Investigation of Fretting Fatigue Failure of Stud Bolt

Analýza porušení svorníku kontaktní únavou

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One of the most commonly recognized causes of metal components failure is fatigue, and fasteners are no exception in this case. In this work, an investigation was carried out of the failure of undercut stud bolts used to fix the industrial vibrating motor. The vibrating motor was fixed in place with a series of stud bolts, which all failed. Fractography analysis of the most preserved fracture surface in SEM confirmed fatigue failure mechanism initiated on opposing sides of the cross-section. Visual observation of the stud bolts indicated an abnormal wear pattern on the surface. The material of stud bolts was subjected to overall examination in terms of its mechanical properties, hardness, as well as microstructure and chemical composition. The ultimate cause of failure was attributed to fretting fatigue, which occurred because of large spacing in clearance hole for stud bolts and relative motion by vibration between bolts and the base plate underneath vibrating motor.

***Key words**: Fatigue; fracture; fretting; failure analysis*

Rozebíratelné spoje, jako jsou šrouby, čepy, kolíky apod., jsou běžně užívány při spojení dvou různých součásti či komponent dohromady. Případné selhání tohoto druhu spoje může vést k vážným škodám na majetku i životech. Obecně je únava považována za jednu z nejčastějších příčin vzniku provozních lomů součástí a uvedené spoje nejsou výjimkou. Tento příspěvek pojednává o analýze příčin lomu svorníku s oboustranným závitem. K lomu došlo téměř na všech svornících sloužících k upevnění vibračního motoru, než byla závada odhalena. Na základě vizuálního posouzení a různého opotřebení lomových ploch byl důvod se domnívat, že k procesu docházelo postupně a každý zlomený svorník pouze přispíval ke kaskádovému efektu a vyššímu zatížení zbývajících svorníků. Fraktografická analýza byla provedena na nejméně opotřebené lomové ploše, kdy bylo pozorováno charakteristické únavové poškození, s místy iniciace na protilehlých stranách povrchu. V tomto místě byl povrch viditelně stlačen a vyskytoval se zde umělý vrub – koncentrátor napětí. Vizuálně byly všechny svorníky povrchově opotřebeny v okolí lomu. Dále bylo provedeno hodnocení mechanických vlastností, tvrdosti a metalografická analýza, aby bylo vyloučeno, že k lomu došlo kvůli materiálové neshodě. Ve všech těchto vyhodnoceních a měřeních svorník vyhověl. Pozornost byla zaměřena na systém ukotvení vibromotoru v základové desce a beranu. Ze schématu byla patrná velká vůle v otvoru pro svorník, v jejímž důsledku došlo k rozvoji kontaktní únavy mezi svorníkem a deskou.

***Klíčová slova**: Únava; lom; kontaktní únava; analýza porušení*

Fatigue is one of the most commonly recognized causes of failure of metals and industrial components overall. [1]. Fasteners, in general, are no exception, and fatigue remains the most frequent cause of fasteners fracture. When investigating fatigue failure of fasteners, several possible causes come into consideration, such as inadequate design and material, insufficient preload or excessive loading. Fatigue resistance of fasteners depends highly on preload, and little damage occurs to fastener if the cyclic load is lower than preload [2, 3].

Fatigue life and endurance limit in plain fatigue conditions are significantly reduced by contact of the surface with its surrounding environment – a situation called fretting fatigue. Fretting is a special wear process that occurs at the contact area between two materials under load and in the presence of slight relative movement by vibration or other external force. Under these conditions, fatigue strength can be reduced by as much as 50 to 70 % of endurance limit obtained under normal strain conditions [1, 3]. Cracks during fretting fatigue can initiate at very low stresses, below estimated fatigue limit and initiation of small cracks can represent 90% of total component life. The fretting process is commonly divided into three parts: initial surface adhesion, oscillation, and generation of debris and fatigue in the contact area [4 – 6].

Fretting fatigue causes recognizable surface damage of at least one of the contacting surfaces, fretted area is roughened, and steel surface is often decorated with reddish deposits, pits, cracks and spalling. Damage sites often act as regions of crack initiation, and local stress concentrations, which normally support fatigue crack initiation may not play a critical role in this process [7 – 9].

