This paper was presented at the Fourteenth Meeting
“New Trends in Fatigue and Fracture” (NT2F14)
Belgrade, Serbia, 15–18 September, 2014

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THEORETICAL-EXPERIMENTAL FRACTURE ANALYSIS OF A RESPONSIBLE MACHINE PART

TEORIJSKO-EKSPERIMENTALNA ANALIZA LOMA ODGOVORNOG MAŠINSKOG DELA

Originalni naučni rad / Original scientific paper
UDK /UDC: 669.14.018.25:539.42
Rad primljen / Paper received: 25.09.2014

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Keywords
- fracture
- theoretical analysis
- experimental investigations
- non-metallic inclusions

Abstract

The paper presents a theoretical-experimental analysis of possible causes for fracture of a responsible machine part. During exploitation the part is exposed to short, but high dynamic loading and pressure. Because the original material (low-alloyed tool steel) of the broken part is unavailable, the manufacturer is forced to use the substitute material of similar properties. Two massive steel blocks, accompanied by necessary certificates of material quality have been delivered by a very renowned European steel manufacturer. The manufacturer of the final part – the user has also performed the prescribed control of the mechanically– and heat-treated part. Despite all this, the part has broken into several pieces during the very first test run. Then the pieces of broken part were tested. At first, the chemical composition of the base material was investigated and then its mechanical-technological and physical-metallurgical properties. Three possible causes of fracture of the working part have been analysed: structure design solution, error during machining or heat treatment and the disagreement of the declared and the real chemical composition of the steel.

The objective is to point out caution to those who are forced, due to the lack of supply, to substitute the steel type of the manufactured responsible parts, many times verified in operation, with new steel material. Besides standard chemical, mechanical and metallographic investigations, additional tests need to be performed – destructive and non-destructive (e.g. test for non-metallic inclusions, their shape, size and distribution), what in this case has not been done.

Ključne reči
- lom
- teorijska analiza
- eksperimentalna ispitivanja
- nemetalni uključci

Izvod

U ovom radu je prikazana teorijsko-eksperimentalna analiza mogućih uzročnika loma odgovornog mašinskog dela. Za vreme eksploatacije deo je bio izložen kratkom ali ultrabrzom dinamičkom opterećenju i visokim pritiscima. Budući da je havarisani deo izrađen od originalnog niskolegiranog alatnog čelika koji nije bio dostupan, proizvođač je bio prinuđen da koristi kao zamenu drugi čelik sličnih karakteristika. Od strane renomiranog evropskog proizvođača čelika su bila isporučena dva velika čelična bloka, sa neophodnom pratećom dokumentacijom vezanom za kvalitet materijala. Proizvođač finalnog dela – istovremeno i korisnik, je takođe sproveo propisanu kontrolu mehanički i termički obrađenog dela. Uprkos svemu tome, za vreme prve probe došlo je do loma dela. Zatim se pristupilo analizi uzroka havarije. Prvo je ispitan hemijski sastav osnovnog materijala, a zatim i mehaničko-tehnološke i fizičko-metalurške karakteristike. Analizirana su tri moguća uzroka loma radnog dela: konstrukcija, greške nastale za vreme mašinske ili termičke obrade i odstupanje stvarnog i propisanog hemijskog sastava čelika.

Cilj rada je da ukaže svima onima, koji su primorani usled nedostatka zaliha, da zamene čelik koji se koristi za izradu odgovornih delova, a koji je bio proveren u eksploataciji mnogo puta, da budu izuzetno oprezni. Pored standardnih hemijskih, mehaničkih i metalografskih ispitivanja, obavezno moraju da se sprovedu i dopunska ispitivanja – metodima sa razaranjem i bez razaranja (na primer, probe na nemetalne uključke, njihov oblik, veličinu i raspored), što u ovom slučaju nije bilo urađeno.

