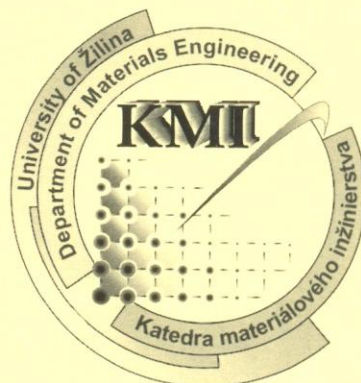


ŽILINSKÁ UNIVERZITA V ŽILINE
STROJNÍCKA FAKULTA
KATEDRA MATERIÁLOVÉHO INŽINIERSTVA



DEGRADÁCIA KONŠTRUKČNÝCH MATERIÁLOV 2013

XIII. vedecká konferencia so zahraničnou účasťou,
konaná pod záštitou dekana Strojníckej fakulty Žilinskej univerzity v Žiline
prof. Dr. Ing. Milana Ságu

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DETERMINATION AND ANALYSIS OF CAUSES FOR A CATASTROPHIC FAILURE OF A RESPONSIBLE MACHINE PART

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1. Introduction

In this paper is analyzed a breakdown of a very responsible machine part, which was subjected to high pressures and impact loading. In manufacturing new parts, due to lack of material which was originally used – steel that was tested in exploitation several times, the steel was used that had similar properties. The renowned European steel manufacturer was selected, which delivered two massive steel blocks, accompanied by necessary certificates on the material's quality. The user had also performed adequate control of the delivered forged pieces, conducted necessary input, process and additional control, of the mechanically and thermally treated part. In exploitation, the finally machined piece has broken into several pieces during the very first test run. This paper deals with discovering the causes of that fracture and points to the reasons why it occurred despite the rigorously conducted control procedures, both by the manufacturer and the final user. Thanks to regulations that the first tests of this class of parts must be conducted without human presence, there were no casualties, just the very costly material losses resulted. Here are presented properties of original material, as well as properties of the alternative material that served as substitution, since the original one was not available. Finally, here are analyzed results of tests performed on the broken part and the possible causes of its failure during the test run are discussed. Results of this paper can be useful to all those dealing with material selection for the responsible machine parts, as an important instruction that besides the standard tests a special control has to be performed for possible presence of non-metallic inclusions.

In papers [1-5] are described, in details, all the causes of damages of various machine parts. Methods for detection of the causes of damages, applied in those investigations, served to authors of this paper in the attempt to discover and explain cause of fracture of the part described here.

2. The most important properties of the original material of the working piece

Material of the original working piece, which proved to be very reliable in exploitation, was the special tool steel, Table 1. This steel belongs into a group of high quality noble tool steels for tempering (P, S <0.012%). Steels of this type are being produced only by special order,

according to specific and controlled technology and very strict and extensive quality control, when all the necessary mechanical and technological-metallurgical properties are being checked, fracture surface and its and fractography are being analyzed, and the fracture mechanics methods are being applied.

Tab. 1 Chemical composition of tool steel - original base material

| Chemical composition % | | | | | | | | | |
|---------------------------------|-----------|-----------|-----------|----------|-----------|-----------|-----------|-----------|----------|
| C | Si | Mn | Cr | Ni | Mo | V | P | S | Cu |
| Prescribed chemical composition | | | | | | | | | |
| 0.36-0.42 | 0.17-0.37 | 0.15-0.35 | 0.80-1.20 | 3.0-3.50 | 0.40-0.70 | 0.10-0.18 | max 0.012 | max 0.012 | max 0.25 |
| ±0.010 | ±0.020 | ±0.020 | ±0.050 | ±0.100 | ±0.020 | ±0.030 | ±0.002 | ±0.002 | +0.002 |
| Manufacturer's attest | | | | | | | | | |
| 0.41 | 0.33 | 0.26 | 1.04 | 3.24 | 0.52 | 0.12 | 0.007 | 0.005 | 0.16 |
| 0.42 | 0.27 | 0.26 | 1.04 | 3.25 | 0.53 | 0.12 | 0.007 | 0.004 | 0.16 |

The permissible deviations of chemical composition, presented in Table 1, under condition that all other technical requirements are satisfied. Besides the chemical composition, the manufacturer also provided the data on the most important mechanical properties of this steel (R_m , $R_{p0.2}$ and KU5), presented in Table 2.

