Case Studies in Engineering Failure Analysis 8 (2017) 28–35

Contents lists available at ScienceDirect

Case Studies in Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/csefa

Failure analysis of the fasten system of wheels used in mining pickup trucks

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ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form 17 February 2017
Accepted 20 February 2017
Available online 6 March 2017

Keywords:
Mining
Bolts
Fatigue
Cracks

ABSTRACT

Regardless of their specific applications, all the vehicles used in mining operations are subjected to severe working conditions that reduce in a considerable amount, their active in-service life. In this work, the causes that promote failure of the fasten system and subsequent ejection of the wheels of passenger pickup trucks used in open-pit mines are analysed. By means of scanning electron microscopy, optical microscopy analyses and hardness tests, it was found that failure of the fasten system is characterised by a series of synergetic steps that include, the plastic deformation of the lug nuts caused by deficient tightening practices, fatigue and plastic deformation of the bolts. When combined, these phenomena leaded to the formation of cracks that propagated in the radial direction of these elements. The reasons that promote the development of this kind of failure are presented and discussed in this investigation.

1. Introduction

Nowadays, safety standards in mining operations are becoming stricter not only because failure of the equipment leads to production delays which undoubtedly, exert considerable economical losses. Regardless of the fact that failures in mines are always reflected as production costs increments, labour safety is always priority at any single step in the production processes even during transport of personal to the mine core or during the operation of specialized equipment [1–8]. Based on this premise, the present investigation deals with the failure analysis of the fasten system of transportation vehicles used in open-pit copper mines, which was expressed as the ejection of the wheels while in motion and that unfortunately, caused human casualties.

2. Experimental procedure

The wheels of the vehicles used for the transportation of employees of an international producer of copper ore, are fixed by a fastening system that includes 12×1.5 mm lug-nuts and their bolts. During operation and given the aggressive conditions of the roads where these vehicles transit and that include trail roads with stones, numerous turns and hills with pronounced steps, the pair lug-nuts tends to lose therefore, the driver needs to fasten the system again without following a defined standard and without using a calibrated instrument. The company claimed that a standard related to proper

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http://dx.doi.org/10.1016/j.csefa.2017.02.001
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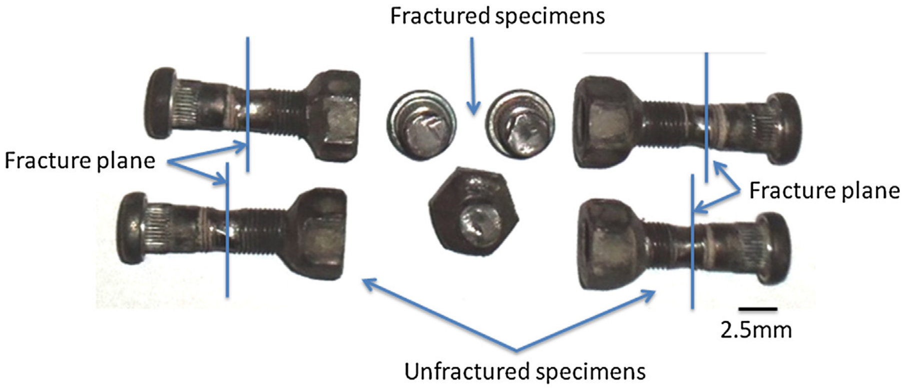

Fig. 1. Photographs of the machines elements before and after failure.

Table 1
Main characteristics of the elements studied.

Element characteristics				Chemical composition Alloying elements % wt					
Machine element	Steel grade	Hardness values (HRC-HV)		Fe	C	Cr	Si	Mn	S
Bolt	SAE 5140	29 HRC	296 HV	Bal.	0.43	1.17	0.218	0.78	0.010
Lug-Nuts	SAE 1020	10 HRC	196 HV	Bal.	0.15	0.054	0.017	0.40	0.016
SuggestedBolt	SAE J429 Grade 5	25-34 HRC	266-336 HV	Bal.	0.28–0.55	–	–	–	0.050
Suggested Lug-Nuts	SAE J995 Grade 5	32 HRC	318 HV	Bal	0.30–0.55	–	–	0.30 min	0.50 max

tightening procedures of the wheels used in this sort of application does not exist. Based on this premise; the wheels are tightened approximately once a week collecting no information on the torque that is applied to the system. To determine the reasons that promoted the development of accidents related to wheel ejection, the components of the wheel fasten system of vehicles that presented this problem were inspected before and after failure.

