost all Post-Soviet States as a result of violations of the centralized supply of new cargo handling equipment at ports and on the enterprises of the country. Only in Ukraine, from 95 thousand operated handling machines, registered with Derzhgirpromnaglyad (in Ukrainian – *Держгірпромнагляд України – Державна служба гірничого нагляду та промислової безпеки України – Держгірпромнагляд України – http://www.dnop.kiev.ua*), over 68 thousand have developed their own regulatory resource. According to the expert technical center of the gantry crane DIALAB (*http://www.dialab.od.ua*), average age of cranes in the ports of Ukraine is 26.3 years, the average degree of deterioration of the park in the industry – 95.2%. The most worn park cranes – in Ilyichevsk Commercial Sea Port (average age 32.3 years); the youngest – in the Yuzhny Sea Port (average age 15.6 years). The average age of cranes in the Sea Port of Mariupol is 23 years, which is twice their standard life. This situation is exacerbated by the fact that the company did not buy a new cargo handling equipment, as previously used. Thus, according to Derzhgirpromnaglyad in Ukraine in 2007, out of 100 cranes purchased by construction companies, only 18 were new. Fundamental change in the next decade is not expected, since the replacement of all handling equipment with an expired service to the new – a serious problem that requires huge investments in the industry.

2. Statement of Research Problems and a Technique of Their Decision

Further operation of cranes with an expired service without proper justification is in increased risk of emergency situations and is not allowed according to Rules of Installation… (НПАОП 0.00-1.01-07). Due to the lack of renewal of the handling equipment it becomes necessary to bring handling machines into operation, which exhausted their normative life. Such decisions must be justified, after expert survey and a full technical examination. Due to the fact that the design of crane steel was laid to significant safety factors, the dominant defect is the loss of physical properties of metals (embrittlement, changes in the endurance limit, yield strength, reduction of impact strength, etc.). To determine the extent of degradation of the physical properties of the metal used destructive methods of control, tests of samples taken from dangerous metal sites (Школьник 1978). Mentioned method has significant drawbacks: a violation of the integrity of the metal, weakening of dangerous places by repair welding, the additional costs for repairing and so on. As an alternative method for destructive testing which can be proposed in recent years is the methods of nondestructive testing: the control of the coercive force, acoustics, emission control, control by setting the hardness of the surface layer of metal and so on. The main requirement for the application of any parameter during the nondestructive testing is its large, monotonic change in the accumulation of damage. Known to date research (Lebedev *et al.* 2002; Болотин 1984; Пустовой 1987; Котельников *и др.* 2004; Лебедев *и др.* 2002; Петрова 2009; Прохоров 2010, etc.) have the following disadvantages:

- virtually no research grades of steel VSt3sp5 (ВСт3сп5) for changes in the process of cycle fatigue indicators such as coercive force, hardness, coefficient of variation of hardness. However, most of crane's metalware, issued before the early 1980's, were made of this;
- study to determine the dependence of the coercive force, hardness, and its scattering depending on the duration of use did not take into account the levels of stress in the test facility, and investigated according to the life of the property, developments in the duty hours and so on (Петрова 2009);
- some studies were performed on samples that were tested in a zone of low-cycle fatigue, while the metal cranes working in the area of multicycle fatigue (Прохоров 2010).

2.1. The Analysis of Existing Scientific Research to Assess the Current State of Metal and Prediction of its Residual Life

Current diagnostic methods can be divided into two major groups – the destructive and nondestructive testing (Amrane, Sidoroff 2011; Petkevičius, Volkovas 2011; Yasniy *et al.* 2011; Stonkus *et al.* 2009, 2011; Leonavičius *et al.* 2010; Kah *et al.* 2009; Kudzys, Lukoševičienė 2009; Juodvalkis *et al.* 2009; Jakušovas, Daunys 2009; Janutėnienė *et al.* 2009; Taylor, Hoey 2009; Caddemi, Morassi 2007; Forsyth *et al.* 2007; Moskvin 2007; Vernon *et al.* 2004, etc.).