In the presented work an investigation was carried out of the failure of undercut double end stud bolt, which was used to fasten industrial vibrating motor in its place. The objective of the investigation was to find the root cause of failure and an overall examination of the material of stud bolts-regarding their mechanical properties.

1. Experimental procedures

1.1 Visual examination

Six stud bolts in total were used to fix vibrating motor, and most of them have failed. Fig. 1 shows one side of the motor with fastened stud bolts and Fig. 2 is an assembly diagram. All of the six stud bolts were provided for investigation. Five of these have already failed, and last unbroken one was significantly damaged by plastic deformation as it can be seen in Fig. 3.

Fig. 1 Image of vibrating engine and stud bolts
Obr. 1 Obrázek vibromotoru a svorníků

Visual inspection was carried out in the first place by macro photos. The primary finding was that all failed stud bolts have fractured on the side recessed into slab foundation, the upper side was provided with hexagon screw head to fasten bolt in its respective hole. Observation of the surfaces indicated wear marks on bolts reduced section, suggesting that wear occurred between the bolt and its clearance hole.

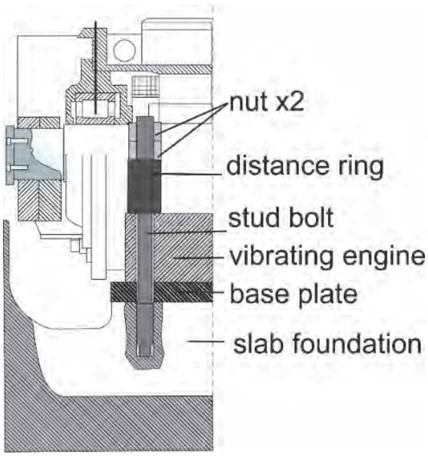

Fig. 2 Assembly diagram
Obr. 2 Schéma sestavení

Significant surface damage of reddish deposits and spalling was concentrated around the fracture surface. Most of the provided stud bolts contained markedly damaged fracture surfaces, a clear sign of rubbing against the other half of broken bolt. There was no point in performing fractographic analysis on these bolts.

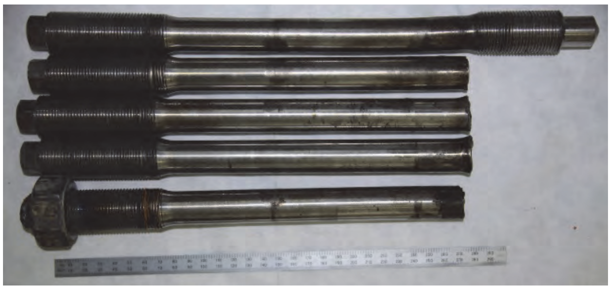

Fig. 3 Fractured and bent stud bolts
Obr. 3 Zlomené a deformované svorníky

Fig. 4 Investigated stud bolts - an area of the fracture
Obr. 4 Analyzovaný svorník – oblast lomu

For this reason, the subsequent material analysis was performed on the stud bolt with most preserved fracture (Fig. 4), which also showed its surface wear marks.

1.2 Fractography analysis

Observation in the scanning electron microscope (SEM) was carried out on the most preserved fracture surface. Separated part of the bolt was ultrasonically cleaned in acetone. Based on the visual investigation, the cause of failure was recognized as fatigue due to the presence of characteristic beach marks as it can be seen in Fig. 5. Two areas with fatigue crack propagation, separated by an area of the final fracture, were present on opposing sides of the cross-section.

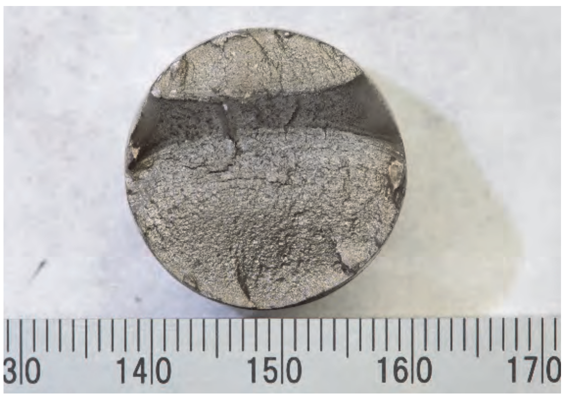

Fig. 5 Investigated fracture surface
Obr. 5 Analyzovaná lomová plocha

Fatigue striations were observed on the fracture surface (Fig. 6). Precise initiation point was found only on one side where the surface of the stud bolt was largely influenced by fretting as shown in Fig. 7 due to contact with the surrounding environment. On the other side, it was possible to pinpoint the area of origin with no precise spot. These findings along with wear marks and presence of black spots and corrosion damage on the surface indicated that fatigue cracks were initiated by the fretting mechanism.

