

Microstructural Characterization and Cause Analysis of Fracture Surface Burrs in Lockbolts

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Abstract: Lockbolts are a category of rivets widely applied in bridge steel structures, mining machinery, rail transit and other fields. After installation, its fracture surface must be regular and free of sharp burrs. Previous inspections identified sharp burrs on the fracture surfaces of some production batches after pintail break-off, indicating noncompliance with the product specifications. Samples exhibiting abnormal fracture surfaces were subjected to systematic failure analysis, including low-magnification examination of acid-etched longitudinal sections, longitudinal metallography, macroscopic and microscopic fractography, and energy-dispersive X-ray spectroscopy of longitudinal sections. The abnormal fracture surfaces were ultimately attributed to banded segregation of Mn or C in the lockbolt core. Differences in solute content disrupted the homogeneity of the steel and produced alternating bands with different ductility and toughness. Under tensile loading, sliding along the segregation bands generated axial cracks. These cracks interacted with transverse cracks originating at the root of the breakneck groove, ultimately producing sharp fracture surface burrs inclined at approximately 45°.

Keywords: Lockbolt; Banded Segregation; Fractography; Failure Analysis of Metallic Materials

1. Introduction

1.1 Research Background

In recent years, increasing demands on fastened joints in modern machinery and equipment, high-speed trains, and high-performance aircraft have made riveting a preferred mechanical joining method worldwide because of its low weight, low cost, high reliability, and simple installation process [1].

During lockbolt installation, the installation tool plastically deforms the collar, forcing the collar metal into the annular grooves of the pin to create a permanent joint [2]. Unlike conventional bolts, which generate clamping force through torque-driven rotation, lockbolts achieve complete engagement between the collar and pin through this installation process, producing a permanent clamping force [3]. Compared with other fastener types, lockbolts offer the following advantages [4]:

1. Excellent mechanical performance: for the same nominal size, a lockbolt assembly provides over 10% more clamping force than a high-strength bolt, improving joint safety.
2. Consistent axial force: the variation in axial force in a lockbolt joint can be kept within 5%, providing greater consistency than the 25% variation associated with bolted joints.
3. Resistance to loosening: fastening is achieved through plastic deformation of the collar. After installation, there is no clearance between the collar and the annular grooves of the pin. Transverse vibration therefore does not cause relative rotation, preventing loosening.
4. Excellent fatigue performance: a smoothly rounded groove profile can reduce stress at the groove root by approximately 30%, substantially extending the fatigue life of the lockbolt.
5. Improved corrosion resistance: the distinctive locking collar structure provides greater corrosion protection at the joint and reduces the likelihood of delayed fracture.

1.2 Overview of Lockbolts

The locking grooves on the pin engage with the collar during installation, while the pull grooves at the pintail provide a gripping surface for the installation tool. In a break-off lockbolt, the pintail separates at the breakneck groove once the tensile load required for assembly is reached [5]. The main research object of this study is the 22 mm-size lockbolt, which consists of a head, a

plain shank, locking grooves, a breakneck groove, and pintail pull grooves, as shown in Figure 1. Its automatic riveting assembly principle and forming process are illustrated in Figure 2.

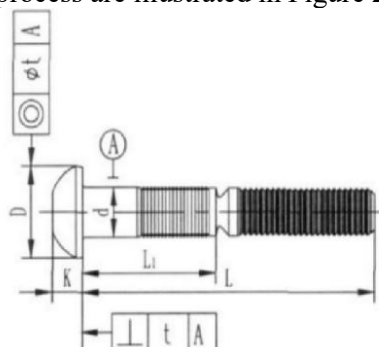


Figure 1. Lockbolts

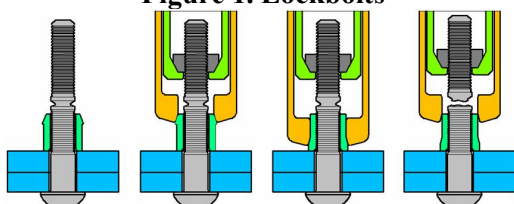


Figure 2. Schematic of Lockbolt Installation

1.3 Scope of the Study

In accordance with the relevant technical requirements, after lockbolt installation, the fracture cross-section of the lockbolts fracture groove shall be regular and free of sharp burrs. Previous inspections revealed uneven fracture surfaces and burrs in some production batches. This study investigated these defects.