INTRODUCTION

We first emphasize that the original part’s material was tested in exploitation several times and that it produced satisfactory results. Then we analyse the alternative steel 40CrMnNiMo 8-6-4 from which the new part was manufactured, since the original steel for the production of this responsible part was not available on the market. The results of the 40CrMnNiMo 8-6-4 steel tests are presented. At the end we analyse results of the tests done on the broken part and we point to possible causes that have led to its failure during the very first test run.

In papers /1-8/ all the causes of damages of various machine parts are described in details. 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 the cause of fracture of the part described here.

As it is emphasized, the original part is made of highly alloyed steel Č57302 (Č57302 has been the internal steel designation used for special purposes), Tables 1 and 2, while steel 40CrNiMoV 8-6-4 (DIN EN ISO 4957) has been chosen as a replacement for the original material. The semi-finished part is purchased in the form of forged piece, dimensions 505 × 560 × 630 mm (2 pieces) and was delivered in the as tempered condition of hardness 301-307 HB. The steel supplier is a renowned company. The steel manufacturer provided the certificate of material properties, according to standard EN 10204/3.1: chemical composition, heat treatment regimes, tempering diagrams and TTT diagram. The chemical composition, thermal-physical and mechanical properties, and microstructure of this steel are given in Tables 3 to 8, according to manufacturer's recommendations, /10/.

Table 1. Chemical composition of steel Č57302 (wt. %).
Tabela 1. Hemijski sastav čelika Č57302 (tež. %)

C	Si	Mn	Cr	Ni	Mo	V	P	S	Cu
Prescribed chemical composition									
036-0.42	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' 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

Table 2. The most important mechanical properties of Č57302.
Tabela 2. Najvažnije mehaničke osobine Č57302

Steel mark	Tensile strength R_m (MPa)	Yield stress, $R_{p0.2}$ (MPa)	Contraction Z (%)	Impact energy (J)	
				20°C	–50°C
Č57302	≥ 950	930	≥ 20	24	10

Table 3. Mechanical properties of steel 40CrMnNiMo 8-6-4.
Tabela 3. Mehaničke osobine čelika 40CrMnNiMo 8-6-4

Properties	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	Z (%)	KU 300 (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

Table 4. Chemical composition of steel 40CrMnNiMo 8-6-4 (DIN EN ISO 4957) (wt. %).
Tabela 4. Hemijski sastav čelika 40CrMnNiMo 8-6-4 (DIN EN ISO 4957) (tež. %)

Elements	C	Si	Mn	Cr	Ni	Mo	P	S
Prescribed chemical composition	035-0.45	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' attest	0.355	0.26	1.53	1.98	1.15	0.21	0.007	0.001

Table 5. Coefficient of linear expansion vs. temperature, $\alpha = \alpha(T)$ (m/m°C).
Tabela 5. Zavisnost koeficijenta linearnog širenja od temperature, $\alpha = \alpha(T)$ (m/m°C)

Steel	Temperature (°C)		
	20-100	20-250	20-500
40CrMnNiMo 8-6-4	11.6	12.8	14.3

Table 6. Thermal conductivity vs. temperature, $\lambda = \lambda(T)$ (W/cm°C).
Tabela 6. Koef. provođenja toplote sa temperaturom, $\lambda = \lambda(T)$ (W/cm°C)

Steel	Temperature (°C)		
	20	250	500
40CrMnNiMo 8-6-4	0.340	0.335	0.330

Table 7. Modulus of elasticity vs. temperature, $E = E(T)$ (MPa).
Tabela 7. Promena modula elastičnosti sa temperaturom, $E = E(T)$ (MPa)

Steel	Temperature, °C		
	20	250	500
40CrMnNiMo 8-6-4	212000	197000	175000

Table 8. Heat treatment regimes and microstructure.
Tabela 8. Režimi termičke obrade i mikrostruktura

Steel	Soft annealing (°C)	Quenching + Tempering		Microstructure
		Quenching (°C)	Tempering (°C)	
40CrMnNiMo 8-6-4	720 (1 h/25 by mm of thickness)	880 (1 min/by mm of thickness) oil/52 HRC	600 (1 h/25 by mm of thickness) air/280-325 HB	Interphase Q+T phase (280-325 HB)

Heat treatment regimes are defined based on the requirements and in accordance to the CCT diagram of the undercooled austenite and the required hardness (Fig. 1), /9/.