Tab. 2 The most important mechanical properties of steel - original base material

| Tensile strength | Yield stress, $R_{p0.2}$, MPa | Area reduction Z, % | Impact energy, J | |
|------------------|--------------------------------|------------------------|------------------|--------|
| | | | 20°C | -50°C |
| ≥ 950 | ≈ 930 | ≥ 20 | min 24 | min 10 |

3. The most important properties of the alternative material

As a substitution for the original material the user selected steel 40CrMnNiMo 8-6-4 (DIN EN ISO 4957). The semi-finished products were purchased in the form of the forged pieces, with dimensions 505×560×630 mm (2 pieces), and state at delivery was tempered (quenched + tempering) up to hardness of 301 – 307 HB. The forged piece supplier is a world renowned company. The attest was issued according to appropriate standard, as well as the data on the steel: chemical composition, heat treatment regimes, annealing diagrams and the KH diagram. The steel's chemical composition is given in Table 3, while the thermal-physical properties, mechanical properties, microstructure and heat treatment regimes are catalogued by the steel manufacturer [6, 7].

Tab. 3 Chemical composition of 40CrMnNiMo 8-6-4 steel

| Elements' content % | C | Si | Mn | Cr | Ni | Mo | P | S |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Prescribed chemical composition | 0.35-0.45 | 0.20-0.40 | 1.30-1.60 | 1.80-2.10 | 0.90-1.20 | 0.15-0.25 | max 0.030 | max 0.030 |
| Manufacturer's attest | 0.355 | 0.26 | 1.53 | 1.98 | 1.15 | 0.21 | 0.007 | 0.001 |

Heat treatment regimes were executed according to demanded requirements and the KH diagram of the under heated austenite decomposition (Figure 1) and the required hardness of the working piece [6, 7].

Hardness was measured after the heat treatment both on the specially prepared samples and on the working piece itself, and it was within limits 325 to 340 (337) HB. The microstructure was estimated as interphase tempering structure. The most important mechanical properties and the impact energy, both at room and lowered temperatures, were determined on specially prepared samples for tensile and impact toughness test, Table 4.

