Study on fatigue resistance of low alloy steels with Mo and Cr

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Abstract. This paper presents, based on a case study, the analysis of the factors that influence the mechanical cyclic fatigue resistance of two grades of low alloy steel with Mo and Cr. It was studied the fatigue behavior in real operating conditions of some active elements manufactured from the two low-alloyed steel grades, elements that are equipping some farm implements. Using the fractographic analysis, optical microscopy and scanning electron microscopy, were analyzed the samples that carried away because of the fatigue fracture. On samples taken from the two brands of low alloy steels with Mo and Cr were performed tempering thermal treatments that modified the structure, in order to improve the operating characteristics. The effect of those thermal treatments was initially observed by microstructural analysis of metallographic prepared samples (by polishing and chemical attack using nital reagent), that revealed a troostite type structure. On the heat-treated samples were determined a number of mechanical properties: hardness, impact strength and tensile test. There was observed an improvement of the impact bending strength for both alloys and a tensile behavior that favors increasing resistance to fatigue.

1. Introduction

In the present study was analyzed the fracture of some active elements (spiral spring tine D45) which equips cultivator Amazone CENTAUR 6001. The cultivators are agricultural machinery which is used to process the earth after plowing, in order to crumble, aerate, mix and level him and extirpate weed roots, without overturning the furrow.

In this case, the Amazone Centaur 6001 cultivator is a trailed machine for total processing, consisting of an equipped grower with active organs with a lance form, fixed on elastic supports. During the working process, on the active organs acts the soil resistance R, balanced by the vectorial sum of the tensile force P, applied at a suspension point of the knife and by the normal component of weight Gn, applied to the systems center of gravity consisting of knife, arm and support.

In practice it appears that many active parts of agricultural machines suffer permanent damage or break after a certain operation period although they subject to far more reduced stress related with the yield stress $\sigma_C$ or material breaking limit $\sigma_R$ against which were calculated to resist [1,3]. This occurs because the loads the active bodies are subjected don’t have a generally static character. The loadings are produced after one alternant symmetrical cycle ($\sigma_{m} = 0$), and the active elements are damaged when stresses exceed the limit of the material fatigue strength $\sigma_{f}$. In practice are taken into account...
also the effects of stress concentrators, the parts dimensions with respect to the specimens and surface processing quality.

For the beginning, we analyzed the fractured areas of the elastic elements (see fig.1.a – fracture initiation marks) and we observed the existence of a typical fracture aspect caused by fatigue upon complex alternating solicitations.

![Figure 1. Aspects of active elements fracture](image)

During a first stage of breakage ( "a" area, fig.1.b.) we notice the existence of a 4 mm crack in the piece depth, an area that, because of the relative movement between the contact surfaces, suffered a cold plastic deformation of the crystallites and, implicitly, has a shiny metallic aspect, as we can see in fig.1.c. The second area, as seen in fig.1.b ("b" area) and in fig.1.d indicates a second breakage stage with oxidized inter-cristalline fracture typical aspect. As we can see in fig.1.b ("c" position) and fig.1.e, the third area indicates the final breakage of non-oxidized surface with inter-cristalline fracture aspect.

In order to conclude on the possible causes of material fracture, it was analyzed both in terms of chemical composition (using an ARL 3560 spectrometer type) and microstructure (fig. 2 a,b). The examined steel fall into the category of heat treatable steel 42MoCr11 grade according to STAS 791-88 or 42CrMo4: 2007 (W 1.7225) grade according to EN 10083: 0.44% C, 0.33% Si, 0.93% Mn, 0.01% P 0.007% S, 1.07% Cr, 0.14% Ni, 0.23% Mo, 0.10% Cu, Fe balance.

Following the metallographic preparation of the sample taken from the fractured area by cutting, grinding, polishing and chemical attack by natal reagent, it was analyzed by optical microscopy (Leica microscope DMI5000) and scanning electron microscopy (Quanta 200 3D), the results being shown in figure 2 a, b.

