ISSN 2250-3153

Failure Analysis of High Tensile Industrial Fasteners

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Abstract- This paper focused on the overview of failure analysis of high tensile fasteners. An industrial fastener comprises a very wide range of items like nuts and bolts, washers, studs, nails etc. Nuts and bolts are used for fastening purpose in industries where the replacement of pieces and the parts is necessary. Although, fastener is a low cost class C item but fastener failure is undesirable as is the first item that gets the blame when there is a failure, aftereffects of fastener failure are cumbersome which cause financial loss to machine & process. Hence, the cause of failure is understood & eliminated.

Index Terms- Hydrogen Embrittlement, Fastener failure, Fasteners plating & baking, Zinc passivation

I. Introduction

Nuts and Bolts are most commonly used items in the family of industrial fasteners and their demand is fast increasing due to expansion of industries in the country. Bolt is a piece of metal rod whose one end is upset and at the other end threading is done. Nut is a device which rolls on bolt threads. In nuts, internal threading is done while bolts bear external thread. Screw, demonstrate their true merit in the movements, assembly etc, of wooden components. Screws are most popular as fasteners which assemble, or join parts together to be made into a complete unit.

Although the fastener is the first item that gets the blame when there is a failure, our experience is that the fastener will meet the specs it was intended to meet the vast majority of the time. At that point putting experienced engineers and equipment to work can save significant time in analyzing the situation and preventing future failures.

II. TYPES OF FAILURES IN FASTENERS

i. Failure as a result of an overload

Many accidents can be characterized as an impact with a non-compliant object such as a truck impacting a concrete bridge support. The fine, gray appearance of the fracture surface is consistent with a sudden overload failure.

ii. Failure from lack of locking mechanism

In order to prevent bolts from loosening over time, various locking mechanisms are employed. They include lock washers, locking nuts, jam nuts, mechanical deformations, wire wrap, cotter pins, metal locks, expansion anchors, helical coils and polymer locking compounds. Machinery that is subject to vibratory environments usually is equipped with some sort of locking mechanism. If the locking mechanism is not applied to the machinery during manufacture, a catastrophic event may result.

iii. Metal fatigue

Metal fatigue is the phenomenon characterized by progressive crack growth during cyclic loading. A crack is often initiated at a flaw or stress riser (sharp notch) in a part. Cyclic forces such as vibrations or repeated impact cause the crack to increase in size until the part can no longer sustain the load, and a final fracture occurs.

iv. Failure from improper torque

When threaded fasteners are utilized, the amount of tightening or bolt torque is often important. Motor vehicle wheel studs require torques ranging from about 100 ft-lbs for smaller vehicles to over 400 ft-lbs for large trucks. The appropriate torque is required in order to prevent relative flexing of the two parts being fastened and to assure an acceptable mechanical connection. Bolt failures as a result of improper torque have occurred in automobile applications.

v. Corrosion failure

Corrosion of metals can be disastrous to threaded fasteners. Surface and pitting corrosion attacks threaded fasteners as a result of contact with moisture or other corroding media. Since bolts often carry high loads, stress corrosion cracking is another corrosion related failure mode. Corrosion, coupled with forces in a bolt, tends to accelerate cracking.

vi. Hydrogen Embrittlement (HE)

A permanent loss of ductility in a metal or alloy caused by hydrogen in combination with stress, either externally applied or internal residual stress.

vii. Galling

If you've ever had the pleasure of installing or removing stainless steel fasteners, you've more than likely experienced galling. Galling is a cold-welding process that results when the threads are in contact under heavy pressure and friction. Or in other words, when fasteners are assembled or disassembled. Read the article to learn more.

III. PROBLEM

A cables and control levers manufacturing company offers a full line of controls and cables for commercial vehicles, industrial machines, construction equipment, boats and special purpose vehicles.

ISSN 2250-3153

They were having bolt failure directly underneath the head of the fastener (Fig. 1).

The failure is a delayed failure. The delay is generally from one to 24 hours after installation.

Fastener was under standard load conditions. They were using higher grade fastener with 32+ HRC.

To avoid corrosion Zinc passivated fasteners are used as area of application is in marines.

Fig. 1 Fastener Failure by observed

IV. OBJECTIVE OF STUDY

- To find the root cause of failure of fasteners.
- Understand the process & factors causing failure.
- Propose best possible remedy to avoid failure & how to eliminate it.

V. METHODOLOGY FOR FAILURE ANAYSIS

According to the problem identified and the objective of study. The proposed methodology includes the step by step procedure to obtain the solution. This includes understanding process flow of metal plating, sample collection for testing.