Destructive testing methods require excavation of the metal from dangerous places of crane's metalware with the subsequent manufacturing samples for testing (tensile, impact toughness, fatigue, etc.).

Methods of nondestructive testing studies suggest metal without recesses of his metalwork.

For the diagnosis of handling machines is more appropriate nondestructive testing, since after his execution metalwork does not require any repair welds, which weaken the metal structure. And one more important aspect is that it needs rather many sample for performing tests (for example, to construct the fatigue curve of the metal should be 30÷45 samples). In this case, it might happen that you need to cut all crane's metalware for preparing samples and this is impossible from a practical point of view.

The main drawback of the most current regulations at the moment for assessment and determination of residual life of metal structures and for handling equipment is the use of such physical and mechanical properties of the metal, whose definition is carried out only by destructive testing, for example – testing of samples of metal handling machine tension, cyclic strength, toughness etc. (Березин 1990).

At the present time to determine the technical state of the object using the physical and mechanical characteristics, which vary for the same metal depending on operating conditions include (Карапаш и *др.* 2004):

- mechanical: elastic modulus, shear modulus, Poisson's ratio, tensile strength, yield strength, tensile strength, etc.;
- physical: density, anisotropy, crystallinity and crystal size, resistivity, permittivity, permeability, etc.

There are some methods which are distinguished for determining the physical and mechanical properties – acoustic, electromagnetic (eddy current), radiation, magnetic, electrical, etc.

The main disadvantage of direct application of these techniques is the need for initial information about the location of the most intense metal valve assemblies to assess their condition, the use of expensive devices for work, bringing to the work of highly skilled engineering staff.

The main directions of research on assessment and prediction of residual life of welded steel structures are:

- the method of witness samples;
- the method of integral-type sensors;
- magnetic method (of the coercive force);
- the method, based on the experimentally established relationship between the scattering of the hardness of the metal and the degree of damage.

2.1.1. The Method of Witness Samples

Samples from the same metal as the metal structure itself, mounted in the most loaded nodes. In this case, damage of the samples collected faster (due to the structural characteristics of the sample) than in the base metal. Faulty witness samples indicate accumulation at the site a certain degree of damage (Конаков, Колмаков 2006).

By erosion we mean the value that determined by the formula:

$$D = \frac{n}{N},$$

where: n – the current number of loading cycles; N – number of loading cycles until a failure.

Such a definition corresponds to a linear damage accumulation theory. In this case, the initial moment of time D = 0, and the final D = 1.

2.1.2. The Method of Integral-Type Sensors

Same as above, but the role of witness samples carry a film of lead or aluminum (Москвин 2007; Троценко *и др*. 2006), which are mounted in the most dangerous areas of metal. As a result of microshear leading to the accumulation of fatigue damage, the metal sensor in the sensor leads to irreversible deformation, a change in the microstructure of the sensor. The accumulation of damage in the sensor is much more intense than in the metal of metal-structure. As metal films assess the extent of damage accumulated in the metal. The main disadvantages of this method are:

- to assess the residual life of metal needed to sensors mounted before the operation design. In reality this is not always possible and therefore the time between metal until the installation of the sensors is determined based on the assumption of uniform intensity of use, which is rather an exception than the rule;
- to be able to draw conclusions, the sensor must have worked together with the steel structure 8÷12 months, thus depriving the method efficiency;
- sensor glue on pre-stressed metalwork and in this case, the laws stress variation for the sensor element and the metal on which it is mounted, will differ by a constant.

2.1.3. Magnetic Method (of the Coercive Force)

It is based on the experimentally established dependence between the values of coercive force in the metal and the degree of damage to the metal. The method is relatively new but rapidly developing. Prochorov (Прохоров 2010), was one of the first researchers who investigated that method of the steel grades used in crane metalwares. What is more, the dependence of the parameters of the hardness in the surface layer in welded specimens and the coercive force of the accumulated damage to steel 09G2S (09Г2С) was analyzed in his paper. Metal samples were prepared in microsections. Since in most types of metal elements are connected by an automatic welding, the samples were made from two sheets connected by a butt weld with its subsequent processing. For the full study examined the properties of the base metal, metal heat-affected zone and seam metal itself. For damage accumulation in metal applied static tensile test and cyclic loading in low cycle fatigue. The degree of accumulated damage was estimated by the ratio of the actual number of cycles and the number of cycles to failure.