2. Experimental Methods

2.1 Basic Procedure for Failure Analysis of Metallic Materials

Failure analysis of metallic components, including fasteners, generally follows a common procedure, which can be summarized as follows [6]:

- 1) Investigate the service conditions and failure circumstances of the component to determine its loading mode.
- 2) Collect samples from the fracture surface and surrounding material and prepare them for examination.
- 3) Examine the fracture surface macroscopically and microscopically to identify the fracture type.
- 4) Examine the microstructure at and near the fracture surface to determine its relationship with the fracture morphology.
- 5) Test the mechanical properties of the samples, including hardness and tensile

strength.

- 6) Use the evidence obtained to identify the cause of failure and propose corrective measures.

2.2 Sample Preparation

1). Sampling

Preserve the entire fracture surface; for a broken lockbolt, both mating fracture surfaces should be retained. Wire electrical discharge machining or cutting with coolant is preferred. Flame cutting or cutting without cooling may overheat and anneal the sample, compromising subsequent microstructural examination.

2). Fracture Surface Preparation

Severe vibration during fastener fracture may deposit dust, metal debris, or coating fragments on the fracture surface, obscuring its microscopic features. Ultrasonic cleaning can be performed using a solvent that does not react with the metal, such as ethanol or acetone. If contamination has already produced an oxide layer, a weak acid such as citric acid can be used to treat the oxide on the fracture surface.

3). Preparation for Microstructural Examination

After sectioning the material near the fracture, the samples were mechanically ground with 220-, 800-, and 1200-grit alumina abrasive papers to progressively smooth the surface. Further polishing with a velvet polishing cloth and polishing suspension removed scratches and surface irregularities introduced during grinding. Subsequent preparation depended on the intended examination. For low-magnification examination, the samples were ground flat with 800-grit abrasive paper and then etched in a 50% hydrochloric acid solution heated in a water bath for 15–20 min to reveal the macrostructure. For metallography, the surfaces were polished to a mirror finish, etched with 5% nitric acid in ethanol, and rinsed with ethanol before observation.

2.3 Challenges and Distinctive Features of the Present Failure Case

Most failures discussed in the literature on metallic materials involve abnormal fracture before a component reaches its design failure load or intended service life: a component breaks when it should remain intact. A mature, comprehensive procedure has been established for analyzing such sudden, unanticipated fracture failures. By contrast, the lockbolt is designed to fracture during installation. Conventional failure analysis

procedures and methods are therefore not fully applicable, and the specific causes of its abnormal fracture behavior require further investigation.

3. Experimental Results and Analysis

3.1 Examination and Testing

The macroscopic appearance of lockbolts with fracture surface burrs is shown in Figure 3(a, c), while lockbolts with normal fracture surfaces are shown in Figure 3(b, d). The uneven fracture surfaces exhibited sharp burrs in the core. Each burr had a relatively smooth inclined face on one side and an axial, woody fracture surface on the other, with a corresponding depression beneath it.

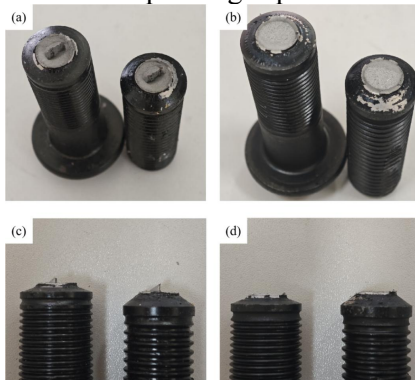


Figure 3. Lockbolt Fracture Surfaces: (a, c) Abnormal Fracture Surfaces; (b, d) Normal Fracture Surfaces

Lockbolts with particularly severe burrs were selected from the same production batch and sectioned as illustrated in Figure 4. The fracture surfaces were examined first. The macroscopic image in Figure 5 shows a distinct woody fracture morphology. According to the literature [7], woody features on tensile overload fracture surfaces generally indicate elemental segregation or inclusions that deflect the crack propagation path during tension. Industrial experience suggests that an axial woody fracture morphology in the core is associated with corresponding banded features in the material, such as banded martensite, sorbite, or segregation bands.