As a first step, the chemical composition of the materials of both components was determined by means of fluoresce spectroscopy. After these tests, specimens with and without failure were carefully sectioned using a precision saw coupled with a diamond disc. Copious amounts of coolant were used during this procedure to avoid sample overheating. Once cut, the specimens were prepared for metallographic inspection following standard procedures that included grinding with various grades of silicon carbide (SiC) emery papers, polishing stages with diamond pastes of 6 and 1 μm on soft cloths and final polishing using colloidal silica. After polishing, the specimens were etched with a solution of 3% nitric acid HNO_3 in ethanol CH_3CH_2OH (Nital 3%). The microestructural features and the failure characteristics of the specimens were analysed using both light optical and scanning electron microscopy coupled with energy dispersive X-rays. In addition, hardness measurements were performed on the specimens at locations of interest using a Vickers indenter applying a 50 g load during 15 s.

3. Results

Fig. 1 shows photographs taken from specimens removed from a wheel before and after failure which is expressed by fracture of body of the bolts. It is worth mentioning that the thread of the lug-nuts did not present fracture but exhibited a considerable amount of plastic deformation. The chemical composition (%wt) and measured hardness values of the lug nuts and bolts taken from the vehicles are presented in Table 1. This table also includes the hardness values and chemical composition of steels that are suggested for machine elements used in this application according to SAE standards [9]. Comparison of the data allows to identify that the chemical composition of the faulty bolts does not vary much from the materials suggested by the standard however, a considerable variation of the chemical composition of the lug-nuts can be observed.

Regarding the metallographic inspection of the specimens, Fig. 2 shows the microstructure that was revealed after etching the polished specimens. From this picture, it is possible to identify that the bolts (Fig. 2a) present a tempered

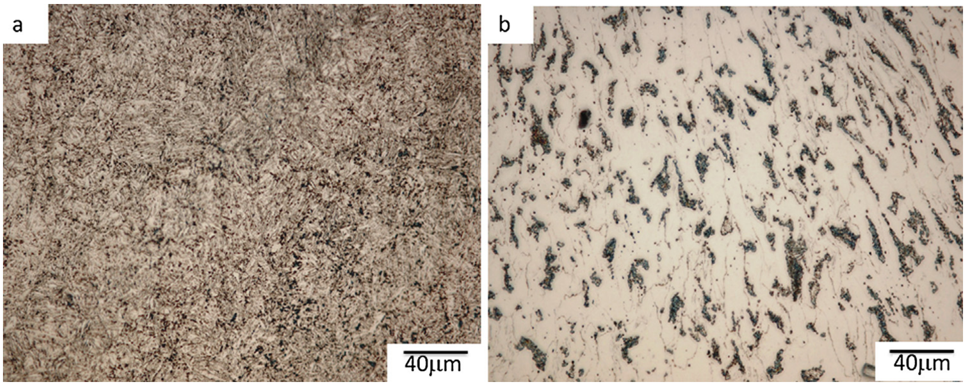

Fig. 2. Microstructures of the machine elements. a) bolts. b) lug-nuts.

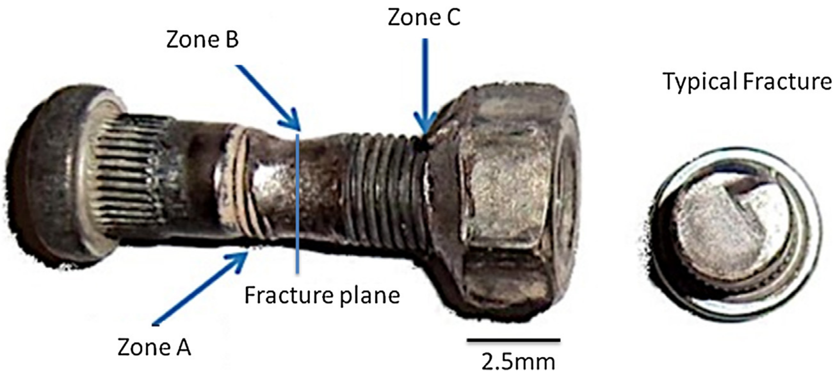

Fig. 3. Characteristic zones formed on the lug nut before failure by fracture.

martensite matrix that is typical of high resistance machine elements for this application [9,10]. Contrarily, the lug-nuts (Fig. 2b) presented a matrix comprised by ferrite grains with dispersed pearlite islands.