Hardness is measured both on specially prepared samples, as well as on the piece itself and was within limits 325-340 (337) HB, /11/. The microstructure is estimated as the interphase structure of tempering. On specially prepared samples for tensile testing and impact toughness, the most important mechanical properties are determined, as impact toughness at room and low temperatures (Table 8). The impact toughness test is done according to standard, /12/. After mechanical processing, nitriding is performed. The depth of the nitride layer, measured on the sample, is $\mathrm{Nht}_{330} = 0.37$ mm, while the surface hardness is 650-670 HV (57.5-58.5 HRC).

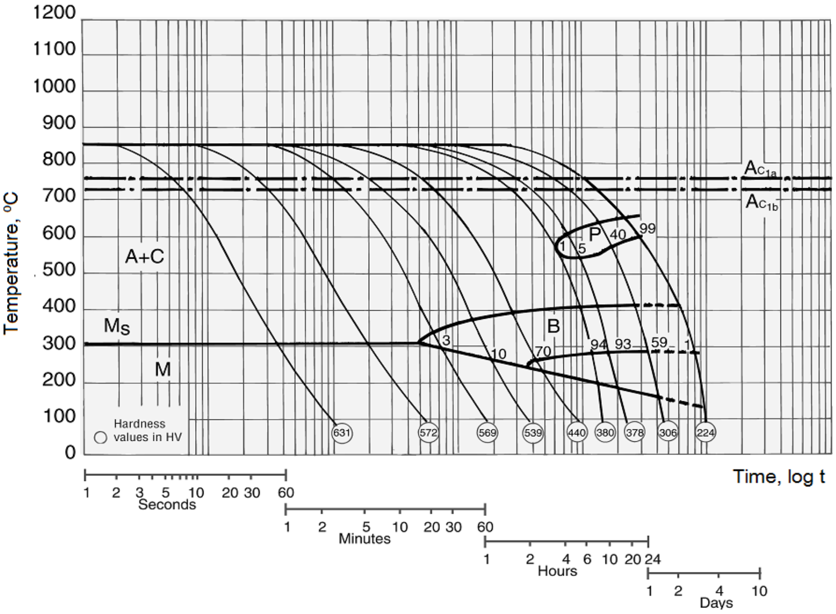


Figure 1. CCT diagram of steel 40CrMnNiMo 8-6-4.
Slika 1. KH dijagram za čelik 40CrMnNiMo 8-6-4

The forged piece is tested by ultrasonic defectoscopy after soft (spheroidal) annealing and rough mechanical processing as well as after tempering heat treatment and final grinding. No inhomogeneities flaws were noticed on the tested piece. The forged piece belongs to class 4, according to standard EN 10228-3. The magnetic flux test of the forged piece is conducted as well.

This inspection, done after heat treatment, revealed no impermissible surface flaws. All tests were performed in the laboratory accredited for non-destructive testing. After the extensive control, the responsible part was mounted on the structure and after the first test run, the failure occurred.

DETERMINING THE CAUSES OF FAILURE

In the analysed case, three possible main causes for the breaking of this part are given (Fig. 2):

1. Bad design solution of the part.
2. Errors during mechanical processing and heat treatment.
3. Errors in the primary production of steel.

Figure 2. Fracture surface appearance of the considered part.
Slika 2. Izgled mesta preloma razmatranog dela

The design drawings are first analysed in detail, but we gave up the possibility of the design error being the cause, since a large number of those pieces are manufactured earlier and they had caused no problems in exploitation. Since heat and mechanical treatments are done according to prescribed requirements, we gave up on investigations in that direction, as well. Thus, we had to perform detailed analysis of the broken piece itself, in order to discover what had caused its failure. To do so, we first checked the chemical composition of the new steel, then its properties: mechanical-technological and physical-metallurgical.