Figure 4. Schematic of Sample Sectioning

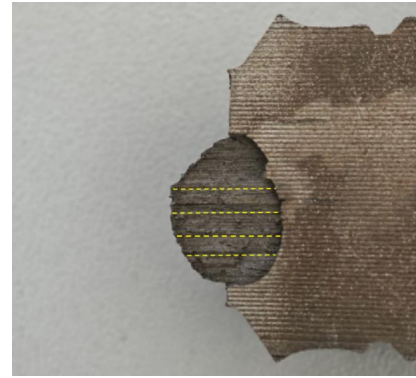


Figure 5. Macroscopic Appearance of the Lockbolt Fracture Surface

Scanning electron microscopy (SEM) revealed extensive intergranular fracture and numerous secondary cracks on the fracture surface, as shown in Figure 6. These features were tentatively attributed to grain-boundary segregation. A small number of quasi-cleavage facets were also observed elsewhere, as shown in Figure 7. Under normal conditions, grain boundaries have greater cohesive strength than the grain interiors. However, impurity enrichment or precipitation of brittle second phases at grain boundaries can make them preferential paths for crack propagation, resulting in intergranular fracture [8]. Energy-dispersive X-ray spectroscopy (EDS) at the bottom of the woody grooves, shown in Figure 8, revealed markedly elevated Mn and S contents, suggesting possible Mn segregation or MnS inclusions.

To further identify the cause of the woody fracture morphology, the internal structure of the samples was examined. Low-magnification observation of acid-etched longitudinal sections was performed first, as shown in Figure 9. Numerous dark segregation bands were observed along the axial direction in the core.

The samples were then examined metallographically, as shown in Figure 10. Dark axial bands were present in the core both near and away from the fracture surface. At higher magnification, these bands showed no distinct grain boundaries and were provisionally identified as Mn or C segregation bands.

SEM examination was conducted to further characterize the banded structure, as shown in Figure 11. Figure 12 shows elongated etch depressions extending along the axial direction in the sample core. EDS confirmed Mn and C segregation within these bands. Solute-rich segregated regions are etched more rapidly and therefore generally appear as dark etch depressions [9].