Alternatively, the visual aspect of near-to-failure specimens taken from a wheel that was not ejected is presented in Fig. 3. From this figure it is possible to note the presence of three characteristic zones. The first of these corresponds to damage of the original limit of the thread of the bolt (zone A) together with two zones that denote severe plastic deformation of the threads of the bolt and the lug-nut (zones B and C respectively). In addition, the wheels that failed during operation of the vehicle exhibited fracture of at least 4 bolts. The results of a greater detail inspection of these specimens conducted with a stereoscope allows to suggest that all of them presented the same distinctive namely beach marks, cracks that propagate from the surface to the centre in the radial direction of the bolt and necking (Fig. 4a–c). Apart from these morphological features, most of the machine elements that presented exhibited a considerable amount of oxide on the fracture surface as it is clearly shown in Fig. 4a.

After the visual inspection of the fractured specimens a metallographic analysis was also conducted for a pair of machine elements before the possible failure of a wheel, i.e. just before tightening practices. The results from this analysis are presented in Fig. 5 where it can be appreciated that, after one week of operation, the lug nuts and bolts are severely deformed judging by the shear pattern that is established in the vertical direction. In addition, void nucleation and crack propagation in the radial direction were frequently observed for both machine elements together with plastic deformation of the crests. In some zones plastic deformation was quite severe that fragments from the lug-nuts were removed and trapped at the interface formed between the machine elements (Fig. 6). Furthermore the lug-nuts also presented a severe overetching this phenomena being only observed particularly at the crests of the thread (Fig. 7) where also, a concentration of plastic deformation and a crack were also found.

4. Discussion

The evidence collected from the specimens that failed, in addition to the information obtained from their metallographic analysis allows to state that the main degradation mechanism experienced by the machine elements deals with fatigue of