The microstructural aspects shown in figure 2 a, b reveal the existence of a relatively large amount of retained austenite resulting from an incorrect heat treatment, with low tempering temperature. This structure significantly reduces the material fatigue resistance, which leads to multiple cracking and premature breaking premature by fatigue stress [4,5]. In figure 2b there are observed oxide inclusions and micro-porosities with spherical shape, which could lead to additional decrease in mechanical properties.

On samples drawn from the same material, were performed tensile tests on the MTS 810.24 machine and hardness tests with a universal machine EMCOTEST type M5C 030 G3.
It was found to obtain an elongation at break lower, of 9%, compared to the minimum elongation of 12% stipulated in the standard. It was also observed that the tensile strength is higher, with a value of 1599 MPa, higher with 500 MPa than the one specified in the standard. Yield is 1156 MPa, also with 256 MPa higher than standard requirements. The determined values indicate a smaller material plasticity and a greater tendency to crack during cyclic mechanical stress in operation.

Hardness test revealed an average hardness of 39.66 HRC, higher than the one specified in the standard for this steel grade, which lies between 20 and 30 HRC in heat-treated condition. This greater hardness lead to a lower elongation at break (decrease of plasticity) of 9% compared to the elongation of 12% stipulated in the standard.

2. Experimental procedure
The experimental procedure presented in this paper was conducted in order to observe the factors that influence the mechanical cyclic fatigue resistance of active elements that are equipping some farm implements, manufactured from low-alloyed steel grades.

For this purpose, we chose two steel grades, low alloyed with Mo and Cr, which chemical composition is presented in table 1.

3. Results and discussions
3.1. Hardness test
After the heat treatment procedure conducted as presented in Table 2, hardness tests were performed on a universal machine EMCOTEST type M5C 030 G3. We obtained the following results: $H_{1\text{medium}} = 34$ HRC, $H_{1\text{medium}} = 49.83$ HRC, $H_{2\text{medium}} = 22.72$ HRC, $H_{2\text{medium}} = 38.15$ HRC.

These values indicate that the samples with low tempering temperature have a higher hardness compared to samples with high tempering temperatures, with about 30% for sample 1 and by about 41% for sample 2, justified by the known effect of favoring the apparition of temper troostite of the high tempering temperature (phase with a lower hardness than the one of temper martensite). At low
tempering temperature, both alloys hardness is higher than the one obtained at high tempering temperature, being noticed a higher hardness for the alloy 1 (0,48% C compared to the 0,3% C).

3.2. Tensile test
The traction diagrams of the four samples were drawn using the MTS 810.24 tensile tests machine.

In figure 3 are comparatively presented the diagrams for two alloys obtained by heat-treatment with low tempering temperature. 1J alloy compared to 2J, as seen from the diagram, have similar maximum breaking resistance of about 1600 MPa. The alloy 2J presents an elongation at break higher than 11%, which justifies a better resilience behavior. A higher elongation is attributed to lower carbon and chromium concentrations, in case of the alloy 2.

The high tempering temperature has as effect an increase of breaking energy, a decrease of hardness and implicitly an increase of breaking elongation, which lead to an increase of fatigue resistance.

3.3. Tensile shock test
The appearance of the fracture surfaces of four samples made by the stereomicroscope method is shown in Figure 4. In the Table 3 are listed the damage values by mechanical shock energy results.

In order to analyze the effect of tempering temperatures on the behavior in operation of the two chosen steel grades, samples drawn from these materials have been subjected to tensile shock test on an resilience pendulum Tinus Olsen type, 406 model.

The appearance of the fracture surfaces of the four samples, made by the stereomicroscope method is shown in figure 4.

In table 3 are listed the values of mechanical shock breaking energies resulted during the tensile shock tests.