As a result of experience, we found that there is a decrease of coercive force in all three zones in the accumulation of damage in the metal.

The results obtained are certainly of value, although they were obtained for the field of low-cycle fatigue. However, their application to the field of industrial machines requires further investigation, since the steel handling machines operate in the zone of high-cycle fatigue under the plan, samples were cut across the rolling, but according to Standard GOST 7564-97 (ГОСТ 7564-97) sampling for determining the mechanical properties must be carried along rolled steel, which significantly affects the results of the experiment.

One of the recent work in this area is (Котельников 2006), the main provisions which are furnished in the Guidelines MV 0.00-7.01-05 (МВ 0.00-7.01-05). To assess the extent of damage of the metal is suggested to use coercive force (see the Standard GOST 30415-96 (ГОСТ 30415-96)), because it is sensitive to changes in the structure of the metal. It is shown that the coercive force depends on: the dislocation density, grain size, the number of inclusions per unit volume of plastic deformation, internal stresses. Achieving the coercive force certain value (depending on the brand of metal) testifies to its limit state. The error associated with the spread of the chemical composition of the steel makes for St3 ± 0.3 A/cm for 09G2S – ± 0.5 A/cm (Котельников 2006). Unlike other methods (the method of strain measurement, the method of photoelasticity, etc.), the magnetic diagnostics by the coercive force reacts to the restructuring occurring residual stresses, mounting tension. As a result of accumulated damage, the coercive force changes its value throughout the life of a structural element, regardless of the conditions and methods of loading. It can be considered that satisfactory weld connection status can be evaluated according to criteria of the magnetic control of the base metal. Magnetic control is accomplished at a distance of 10 to 15 mm from the weld seam and its width must be less than the distance between the poles of the sensor.

With a wide weld control the coercive force is carried out separately – first by the base metal at a distance of 200 mm from the seam, then the immediate vicinity of the weld and finally at the weld centerline. It is shown that the initial value of coercive force in the weld is higher than in the base metal. However, in the base metal damage accumulation processes run faster and destruction occurs at the same values of coercive force.

Disadvantages:

- the coercive force has a maximum value in the direction of principal stresses. In this case, before work is necessary to know in advance the principal axes of stress in the experimental field. The principal axes can be determined either by calculation or experimentally (gradually turning the poles of a magnet) and, for example, a method based on the change in the scattering of hardness with increasing damage in the metal does not have this drawback, since based on a scalar parameter;
- do not take into account a significant change in coercive force depending on the thickness of the metal under consideration, which requires a table to bring the values of coercive force, resulting in different thicknesses, to an equivalent value;
- the main type of testing, which subjected the samples – static stretching. This type of loading is not specific to crane steel structures. Tests to detect the variation of coercive force in fatigue tests of samples made in insufficient (4 samples for the four abstract modes of loading).

Option of coercive force is sensitive to the residual and assembly stresses. This fact is valuable, since no computational methods, nor the majority of experimental methods (e.g. strain gauge experiment) can not determine the existence of a metal, residual stresses and their magnitude.

According to the Guidelines MV 0.00-7.01-05 (MB 0.00-7.01-05), the coercive force in the accumulation of damage must rise, but the results of Prochorov (Прохоров 2010) contradict this assertion, that raises the need for more research in this direction.