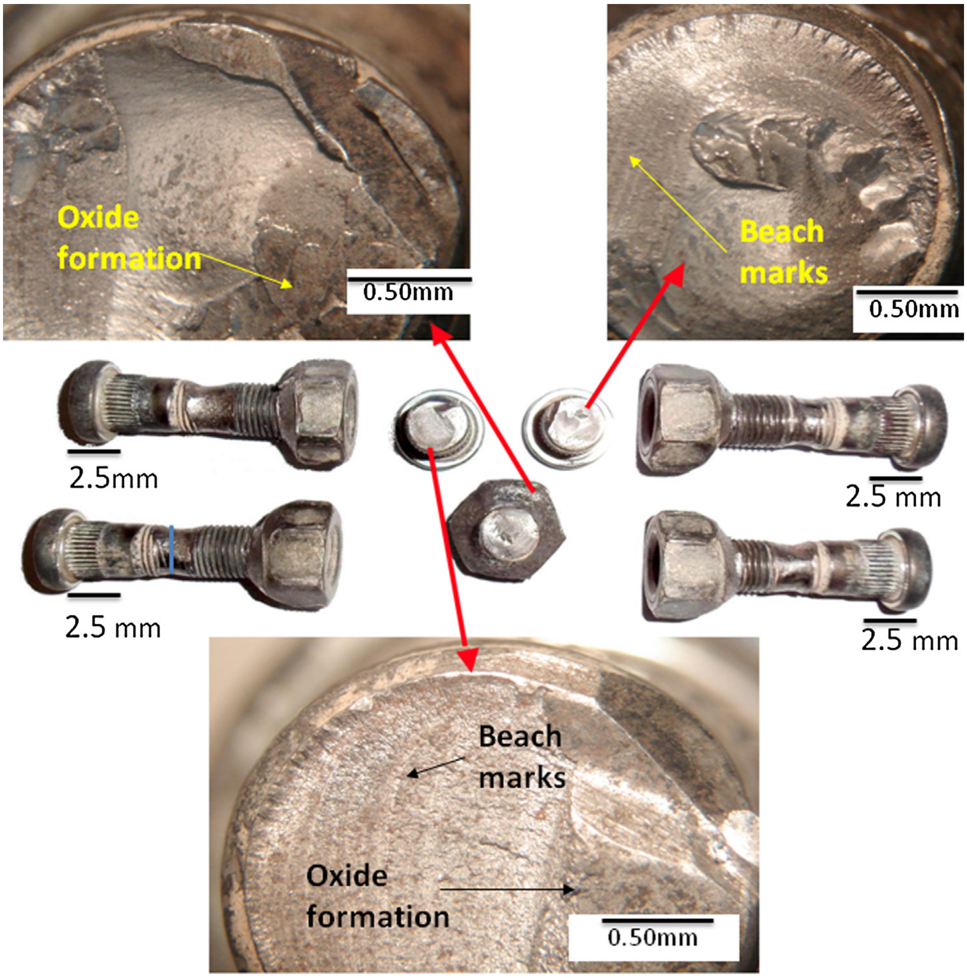

Fig. 4. Characteristic zones formed in fractured specimens.

the bolts, a phenomenon driven by plastic deformation of the lug-nuts. The steps in which this process occurs is explained accordingly.

As a first premise and by means of the metallographic analysis, it was determined that the lug-nuts of specimens that presented failure presented a ferritic-pearlitic microstructure. From the point of view of the theory of mechanical design and defined standards that apply to machine elements for automotive applications [9,10], the combination of these materials particularly for this application is not suitable given that bolts of high strength steel must be coupled with lug-nuts of similar metallurgical characteristics; this of course was not the case and lug nuts similar to an AISI 1020 steel were used [11]. In addition, during this inspection, it was also found that severe plastic deformation was experienced by the lug-nuts as it shown in Figs. 5 and 6. The deformation experienced by these machine elements in faulty specimens can be associated with the overtorque applied every time that the lug-nuts where tightened when they became loose. Certainly this action exerted a stress sate that clearly exceeded the yield strength of these elements and caused plastic deformation by cold working which can be proven by the microhardness values taken at these zones which are shown in Fig. 8. These values where obtained after the development of tightening experiments in pair of new machine elements with a digital torque wrench which prove that, when the torque exceeds a value of 167.5 N-m (which is the value of torque suggested for this vehicle according to the manufacturer), plastic deformation occurred.

Upon the deformation of lug-nuts, gaps were created at different zones between the lug-nuts and bolts that promoted the formation as non conformal contact surfaces as it was shown in Figs. 6 and 7. Given the harsh conditions of the roads where these vehicles transit, undoubtedly, a vast amount of cyclic loads acted on the bolts (as it was suggested by the shear pattern that can be clearly appreciated in Fig. 5) and, as these elements were not properly fixed the tension applied to them was lost, they entered into a fatigue state. The nucleation and propagation of cracks from the surface of the bolts to their geometrical centre shown in Fig. 7 can be considered as the main evidence that supports this phenomenon. Once a considerable amount of cracks were developed, fracture of the bolts occurred (Fig. 4) and with this, the detachment of the wheels from the vehicle.