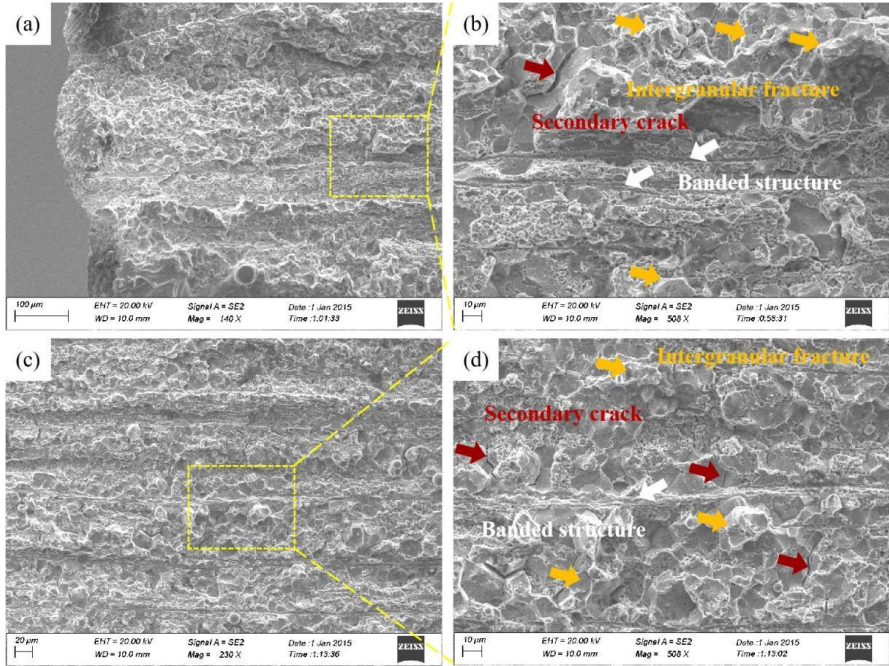


Figure 6. Micrographs of Different Regions of the Lockbolt Fracture Surface

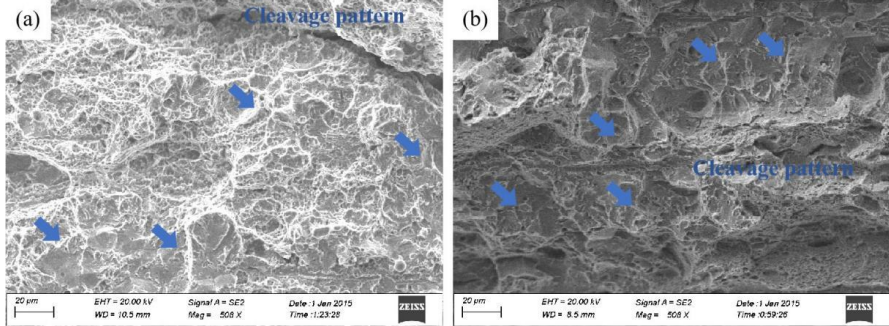


Figure 7. Micrographs of the Lockbolt Fracture Surface

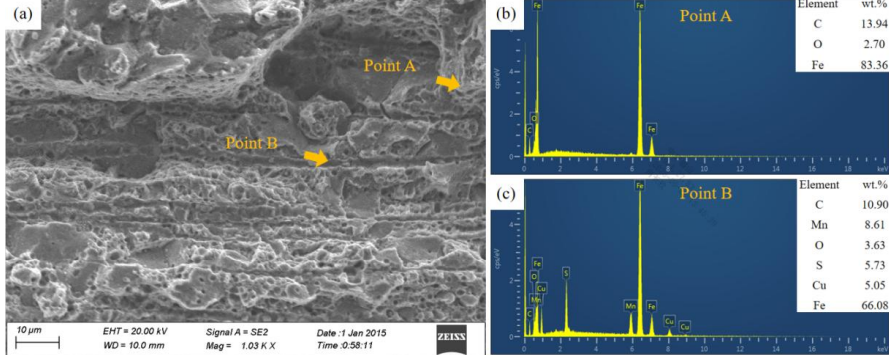


Figure 8. EDS Results for the Lockbolt Fracture Surface



Figure 9. Longitudinal Macrostructure of the Lockbolt

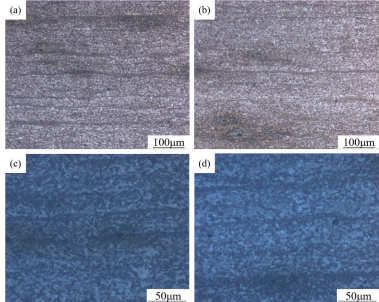


Figure 10. Longitudinal Microstructure of the Lockbolt

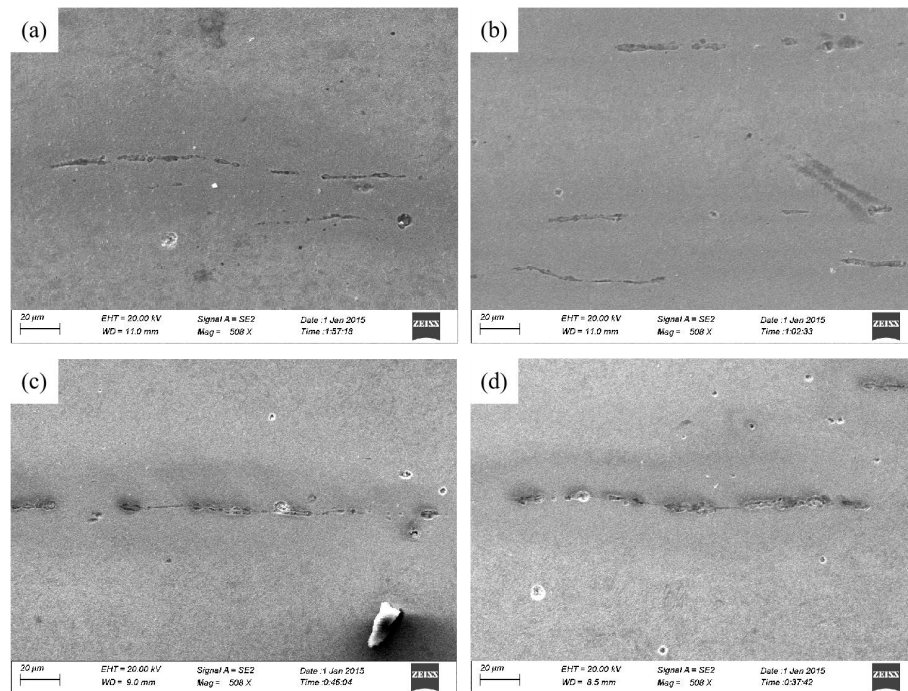


Figure 11. SEM Images of Axial Segregation Bands at Different Locations in the Lockbolt