Theoretical analysis of possible causes of fracture

Cracks during the additional heating

During additional heat treatment of the low alloyed steel, or during operation at elevated temperatures, cracks can appear in the HAZ. Factors contributing to the appearance of cracks are primarily related to chemical composition of the steel, the high level of residual stresses in combinations of locations of their actions and the range of operating temperatures.

The majority of alloyed steels is to a certain extent prone to an increase in brittleness in the zone of grain coarsening within the HAZ at temperatures of about 600°C. Elements that stimulate the increase in brittleness are: Cr, Cu, Mo, B, Nb and Ti, while S, possibly P and Sn influence the brittle intercrystalline form of cracks during the additional heating. Mo-V and especially Mo-B steels are sensitive to the formation of cracks during additional heating, especially if the content of vanadium is above 0.1%. A relative influence of various elements is quantitatively expressed by the formula of Nakamura and Ito, /9/:

$$P = Cr + 3.3Mo + 8.1V - 2 \tag{1}$$

$$P = Cr + Cu + 2Mo + 10V + 7Nb + 5Ti - 2 \tag{2}$$

When $P \geq 0$, steel can be prone only to cracks during additional heating. The considered steel is, according to given formula, prone to formation of cracks.

The Nakamura – Ito formula (1) is related to Japanese low alloyed Cr-Ni-Mo steel HT70 steel which by composition corresponds to steel 40CrNiMoV 8-6-4. Steels that are prone to formation of cracks during additional heating in practice are steels with Mo or Cr-Mo over 1.18%, if each of them has $P > 0$. That could be partially the cause of this type of flaw. There are some indications that the structure of the steel itself is poor, what causes low toughness, thus the steel becomes prone to increased brittleness at elevated temperatures. However, additional heating cracks mainly appear in thick cross-sections (above 50 mm), suggesting that the high level of residual stresses is necessary for cracks to appear. The additional heating has caused cracks to appear also during component operation, if it is exploited at elevated temperatures or if the component is exposed to tensile stresses.

Tempering embrittlement

If the alloyed steel is maintained within the temperature range 375-575°C for a certain period of time, as for a majority of steels with similar chemical composition, during slow cooling through this range, the transition temperature can increase. The proneness of steel to temper embrittlement is normally determined by the change of temperature that corresponds to the impact energy of 55 J or 50% of the laminar structure on the fracture surface, that corresponds to a transition temperature after the action of a standard combination of time and temperature (FATT) (Appearance of the fractured surface can also be used as a criterion for determining the transition temperature. Ratio of the fractured surface that belongs to laminar structure and the shearing surface can define the transition temperature (FATT 50).). Gradual cooling to which the samples are exposed to in order to increase the time period for the series of decreasing temperatures within the temper embrittlement range is mostly used in studying this phenomenon. Gradual cooling is significant for the inspection test, while for quantitative results it is necessary to expose samples to a constant temperature for a longer period of time. Real chromium steels are very prone to temper embrittlement, but with the addition of 0.5% Mo, it decreases. Elements that significantly enhance brittleness are Sb, P, Sn, while Mn, V, B and S slightly increase the proneness towards temper embrittlement, /9/.

Embrittlement and alloying elements are synergic, thus for example Mn and Si enhance the influence of P. For self-hardened and tempered 325Cr-1Mo steel with $S < 0.02\%$ and $Sb < 0.004\%$ proneness towards embrittlement can be determined by the Watanabe factor, *J*, /9/:

$$J = (\mathrm{Mn} + \mathrm{Si}) \cdot (\mathrm{P} + \mathrm{S}) \cdot 10^4 \qquad (3)$$

– for original steel:

$$J^{os} = (0.35 + 0.37) \cdot (0.012 + 0.012) \cdot 10^4 = 172.8 \qquad (4)$$

– for replaced steel:

$$J^{es} = (1.53 + 0.26) \cdot (0.007 + 0.001) \cdot 10^4 = 143.2 \qquad (5)$$

Factor *J* can be decreased by lowering the content of Si and by controlling P, S, Sn and Sb. Level of Mn can not be reduced without loss of tensile properties. Negative influence of P is prominent if the contents of C and Ni are increased.