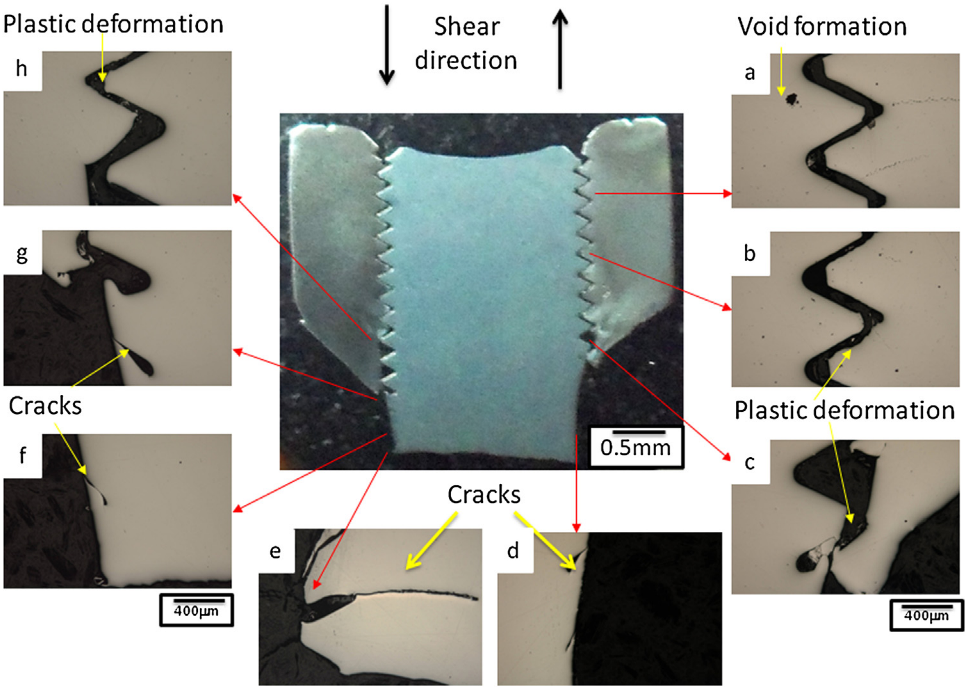

Fig. 5. Severe plastic deformation of lug-nuts and bolts, and phenomena that comprise this degradation mechanism.

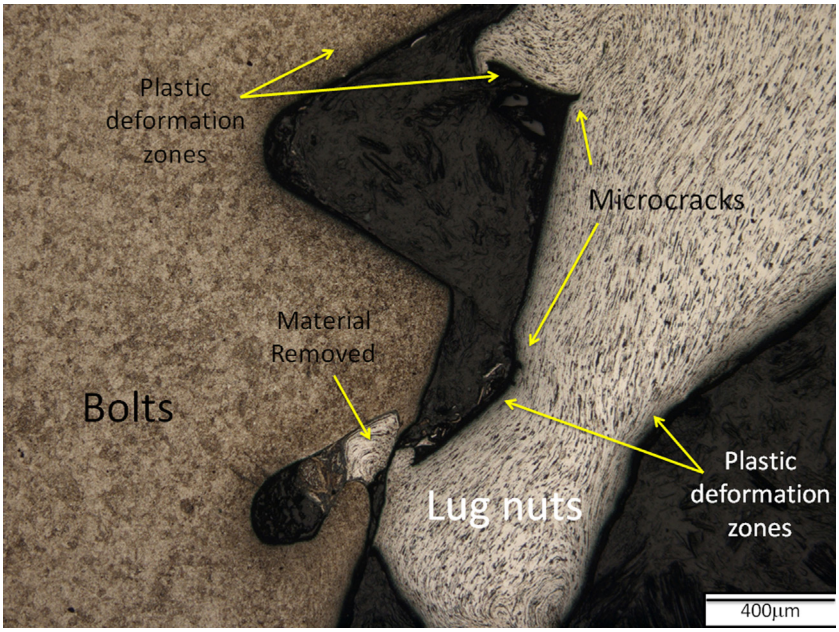

Fig. 6. Greater detail optical micrograph showing localized plastic deformation of lug-nuts and bolts.

Another important aspect that was found during the metallographic inspection of a particular set of faulty specimens, was the formation zones (revealed by means of overetching of the samples during metallographic preparation) localized at the top of the crests of the thread, in fact, some of these zones also presented some degree of plastic deformation as it can be appreciated in Fig. 7 and with greater detail in the backscattered electron micrograph shown in Fig. 9. This micrograph suggests the existence of a phase transformation from martensite to ferrite where the plastic deformation of the latter phase is also observed. This phenomenon can be associated with various mechanisms the most common among these, decarburization during heat treatment practices [12]. This was probably the case because the carbon content %wt that