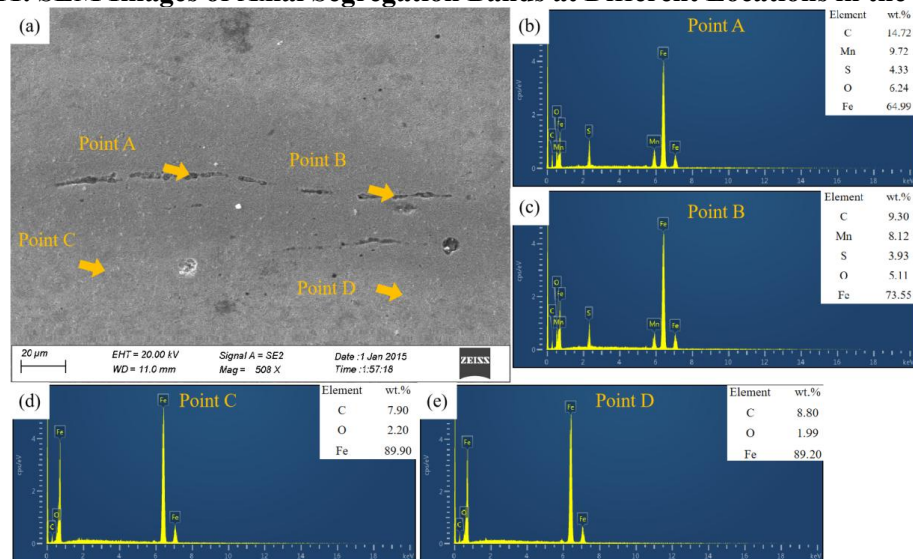


Figure 12. EDS Results for Axial Segregation Bands in the Lockbolt

3.2 Analysis and Discussion

The preceding examinations identified axial elemental segregation bands in samples with abnormal fracture surfaces. During industrial solidification, relatively rapid cooling means that diffusion in the solid phase is much slower than the advance of the solidification front. Solute atoms cannot diffuse sufficiently, leading to nonequilibrium solidification. The dendrite cores solidify first and become solute-depleted, while solute enrichment in the interdendritic regions produces dendritic segregation [10]. When the cast billet is rolled into wire rod, the dendrite arms and segregated interdendritic regions of both

equiaxed and columnar grains are elongated into bands parallel to the rolling direction [11]. In production, the persistence of dendritic segregation and macrosegregation means that fine segregation bands can remain in the steel even after extensive deformation. The literature [12] indicates that axial segregation bands or banded microstructures are common in hot-rolled wire rod and wire rod for cold heading. These features cause mechanical anisotropy: they have relatively little effect on tensile strength in the rolling direction but substantially reduce transverse ductility and toughness.

Axial elemental segregation in the core disrupts the homogeneity of the steel, producing

alternating solute-rich and solute-depleted bands. Adjacent bands differ markedly in microstructure and mechanical properties, creating alternating regions with different ductility and toughness. These differences promote stress concentration between neighboring bands [13]. Under axial tension, stress concentration at the breakneck groove causes cracks to initiate at the groove root and propagate transversely toward the core. At the same time, tensile deformation causes sliding along the edges of the segregation bands, generating axial cracks. Cracks in these two directions propagate almost simultaneously and interact, ultimately producing the inclined face of a sharp fracture surface burr at an angle of approximately 45° , as illustrated in Figure 13.