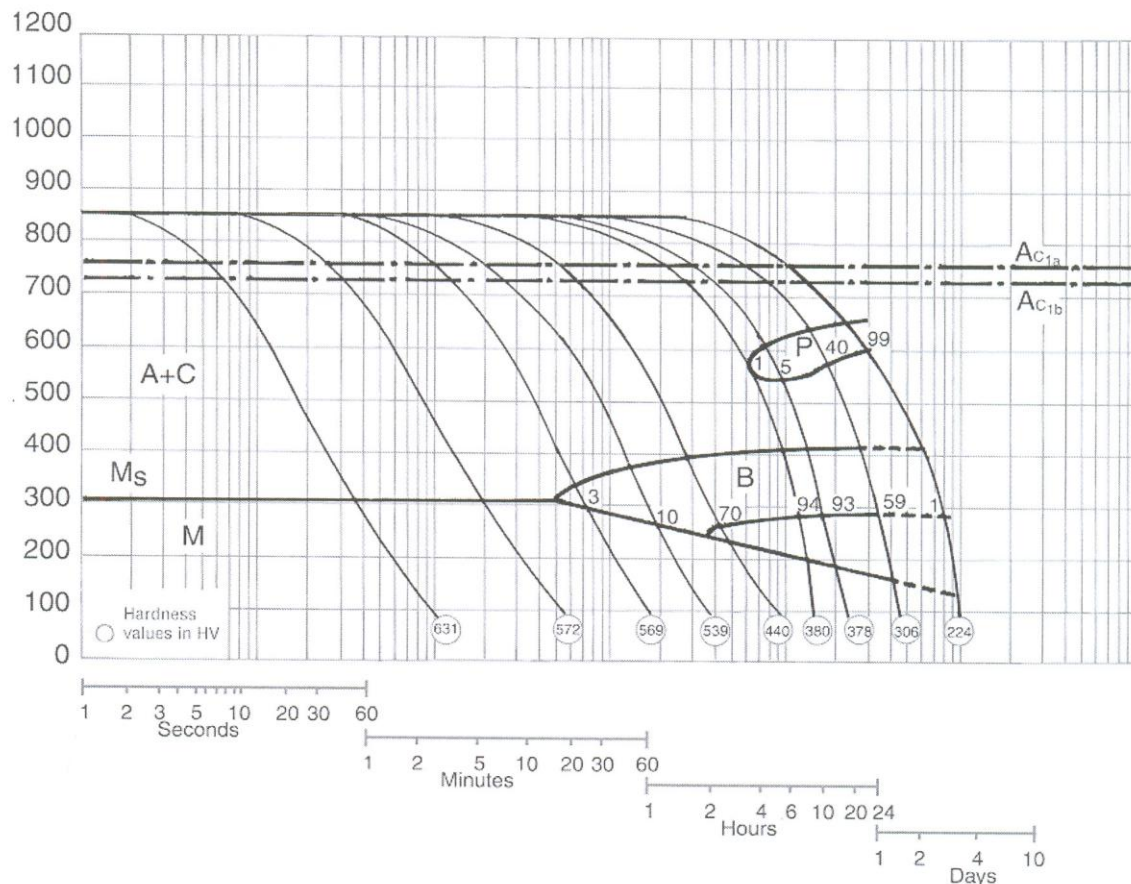


Fig. 1 Continuous-cooling transformation diagram for 40CrMnNiMo 8-6-4 steel

Tab. 4 The most important chemical properties of 40CrMnNiMo 8-6-4 steel

| Properties | $R_{p0.2}$, MPa | R_m , MPa | A_5 , % | Z , % | KU 300/5, J | |
|------------|------------------|-------------|-----------|---------|-------------|--------|
| | | | | | +20 °C | -40 °C |
| Sample 1 | 951 | 1061 | 14.6 | 53.30 | 30 | 25 |
| Sample 2 | 958 | 1082 | 13.0 | 46.20 | 30 | 19 |
| Sample 3 | 1008 | 1118 | 13.3 | 41.20 | 30 | 23 |

Besides the heat treatment, the chemical-heat processing – the nitriding, was also performed. The depth of the nitrided layer, measured on the sample, was $N_{ht330} = 0.37$ mm, while the surface hardness was 650 – 670 HV.

The forged piece was tested after the soft (spheroid) annealing and rough mechanical treatment, as well as after heat treatment of tempering and final grinding. No inhomogeneities were noticed on the tested sample. The forged piece corresponds to class 4 according to standard EN 10228-3. The magnetostatic test of the forged piece was also conducted (test with magnetic particles). This control also did not show any unallowable surface flaws. All the tests were conducted in the accredited laboratory for nondestructive testing. Besides those tests the dimensions of the working piece were measured, but those results were of no particular

importance for the purpose of this work. After the extensive control was performed, the working piece was mounted to the device and after the very first test run the breakdown occurred.

4. Determination of the breakdown causes

The authors of this paper were invited to investigate and possibly to discover the cause(s) for this fracture. There were three possible causes for fracture of this working piece:

1. Bad design solution,
2. Error during the machining and heat treatment and
3. Deviation of the declared from the real chemical composition of steel.

The construction drawing was first analyzed, but the possibility that this was a design mistake was discarded, considering that a large number of working pieces, designed according to that solution, was previously manufactured and they lasted through several thousands of tests – significantly more than predicted by technical conditions.

Since the heat treatment, as well as mechanical machining were conducted in accordance with required demands, it was obvious that the error was not to be sought in this direction.

Thus, the detailed analysis of the broken part was performed (Figure 2), where the possible cause of the breakdown was looked for. For that purpose, the chemical composition of the base material was investigated first, while its mechanical-technological and physical-metallurgical properties were checked later, as well.

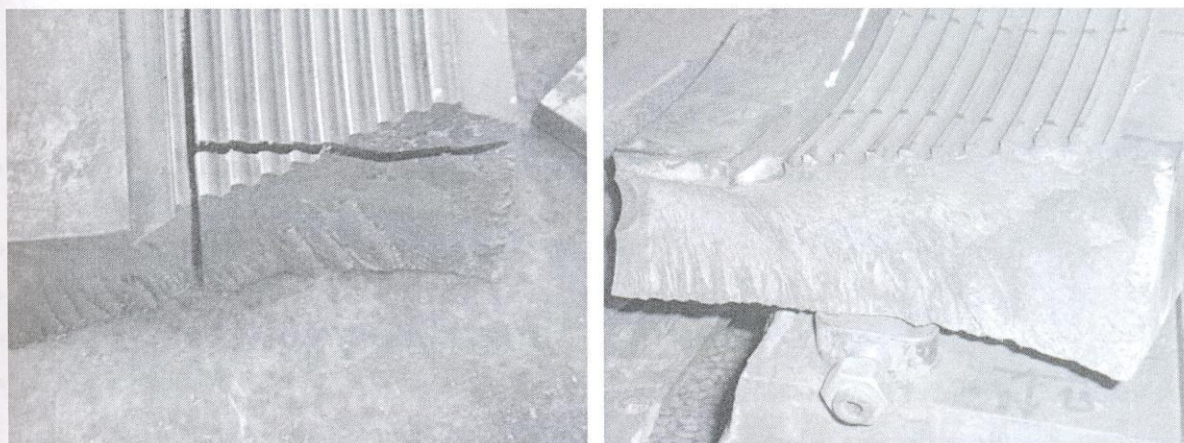


Fig. 2 Appearance of some fracture surfaces of the broken part

a. Chemical composition verification

By the spectrographic analysis method the chemical composition was established on samples close to the fracture surfaces, Table 5.