2.1.4. The Method, Based on the Experimentally Established Relationship Between the Scattering of the Hardness of the Metal and the Degree of Damage

Interest to change the parameter of hardness as a result of accumulation of fatigue damage in metal came from researchers for a long time (Булычев, Алехин 1990; Марковец 1979). Ivanova (Иванова 1963) summarizes the scientific researches undertaken in this direction in her paper. The following describes the major trends identified by hardness:

- with the increasing number of cycles the amount of metal in which a change in the hardness increases, while the grains, which are the maximum stresses, the hardness increases. Then the increase in hardness in the hardest place stops and begins to decrease. The hardness of the same metal in neighboring volumes, where the operating voltage is less continues to rise. With further increase in the number of cycles the hardness in the amount of metal with a maximum voltage drops to its initial value and continues to decrease monotonically;
- hardness of the samples brought to failure under various cyclic stresses are very similar to each other. It should be noted that if the measure directly to the hardness of the fracture surface, the differences in the values of firmness of the samples that were destroyed during cyclic and static loading, cannot be detected;
- hardness measurements of samples subjected to cyclic bending in asymmetric cycle, showed that the distribution of hardness along the sample length remains the same as for the samples tested under symmetrical load. Increasing the amplitude of cyclic stress at a constant number of cycles leads to qualitatively the same changes in hardness, which increased the number of cycles at constant amplitude cyclic stress.

Can be expected that the hardness of the surface layer of metal is an objective indicator that does not depend on the amplitude of the stress, mean stress cycle, the type of loading (tension, compression, bending and twisting), and varies in proportion to the accumulated damage in the metal.

The dependence of the change in the hardness of the damaged metal has a rather shallow part of a range of cumulative damage from 0.7 to 1. If you use this relationship to determine the state of metal it can be considerable error in estimating the degree of damage accumulation in metals using the experimental dependence in the above range of damage. However, this part of the dependence is of great interest in assessing the residual life of steel handling machines with expired service life.

One of the recent studies (Lebedev *et al.* 2002; Лебедев *и др*. 2002) on the behavior of the hardness of the metal showed that the hardness method, which is applied to evaluate the technical state (qualities) of the metals is insensitive (the dependence is not always unambiguous) to transform the structure of the metal in the process of use. To quantify the effect of decreasing the homogeneity of the metal is it suggested to use the coefficient of homogeneity and coefficient of variation for measuring the hardness (Lebedev *et al.* 2002; Лебедев *и др*. 2002, 2003; Петрова 2009). These options allow you to evaluate the degree of damage of the metal on the first and second stages of destruction – i.e. before the development of the main crack.

Estimated damage of metal deformation loosening (irreversible increase in the pore) were based on data from other researchers who have identified an increase in volume of the metal with increasing cumulative damage to it. During the experiment, measurements were made of hardness of the surface layer of metal pipes, which were operated for a long time and a similar new metal pipes. It was found that:

- if the service life under cyclic loading is as in the case of prolonged static loading, there is an increase of hardness;
- the hardness varies little with the accumulation of damage in the metal. More addictive shows the coefficient of homogeneity (m), which is a parameter Weibull distribution. Lower level m corresponds to the low degree of damage and vice versa.

The main disadvantages in terms of applicability to the diagnosis of metal-structure port handling machines are the following:

- investigated steels VSt3sp5 (ВСт3сп5), 20HN3A (20ХН3А), 17G1S (17Г1С), while the majority of crane's metalware since 1980 are made of 09G2S (09Г2С);
- much attention is mainly paid to the static tests, the results of which determine the relationship between the coefficient of variation of Vickers hardness and the erosion of the metal. However, the handling machines work in cyclically varying loads;
- research carried out regardless of the level of operating stress amplitude, while it is known (Collins 1993) that different levels of operating stress amplitude correspond to the different laws of damage accumulation.

The most promising are the last two methods of control – the hardness of the surface layer of metal (either parameter computed on the basis of hardness) and the parameter of coercive force. However, as shown in this chapter, many aspects of their application are still not fully understood.

The main requirement for choosing this property is a good correlation between its change and the accumulation of damage in steel structures. The developed approach tries to evaluate the possibility of further exploitation of the reloading machine with outdated, based on the real state of the metal in hazardous areas, while maintaining their integrity. This will help to divide any handling machinery into two groups: cranes with a large residual resource, which can be operated on; and cranes, which have exhausted their resources in full and further operations will lead to accidents only (Fig. 1).