![Figure 3. Comparative traction diagrams of samples 1J and 2J.](image)

![Figure 4. Macroscopic aspect of fracture surfaces (40x): a) sample 1, b) sample 2, c) sample 1J, d) sample 2J.](image)

| Table 3. Mechanical shock breaking energies values |
|-----------------------------------------------|
| Mechanical shock breaking energy KV (J) | Sample 1 | Sample 2 | Sample 1J | Sample 2J |
|-----------------------------------------------|
| 52.015 | 65.908 | 12.301 | 21.888 |

It is observed that the mechanical shock breaking energy of sample 1 with high tempering temperature compared to the one of sample 1 with low tempering temperature is over 4 times higher.
The same trend of increasing the breaking energy, once with the increasing of tempering temperature is observed also in the case of the sample 2, where the ratio is more than 3 times higher.

One of the factors that influence the hardness growth and the decrease of breaking energy is the element carbon, as observed from the mechanical shock breaking energy values specified in table 3.

3.4. Cyclic fatigue test
The cyclic fatigue test was carried on the servo-hydraulic MTS model 824.10 equipment, using a alternating symmetrically cycle, at a maximum tension of 60% of the tensile strength Rm. We chose the alternating symmetrical cycle because it is nearest to the loading on the elastic elements studied in this paper. For this purpose were conducted successive tests at two different frequencies: 1 Hz to 5 Hz.

![Figure 5](image)

**Figure 5.** Loading-time diagrams generated at the cyclic fatigue test of sample 2 at: a) 5Hz, b)1Hz.

In figure 5 are presented the diagrams generated during the cyclic fatigue test in case of sample 2 at different frequencies, which failed after 141957 cycles comparatively with the case of sample 2J which failed after 122473 cycles.

3.5. Microscopic aspects
Samples subjected to heat treatment were analyzed in terms of microstructure aspects using both optical microscopy and scanning electronic microscopy, the images resulted are presented in fig. 6-9.

![Figure 6](image)

**Figure 6.** Microstructural aspects of sample 1, realized using:
 a) optical microscopy (1000x), b) scanning electron microscopy (3000x)

![Figure 7](image)

**Figure 7.** Microstructural aspects of sample 1J, realized using: 
 a) optical microscopy (1000x), b) scanning electron microscopy (3000x)
In case of sample 1 is observed on the image obtained by electron microscopy (fig.6.b) the formation of a troostite type structure. The observations are complemented by images obtained by optical microscopy (fig.6.a), where a large amount ferrite is visible (white areas) and also several areas with residual austenite.

On the sample 1J are observed both on the microstructures obtained by optical microscopy (fig.7.a) and by scanning electron microscopy (fig.7.b) the maintaining of martensite needles and especially the appearing of the bainite structure accompanied by residual austenite.

Figure 8. Microstructural aspects of sample 2, realized using:
   a) optical microscopy (1000x), b) scanning electron microscopy (3000x)

Figure 9. Microstructural aspects of sample 2J, realized using:
   a) optical microscopy (1000x), b) scanning electron microscopy (3000x)

Analyzing the microstructural aspect of the sample 2 (fig.8.a, b), we noticed the formation of an troostite structure with ferritic background and residual austenite areas, but with a higher amount of ferrite than sample 1, explained by the lower carbon content of the steel. In case of sample 2J is very clearly observed the martensite structure, especially on the secondary electron image (fig.9.b), while on the image obtained by optical microscopy (fig.9.a) are visible areas of residual austenite (with white color).

4. Conclusions
It is observed that the effect of high tempering temperature is visible in both types of alloys, in the sense of obtaining troostite structures that improve substantially cyclic fatigue behavior and resilience. The amount of ferrite observed in sample 1 compared to that seen in sample 2 is higher at high tempering temperatures, because of the lower carbon percentage of the sample 2.

Following the experiments carried out in this paper it was observed that the structures formed after the thermal treatment with high tempering temperature, troostite type with ferrite areas and residual austenite, shows higher breaking energies, smaller hardness and respectively higher fatigue resistance.

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