Phosphorus is dissolving in α and γ-Fe, causing the worsening of the alloys' plasticity properties. The content of phosphorus in steel can not exceed 0.025-0.008% (in the original material max 0.012% of P, while in the substituted material it is significantly higher, e.g. 0.030%).

Silicon is not subjected to segregation and it prevents segregation of S and P.

Creation of initial cracks during the tempering of steel with the addition of vanadium is a consequence of the highly dispersive phase of vanadium carbides (VC). Excreted VC particles harden the grain significantly, prevent deformation of the grain boundary surface and increase the brittleness. Slip along the grain boundaries eventually leads to the appearance of micro-cracks, and then crevices.

Experimental analysis of possible causes of fracture

Chemical composition checking

By the method of the spectrographic analysis of the broken pieces, the chemical composition of the part was established (Table 9).

Table 9. Chemical composition of steel 40CrMnNiMo 8-6-4.
Tabela 9. Hemijski sastav čelika 40CrMnNiMo 8-6-4

Content of elements	C	Si	Mn	Cr	Ni	Mo	P_{max}	S_{max}
Prescribed chemical composition	035-0.45	0.20-0.40	1.30-1.60	1.80-2.10	0.90-1.20	0.15-0.25	0.030	0.030
Manufacturer' attest	0.355	0.26	1.53	1.98	1.15	0.21	0.007	0.001
Analysis of fractured location	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%)							

a) Tensile testing b) Impact toughness testing and microstructure

Figure 3. Sampling locations on the broken part.
Slika 3. Mesta uzimanja uzoraka sa havarisanog dela

Table 10. Mechanical properties of steel 40CrMnNiMo 8-6-4.
Tabela 10. Mehaničke osobine čelika 40CrMnNiMo 8-6-4

Properties	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	Z (%)	KU 300 (J)	
					+20°C	–40°C
Prescribed	1030	1095-1155	–	–	14	10
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	–	–	–	–	–	6

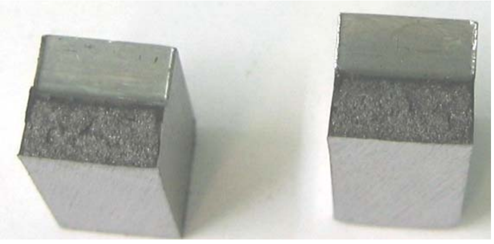
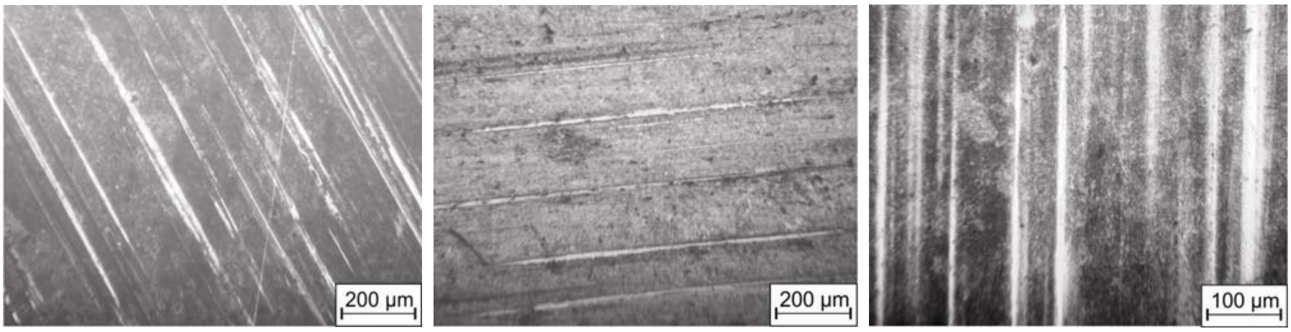


Figure 4. Location for microstructural test KU 5 on specimen (4).
Slika 4. Mesto kontrole mikrostrukture KU 5 na uzorku (4)



Phosphorus segregation – bright stripes/Segregacija fosfora – svetle trake

Figure 5. Microstructure of metallographic slits taken from different zones of fracture.
Slika 5. Mikrostruktura metalografskih izbrusaka pripremljenih iz različitih zona preloma

Mechanical-technological tests

Samples are prepared from broken pieces for the determination of the most important mechanical properties: tensile properties (Fig. 3a), impact toughness at room and lowered temperatures (Table 10, Fig. 4), /12/, as well as microstructure (Fig. 5).