Step 1: Understanding field conditions, loads experienced by the fastener, and other factors

Step 2: Collecting sample of both the failed piece(s) and unused parts from the same lot.

Step 3: Lab analysis - Laboratory testing will confirm whether there are any issues with that lot.

Step 4: Understanding & monitoring processes done on fastener – Plating/Galvanizing

Step 5: Finding root cause of failure in process/product selection.

Step 6: Suggesting best possible alternative.

Step 7: Comparing the results obtained with respect to the prior failure rate.

Step 8: Application of best suited process.

A. Field condition

- The failures occurred sometime after installation, usually between one and twenty four hours.
- The part was under design stress when failure occurs.
- Fastener was Zinc passivated to avoid failure due to metal corrosion.
- High tensile grade fastener was used to sustain more tensile strength.

B. Sample Selection

A Sample of 100 Pcs. is taken from both the failed piece(s) and unused parts from the same lot for LAB Analysis. LPS has a NABL certified laboratory in plant premises for testing of fasteners.

C. LAB Analysis Result

Fastener testing shows following result:

1. Unused fasteners meet the appropriate standards. Their material composition & strength was as per manufacturing IS standards.

2. Failed pieces have shown variation in tensile strength. LAB analysis shows that 97% fasteners failed due to Hydrogen embrittlement, 2% failed because of tensile failure due to over tightening & 1% due to metal corrosion. The root cause of the failure is because of hydrogen embrittlement.

After analyzing the process flow chart & type of fastener used it is found that they were using zinc passivated fastener to avoid metal corrosion. Hydrogen is getting induced in zinc plating (galvanizing) process. Hydrogen ions, which will later combine to form hydrogen molecules, trapped within grain boundaries promoting enhanced de-cohesion of the steel which caused fastener failure.

D. PROCESS FLOW CHART

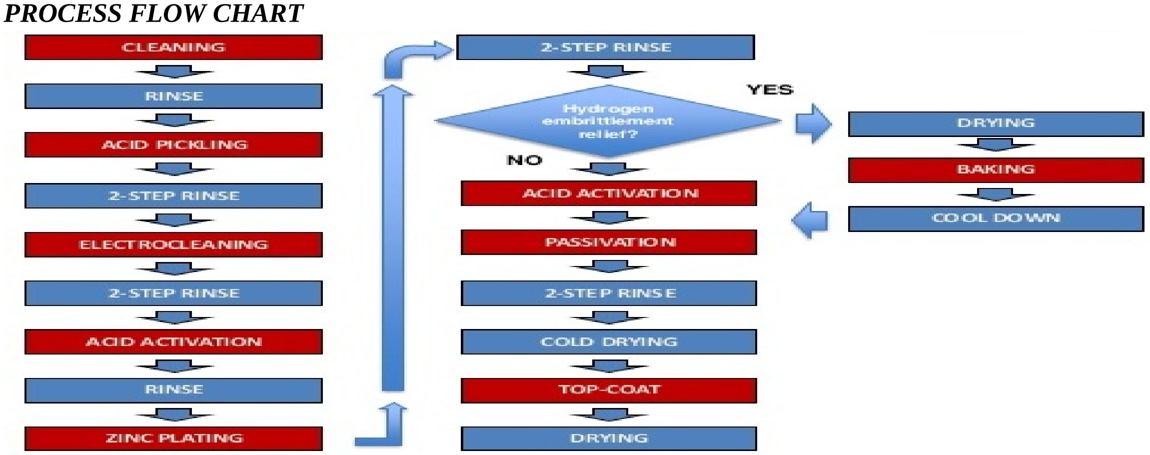

Fig. 2 Process flow chart for material plating

Fig. 2 Process flow chart for material plating

E. Hydrogen Embrittlement

Hydrogen embrittlement can be described as absorption of hydrogen ions, which will later combine to form hydrogen molecules, trapped within grain boundaries promoting enhanced de-cohesion of the steel, primarily as an intergranular phenomenon. Hydrogen embrittlement is generally associated with high-strength fasteners. Hydrogen embrittled fasteners or parts under stress can fail suddenly without any warning. Hydrogen embrittlement can occur whenever atomic or protonic hydrogen is produced from a reaction, e.g. acid pickling can react iron and hydrochloric acid to diffuse hydrogen in iron.

Hydrogen embrittlement is generally associated with high-strength fasteners made of carbon and alloy steels. Hydrogen embrittled fasteners or parts under stress can fail suddenly without any warning. Hydrogen is the most common element in the world and many acidic and oxidation reactions with steel will liberate hydrogen in various amounts depending on the specific chemical reaction.