Recently, for the diagnosis of crane metal it is widely distributed magnetic method for setting the coercive force (H_c). Existing guidance on the definition of metal state on the basis of the values of the coercive force indicates the difference of the laws change H_c depending on the level of stresses acting in the test cell. However, the results of experiments satisfy only for the four levels of stress (Guidelines MV 0.00-7.01-05 (MB 0.00-7.01-05)).

The purpose of this paper is to propose a model by which you can find the variation of coercive force at an arbitrary level of stress. It is based on data from the experiment in the Guidelines MV 0.00-7.01-05 (MB 0.00-7.01-05).

If the expert examination of metal gets into a dangerous element of the value of the coercive force H_c = 4 A/cm, then this information is not sufficient to assess the extent of accumulated damage. For uniqueness it is necessary to know the stresses acting in the element, since a high stress (350 MPa), the acting stresses the value of H_c = 4 A/cm corresponds to 95% of the residual resource (Fig. 2), and low stress (200 MPa) – 10% residual resource.

3. Solving Tasks Results

For the convenience of the subsequent arguments we construct the dependence of $H_c = f(N)$ in the coordinates of H_c, affection (D) (Fig. 2). By D we mean the damage accumulated in the metal under the action of a certain number of cycles (Voyiadjis, Kattan 2005; Lee *et al.* 2004), but for simplicity we use a linear hypothesis for summation of damages in the determination of this parameter: $D = n/N$. According to the linear hypothesis of damage accumulation, n – the current number of loading cycles; N – number of loading cycles until a failure

The experimental data was used on the basis of approximating polynomial. Approximation was carried out by least squares. Fig. 3 shows a graph of the approximating polynomial and the experimental points.

Fig. 1. Gantry crane accident

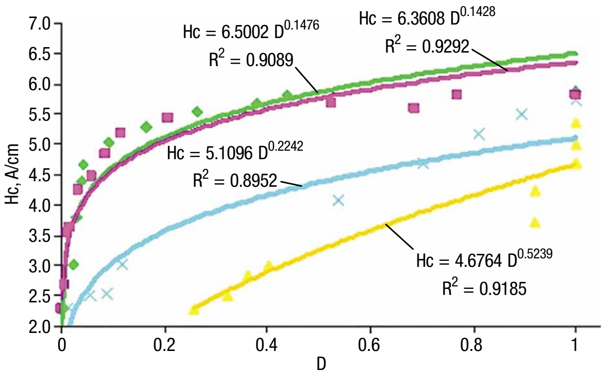

Fig. 2. Dependence of the parameter H_c from damaged metal sample: green – 350 MPa; purple – 300 MPa; turquoise – 250 MPa; yellow – 200 MPa)