Tab. 5 Chemical composition of 40CrMnNiMo 8-6-4 steel

| Elements' content % | C | Si | Mn | Cr | Ni | Mo | P | S |
|---------------------------------|---|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Prescribed chemical composition | 0.35-0.45 | 0.20-0.40 | 1.30-1.60 | 1.80-2.10 | 0.90-1.20 | 0.15-0.25 | max 0.030 | max 0.030 |
| Manufacturer's attest | 0.355 | 0.26 | 1.53 | 1.98 | 1.15 | 0.21 | 0.007 | 0.001 |
| Analysis in the fracture zone | 0.36 | 0.24 | 1.43 | 2.00 | 0.94 | 0.15 | 0.012 | 0.004 |
| | [plus impurities: V= 0.020%; Al= 0.022%; Ti= 0.033%; Cu= 0.13%] | | | | | | | |

B. Mechanical-technological investigations

From the broken pieces (Figure 3) the samples were prepared for determination of the most important mechanical properties: impact energy at room and lowered temperatures (Table 6) and microstructure and hardness distribution.

The measured hardness after the heat treatment – tempering (quenching + tempering) was about 317 HB (SRPS C.A4.003).

C. Physical-metallurgical investigations

1. The nitriding zone hardness was about 742 HV1 (≈ 62 HRC) (DIN 50150);
2. Macrostructure – Visually – after deep etching of the metallographic platelet taken further from the fracture zone no flaws of the porosity type, visible to the naked eye, were noticed, neither the nonmetallic inclusions, nor cracks (according to SRPS C.A3.015);
3. Microstructure – The interphase tempering structure with prominent with stripes (Figure 4, etched in 2% nital¹). Phosphorus segregations (white stripes) were observed on ten samples etched in Oberhofen reagent.

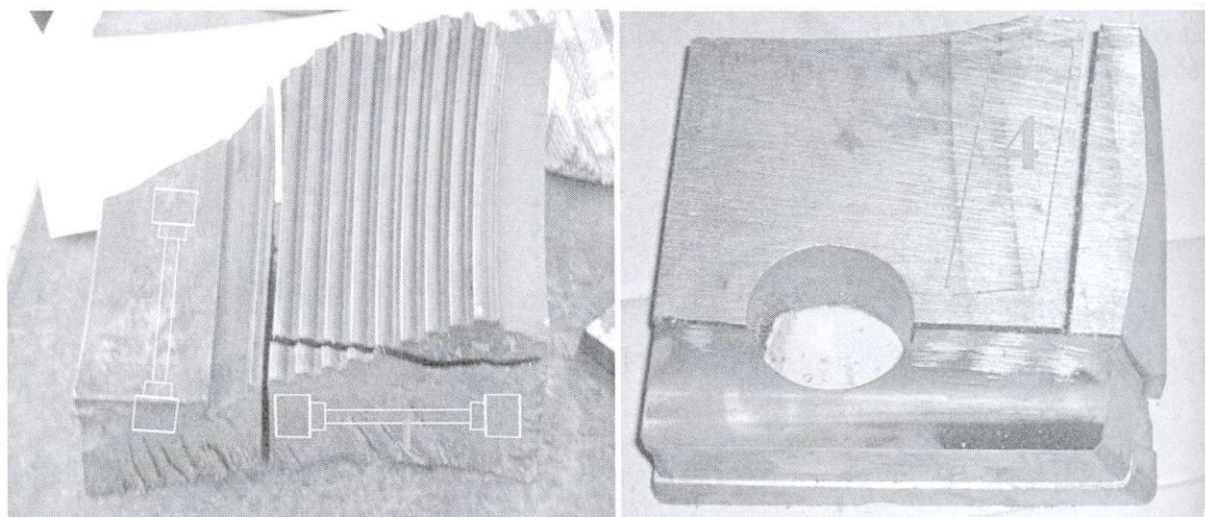


Fig. 3 Places where the samples were taken from: for the tensile test (left) and for the microstructure and impact toughness determination (right).