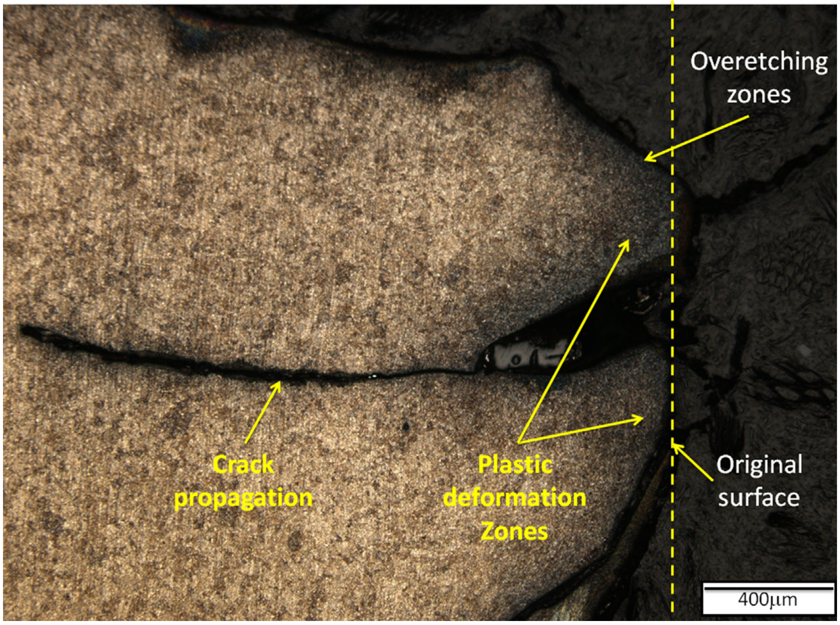

Fig. 7. Localized overetching, plastic deformation at crests and fracture propagation in a bolt.

measured at various of these zones by point energy dispersive X-ray analysis (EDX) in the SEM (Fig. 9b and c), suggests that

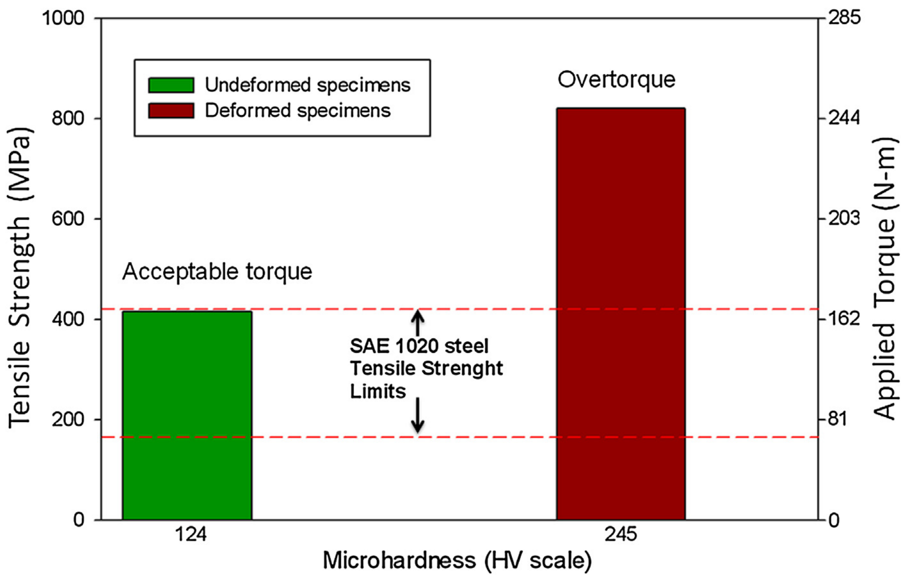

Fig. 8. Tensile strength equivalent to their Vickers hardness number of the bolts after the application of different torque values.

the carbon content measured at point 1 in Fig. 9a) in the martensite region, is greater (0.25%wt) than the carbon content in ferrite that resulted (0.09%) (marked as point 2 in Fig. 9b), suggesting that a phase transformation could occur at this location. However, as EDX analyses have only a semi-quantitative character, micro-hardness measurements were taken using the Vickers scale showing that the hardness values taken in the ferrite region (HV = 150 ± 15) are effectively lower if compared with the values of hardness taken in the martensitic matrix (HV = 320 ± 5) proving that a different phase composition exists at these regions.

Ofer et al. [12] suggested that local decarburization of tool steel machine elements promotes failure by crack formation due to phase mismatch hence; the differences in the elastic properties between ferrite and martensite at the crests of the thread and the strain accumulated due to cold working are enough reasons to promote crack nucleation and further