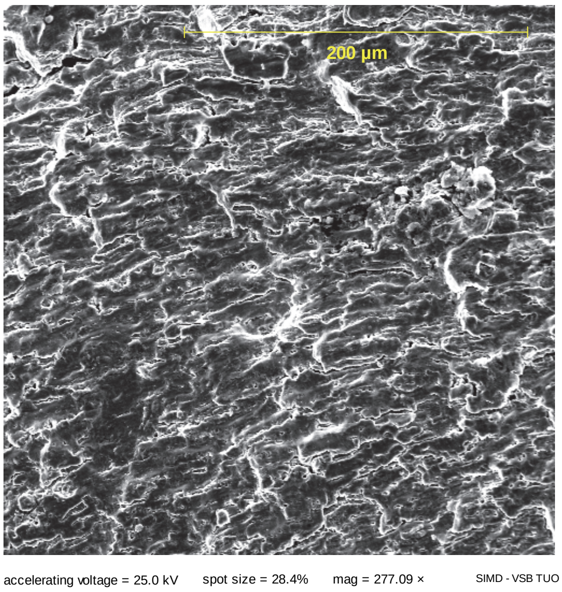

Fig. 6 Fatigue striations on the fracture surface
Obr. 6 Únavové striace na lomové ploše

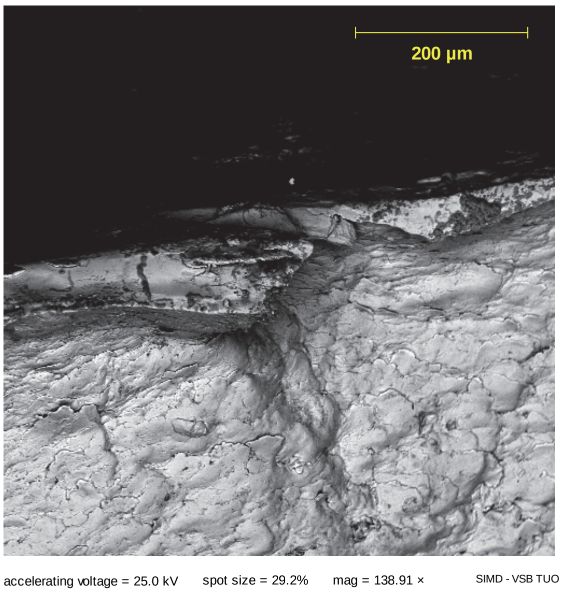

Fig. 7 Initiation area of fretting
Obr. 7 Místo iniciace a otěru

1.3 Microstructure examination

A sample of material from stud bolt was separated from the area near the fracture surface. Prepared specimen was observed in the metallography microscope after grinding and polishing, firstly in unetched condition, subsequently after etching in Nital 4% reagent. Unetched condition revealed the presence of a large amount of fine MnS inclusions. The material microstructure was found to be tempered martensite. At the edge of the shaft no visually recognizable area of decarburization was observed. Large areas of sorbite/ferrite were present in the whole cross-section shown in detail in Fig. 8. No information about applied heat treatment was provided, therefore, no judgement could be made whether this state of the microstructure is per standard or not.