Tab. 6 Investigation results of the most important mechanical properties of 40CrMnNiMo 8-6-4 steel

| Properties | $R_{p0.2}$, MPa | R_m , MPa | A_5 , % | Z , % | KU 300/5, J | |
|------------|------------------|-------------|-----------|---------|-------------|-------|
| | | | | | +20 °C | -40°C |
| Sample 1 | 892 | 1035 | 15.8 | 52.40 | 18 | 15 |
| Sample 2 | 912 | 1041 | 16.2 | 51.00 | 21 | 15 |
| Sample 3 | 902 | 1032 | 14.6 | 54.00 | 22 | 12 |
| Sample 4 | 895 | 1028 | 16.4 | 52.30 | 14 | 17 |
| Sample 5 | 937 | 1122 | 11.8 | 49.20 | 10 | 6 |

¹ 2% solution of nitric acid (HNO₃) in denatured alcohol.

- Visual investigations – Based on the appearance of the fracture surfaces, one could conclude that it belongs to a class II for evaluation of the stripeneness of fracture, level 5 (dendritic fracture), where material of the forged piece with the stripe-like fracture of level 4 and 5 is discarded as reject;
4. Content of the nonmetallic inclusions was checked according to standard SRPS C.A3.015.

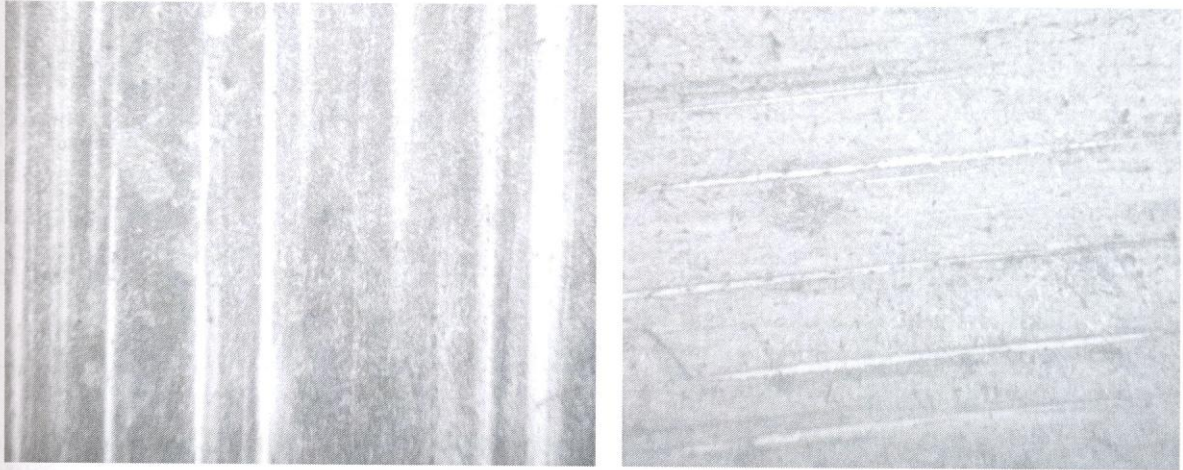


Fig. 4 Microstructure of metallographic ground samples from different fracture zones (200x)

5. Discussion of obtained test results

- Results of chemical analysis of the delivered sample satisfy the requirements prescribed for the class to which steel 40CrMnNiMo 8-6-4 belongs;
- Hardness is somewhat lower with respect to requirements from the construction documentation;
- Yield stress and tensile strength are somewhat lower with respect to the original steel;
- Absorbed impact energy at + 20°C satisfies requirements of the original steel;
- Absorbed impact energy at – 40°C does not satisfy requirements of the original steel;
- Metallographic analysis of the fracture surfaces, on a sample with the impact energy of 6 J at – 40°C (Table 6 – sample 5) showed segregations of phosphorus over 1/3 of the surface (Figure 4);
- Depth and quality of the nitrided layer satisfied the demanded requirements;
- Macro investigations of the fracture surface provided the conclusion that its appearance belongs to a class II for estimate of the stripeneness of fracture, level 5 (wood-like fracture);
- Semi-finished forged pieces that have stripe-like fracture of levels 4 and 5 are discarded as rejects;
- Microstructure satisfies requirements for the tempered state of steel;
- Presence of phosphorus segregations in microstructures at ten plate-samples taken from different places in the fracture zone, points to the fact that material was of the unacceptable quality, since those inhomogeneities in material increase its brittleness.

6. Conclusions

In this paper is pointed to possibility of unacceptable flaws in material for manufacturing of the very responsible part, despite the extensive control, conducted by the steel manufacturer and