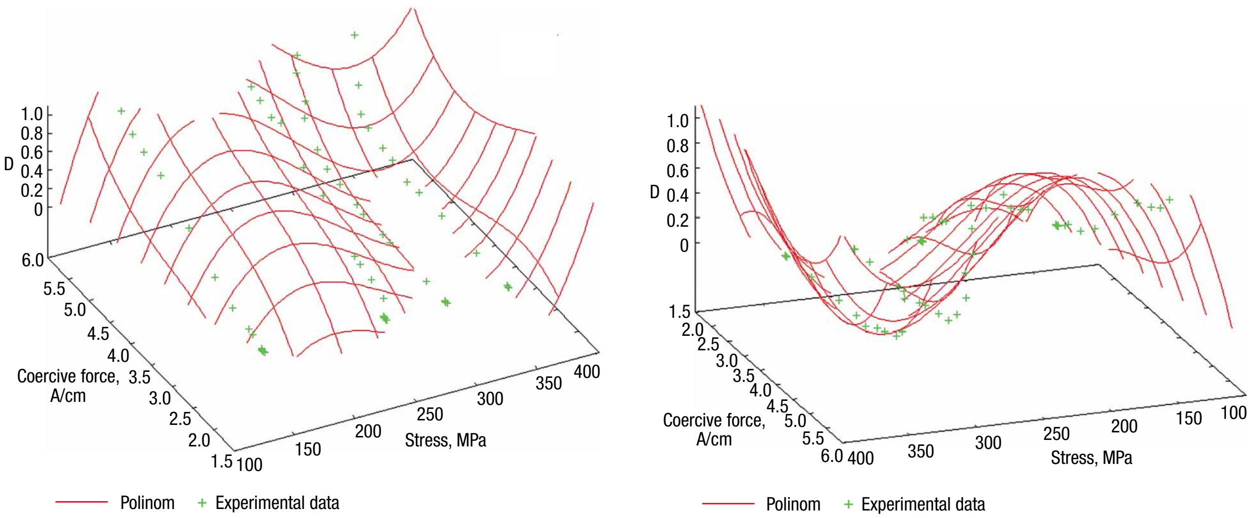

Fig. 3. Approximating curve and the experimental data

The analytical expression for the polynomial has the form:

$$D(\sigma,H_c)=0.705418\cdot10^{-6}\cdot\sigma^3+0.0586377\cdot H_c^3-1.17296\cdot10^{-5}\cdot\sigma^2\cdot H_c+0.00042347\cdot\sigma\cdot H_c^2+0.00131768\cdot\sigma\cdot H_c-0.000511574\cdot\sigma^2-0.759132\cdot H_c^2+0.125177\cdot\sigma+2.96663\cdot H_c-13.3748.$$

Knowing the stress in the metal site and the value of the coercive force it can determine the degree of accumulated fatigue damage. With this mathematical model, it is possible to predict with 95% probability that the accuracy of the damage will be within 30% of the absolute error. Error estimation was done using Pearson's criteria.

Due to the large relative error in determining the damage of the most loaded metal sites it is invited to use the option of coercive force for rapid assessment of the damage of the metal and the containment of dangerous places. After finding the dangerous places to be adopted more accurate (and usually less productive), another method, for example, the scattering of hardness can be used.

4. Conclusions

1. Standard approach to determine the residual life of metal to date does not exist, and existing techniques have several significant drawbacks:
   - most approaches based on application of destructive testing, which entails a violation of the integrity of the investigated steel, the need for subsequent repair of the element from which the hollow metal, the additional time and expense;
   - virtually, there are no studies carried out about the metal constructions produced fromVSt3sp5 (ВСт3сп5) steel in order to evaluate the changes in the coercive force, hardness and hardness of the scattering in the high-cycle fatigue. However, it is known that the main load-bearing elements of metal handling equipment are produced from this material;
   - in studies to identify these dependencies are not taken into account the stresses that existed in the test facility;
   - tests were conducted in the area of low-cycle fatigue.
2. Parameter used to evaluate the residual life, should refer to non-destructive inspection methods and meet the following requirements:
   - parameter should vary in proportion to damage the metal;
   - parameter must be monotonically increasing (decreasing) and a rather 'strongly' depend on the metal accumulation of damage.
3. A review to date of scientific papers on assessing the residual life of metal-structure of port handling machines for the study were selected indicators such as the hardness of the surface layer of metal, which characterizes the resistance to plastic deformation of the local volumes of metal and the coercive force.
4. Upon review of the work it was turned out that there was conflicting information about the behavior of the parameter in the coercive force. According to some data, it increases in the accumulation of damage, according to other sources – is decreasing.
5. To overcome this kind of ambiguity it is necessary to hold a series of experiments to obtain qualitative and quantitative relationships between the studied parameters and damage accumulated in the metal as a result of cyclic loading, since, according to research carried out by Gohberg (Гохберг 1969) for handling equipment, heavy and very heavy modes, the reliability of metal structures by the resistance of fatigue.
6. The dependence of the coercive force of the number of cycles that used handling equipment is not unique and varies depending on the magnitude of maximum stress cycle, operating in dangerous sites.
7. To estimate the residual life of metal structures for lifting equipment it is necessary to know the variation of coercive force at each level of stress.
8. The model, which can be used to find the extent of the damage site on the metal values of stress and the coercive force.
9. Due to the large error in determining the status of hazardous metal components in the parameter of the coercive force is proposed to use this method to find the most dangerous elements of crane steel structure and rapid diagnosis of their condition. For more accurate determination of damage accumulation in dangerous sites can be used such techniques as a method of scattering of hardness, etc.

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