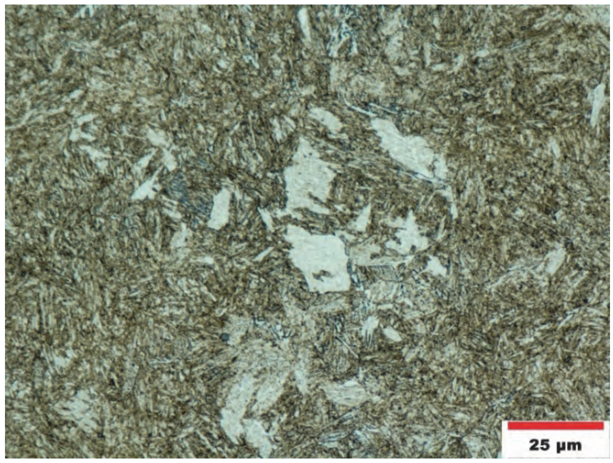

Fig 8 Detail of the microstructure
Obr. 8 Snímek mikrostruktury

1.4 Chemical composition

The chemical composition of the material was tested by X-ray fluorescence spectrometer. According to results listed in Tab. 1, steel was described as medium carbon grade with low content of alloying elements Ni, Cr, and Mo. This chemical composition was recognized to be close to AISI 9840 grade, although precise information about steel composition was not provided, because whole mounting assembly of vibrating motor is part of the intellectual property of its producer and supplier.

Tab. 1 Chemical composition of steel (wt. %)
Tab. 1 Chemická analýza použité oceli (hm. %)

C	Mn	Si	P	S	Cu	Ni
0.41	0.71	0.27	0.015	0.0236	0.24	0.87
Cr	**Mo**	**V**	**Ti**	**Al-c**	**Nb**	**N**
0.9	0.189	<0.004	<0.002	0.023	<0.003	0.009

1.5 Mechanical testing

Mechanical properties of the used steel were investigated. New stud bolt, which was meant to replace the failed ones, was supplied for this purpose. Same steel grade and heat treatment were guaranteed. Two round specimens were machined for the tensile test according to ČSN EN 6892-1. Both specimens provided almost identical results as listed in Tab. 2. Yield strength determined by 0.2 offset method was determined to be 929 MPa and ultimate tensile strength of 1041 MPa with elongation A of approximately 15%.

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Hardness HV 10 was measured across cross-section in a single line into to the depth of 3 mm under the surface. Specimen prepared for observation of microstructure was used in this test. Three indentations were made in the depth of 0.3 mm to verify hardness value close to the surface and confirm or rule out the effect of decarburization. Average hardness in this depth was 317 HV10, near the overall mean hardness of 320 HV10. Effect of decarburization was not recognized in this test, and it is in accordance with microstructure observation.

Tab. 2 Results from tensile test
Tab. 2 Výsledky tahové zkoušky

Spec. no.	**YS**	**UTS**	**A**	**Z**
	(MPa)		**(%)**	
1	929	1041	15.0	58
2	929	1040	15.3	57

2. Discussion

According to the results of mechanical properties and metallurgical structure, the material of stud bolts was not found defective and should be considered suitable for its application containing both tempered martensite and moderately high yield strength. Presence of two fatigue propagation areas indicated that the surface of the stud bolt was subjected to fretting on opposing sides. After the initial spread of the short cracks, their propagation was further enhanced by alternate bending motion induced by vibrating oscillations of the engine. This process was more severe when more stud bolts failed, causing a cascade effect, because the amplitude of free motion was larger. As it was observed on the last unbroken stud bolt, it has experienced even minor plastic deformation due to excessive loads and large amplitude of oscillations. Severely worn areas were observed on the surface of stud bolts along with already developed cracks. According to general assembly schematics in Fig. 1b, the main cause of failure is due to improper design of the mounting assembly. The surface of stud bolt comes in contact with a base plate underneath the vibrating engine. An actual clearance hole is too large and reduced section of the bolt should be enclosed in the housing ideally. In this case, the amplitude of oscillatory motion caused fretting damage on the lower side of stud bolt.

Conclusions

In this paper, the failure of undercut double end stud bolt was analyzed to determine the failure mechanism with the use of fractography analysis and examination of its microstructure and mechanical properties. Fretting fatigue was identified as the cause of failure because of relative motion between stud bolt and the base plate of vibrating motor. Cracks initiated by fretting were then propagated as fatigue cracks due to alternate bending loading leading to a series of subsequent fractures. Reduction of oscillatory motion or clearance hole redesign is necessary to prevent such failures in the future.

Acknowledgments

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