Physical-metallurgical tests

- Hardness of nitride layer is 42 HV1 or 62 HRC;
- Macrostructure – visually – after deep etching of the slit taken from the location further away from the crack zone. No flaws visible to naked eye are noticed (flaws like porosity, nonmetallic inclusions, crevices etc., according to ISO 4969:1980);
- Microstructure – interphase temper structure with prominent white stripes (Fig. 5, etched in 2% nital). Etching in Oberhofer reagent of about ten slits taken directly from the fractured surface shows segregation of phosphorus, presented in Fig. 5;
- Hardness, as measured according to /11/, equals 317 HB;
- Depth and hardness of the nitride layer;
- Visual investigations, based on the appearance of the fractured surface, it can be concluded that it belongs to scale II for estimated laminarity of the fracture, to a degree 5 (wooden fracture).
- Content of nonmetallic inclusions (SRPS EN 10247: 2011) - A1D2;
- Hardness of the nitride surface is measured according to appropriate standard, /13/, and it is 742 HV0.5.

DISCUSSION AND COMMENTS

- Hardness is somewhat lower with respect to the required;
- Chemical analysis results of the provided sample satisfy conditions prescribed for quality of the material steel 40CrMnNiMo according to DIN (2738 ISO-BM);
- Yield stress and tensile strength are somewhat lower with respect to the required values for quality of steel Č57302;
- The impact energy at +20°C satisfies requirement for steel Č57302; but the impact energy at –40°C does not;
- Metallographic analysis of the fracture zone on samples and with impact energy of 6 J at –40°C are with segregations of phosphorus on 1/3 of the fracture surface (Fig. 4);
- Depth, quality and hardness of the nitride layer satisfies prescribed requirements;
- Macro-survey of the fracture surface: appearance of the fractured surface belongs to scale II for the estimate of fracture laminarity, degree 5 (wooden fracture);
- Semi-finished forged pieces that have laminar fracture of degrees 4 and 5 should be rejected as scrap;
- All investigations are done on samples taken from the forged piece;
- Microstructure satisfies the prescribed requirement for the tempered steel;
- Presence of phosphorus segregation within the microstructure of ten samples taken from different places within the fracture zone point to the fact that the material is of unacceptable quality, since the inhomogeneity of this type in material increases its brittleness.

CONCLUSIONS

The paper points out the possibility of the presence of unacceptable flaws in the material for responsible structural parts, despite the control conducted by the material supplier and customer. Detailed investigations of the causes for the catastrophic failure involved taking samples from the fracture zone and its vicinity, where numerous unacceptable segregations of nonmetallic inclusions are detected in the steel 40CrMnNiMo 8-6-4. Compounds are of sulphide and phosphate character and they are the main cause of premature fracture of the part. Present segregations of phosphorus during the forging phase create micro and macro-cracks which expand during further heat treatment and during exploitation. This conclusion is drawn from the sample with the impact energy of only 6 J.

Macrographic and micrographic investigations of larger number of samples from the fracture zone, the presence of numerous stripes of nonmetallic inclusions is confirmed, that originated already in the manufacturing process of the primary steel. The considered steel 40CrMnNiMo 8-6-4 does not comply with the prescribed requirements.

Finally, we must emphasize again, that this work points out the importance of performing additional tests, besides standard chemical, mechanical and metallographic tests which would establish whether the substituting material complies with all the prescribed requirements. Here we especially recommend destructive and non-destructive additional tests to be done, e.g. those which would check the presence of non-metallic inclusions, their shape, size and distribution in the material, for they are the cause of this particular steel part fracture.

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