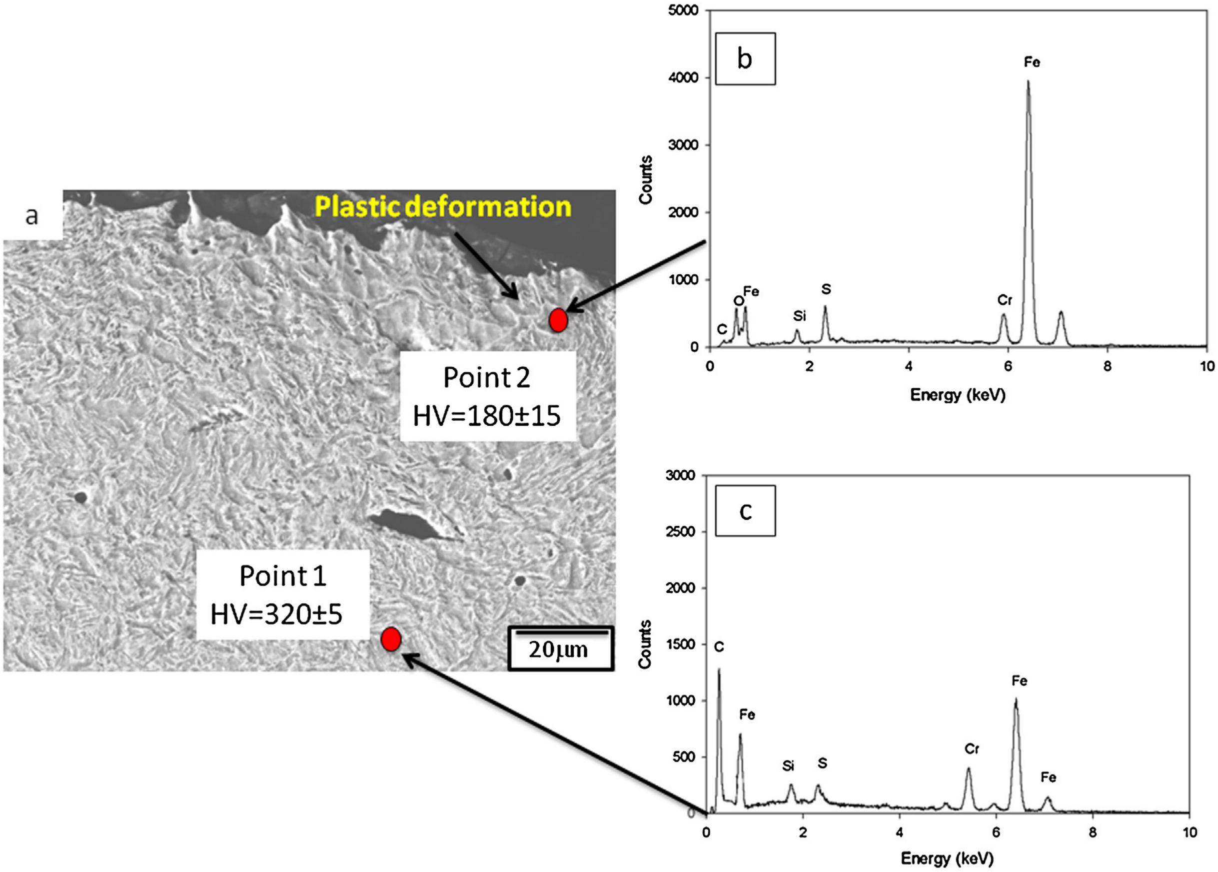

Fig. 9. Scanning electron micrographs and energy dispersive X-Ray analyses of characteristics zones formed in the bolts.

propagation at these locations. The mechanism here presented agrees with the investigation conducted by Baggerly [13,14] that suggests that strain hardening resulting from the application of overtorque of high strength lug-nuts leads to fracture of high strength bolts. Unfortunately establishing whether decarburization of these zones was due to deficient heat treating practices or by frictional heating given by the contact of machine elements that do not fit properly cannot be solved with the information collected from the specimens that presented failure at this point.

5. Conclusions

The detachment of wheels from vehicles used in open-pit mine operations is directly related to a bad combination of materials for the application and the overtorque applied by the driver when the wheels became loose. This action caused the plastic deformation of lug-nuts leading to establishment of non conformal surface established between the machine elements and that exert a fatigue state in the bolts and that promotes fracture during operation. Local decarburization of bolts can be considered as another reason that promotes crack and subsequent failure of bolts even though the reasons that promote the presence of this phenomenon could not be defined.

Acknowledgments

The authors would like to thank the National Council for Science and Technology Mexico (CONACyT) Universidad Autónoma de Nuevo León (UANL) in Mexico and, SIMET-USACH and DICYT from Universidad de Santiago in Chile for the support provided to develop this investigation.

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