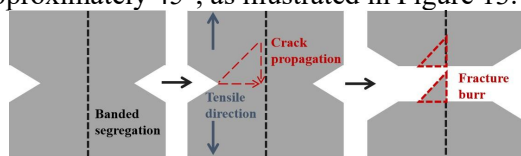


Figure 13. Schematic of Burr Formation on the Lockbolt Fracture Surface

3.3 Recommendations for Further Improvement

According to the literature [14], elemental segregation during steel solidification is the fundamental source of banded segregation in wire

rod, and severe segregation generally persists through rolling into the final rod. Controlling the casting process can therefore prevent banded segregation at its source. Specific measures include increasing the pouring superheat, increasing the intensity of electromagnetic stirring, and optimizing strand withdrawal. Segregation of alloying elements in steel ingots can also be reduced or eliminated by high-temperature diffusion annealing. Prolonged diffusion of alloying atoms at elevated temperature homogenizes the ingot, eliminating dendritic segregation and segregation-derived carbides while improving its structure, hot workability, and mechanical properties [15].

Lockbolts that previously exhibited severe fracture surface burrs were subjected to diffusion annealing at 1050°C for 4 h, followed by quenching and tempering. This treatment substantially reduced burr formation. Samples from the treated batch were examined metallographically, as shown in Figure 14. Axially aligned metal flow lines were no longer visible in the longitudinal sections. The previously continuous segregation bands had become spheroidized and discontinuous, indicating a substantial reduction in banded segregation.

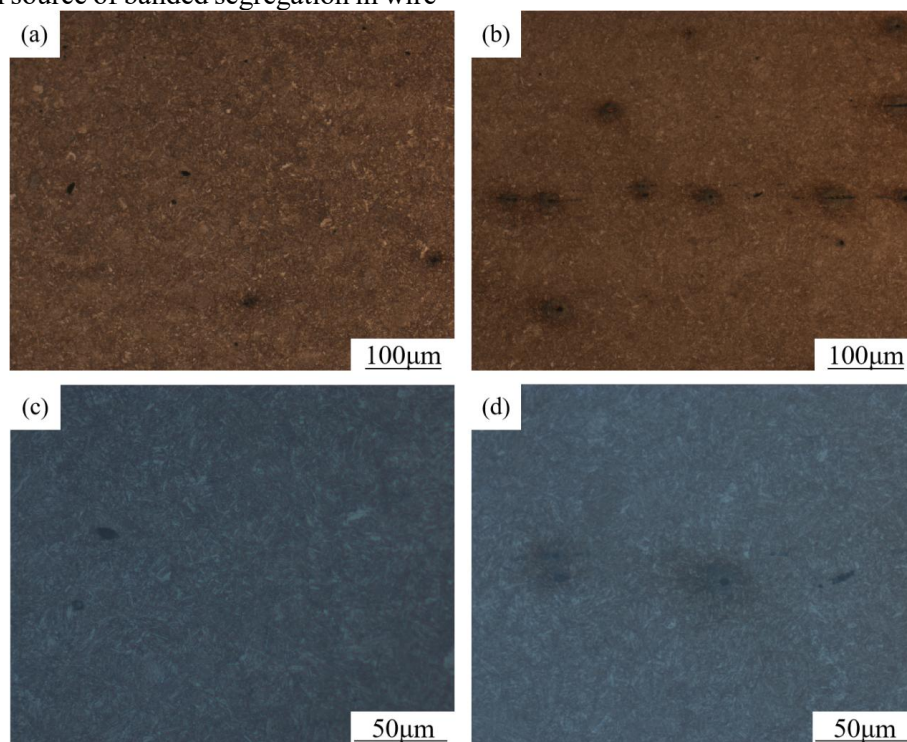


Figure 14. Microstructure of the Lockbolt after High-Temperature Diffusion Annealing

4. Conclusions

This study investigated fracture surface burrs in

lockbolts and reached the following conclusions: (1) Lockbolts exhibited sharp fracture surface burrs and predominantly intergranular fracture.

These defects were attributed to axial segregation bands of elements such as Mn and C along grain boundaries in the lockbolt core.

(2) Axial segregation bands in the core disrupted the homogeneity of the steel and produced alternating regions with different ductility and toughness. Tensile loading caused stress concentration and premature axial cracking at the segregation bands. These cracks intersected with transverse cracks from the breakneck groove, ultimately forming sharp fracture surface burrs.

(3) Processing trials demonstrated that high-temperature diffusion annealing at 1050 °C for 4 h effectively reduced banded segregation in the lockbolt core. Further work is needed to establish the detailed processing procedure.

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