Hydrogen embrittlement can occur whenever atomic or protonic hydrogen is produced from a reaction, e.g. acid pickling can react iron and hydrochloric acid to diffuse hydrogen in iron. During acid pickling hydrogen can be diffused into the iron. Electroplating is another process to introduce hydrogen into a metal in both the acid pickle and the plating processes.

Conditions for hydrogen embrittlement failure

Three conditions must be met to cause hydrogen embrittlement failure:
(i) steel that is *susceptible* to hydrogen damage,
(ii) *stress* (typically as an applied load), and
(iii) atomic *hydrogen*.

If all three of these elements are present in sufficient quantities, and given *time*, hydrogen damage results in crack initiation and growth until the occurrence of fracture. *Time to failure* can vary, depending on the severity of the conditions and the source of hydrogen.

Source of Hydrogen ions

Frequently, hydrogen is introduced to the fastener during the electroplating process. In these cases, the hydrogen is absorbed into the fastener during the acid cleaning or descaling process and is then trapped in the part by the plating. A subsequent baking process is typically employed to remove or displace the trapped hydrogen. Even proper baking is no guarantee of freedom from hydrogen.

Effect of Hydrogen ions

Hydrogen embrittlement failures occur where the stress in the screw or bolt is most highly concentrated when installed in an application. When tension is applied to the fastener, the hydrogen tends to migrate to points of high stress concentration (under the head of the fastener, first engaged thread, etc.). The pressure created by the hydrogen creates and/or extends a preexisting crack which grows under subsequent stress cycles until the bolt breaks.

For example, electroplating provides a source of hydrogen during the cleaning and pickling cycles, but by far the most significant source is cathodic inefficiency. A simple hydrogen bake out cycle can be performed to reduce the risk of hydrogen damage.

Factors That Influence Hydrogen Embrittlement on Parts

The severity and mode of the hydrogen damage depends on:

- A tensile strength > 1050MPa, 1000N/mm2 or
- A hardness > 32 HRC or above (10.9 grade fasteners or above)
- Source of hydrogen—external (gaseous)/internal (dissolved).
- Exposure time.
- Temperature and pressure.
- Presence of solutions or solvents that may undergo some reaction with metals (e.g., acidic solutions).
- Amount of discontinuities in the metal.
- Treatment of exposed surfaces (barrier layers, e.g., oxide layers as hydrogen permeation barrier on metals).
- Final treatment of the metal surface (e.g., galvanic nickel plating).
- Method of heat treatment. Level of residual and applied stresses.

Methods of Checking Hydrogen Embrittlement[2]

When metals are subjected to pickling processes, the metals are dissolved by the acids and hydrogen is generated. The hydrogen is also generated during electrolytic de-greasing, electrolytic pickling, and electro-plating. This hydrogen is occluded (absorbed) by the base metal, especially steel alloys and makes the steel brittle. This phenomenon is the Hydrogen Embrittlement. Parts with hydrogen embrittlement can break after being subjected to loadings. Here, we'll look delta method to see how much hydrogen embrittlement there is on plated steel.

ISSN 2250-3153

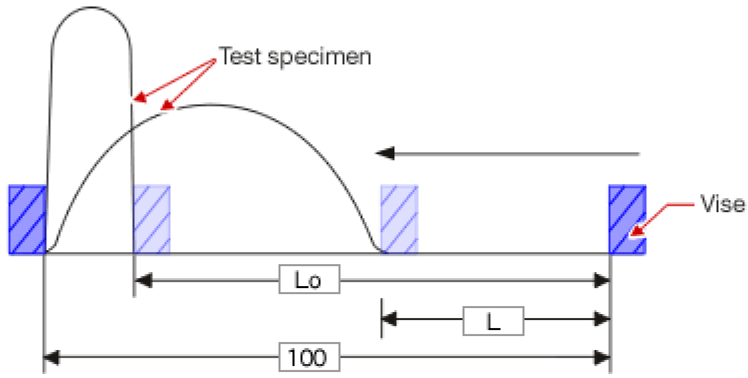

Fig. 3 Method of Checking Hydrogen Embrittlement

The method uses steel plates made of alloys susceptible to hydrogen embrittlement, press bent in a constant speed vise, and the vise travel distance to the point of breakage is measured. The distance traveled indicates the degradation of flexibility of the test specimen, in turn indicates the extent of the hydrogen embrittlement. It is also called "Slow press-bent destruction method". Fig. 3 above shows the measurement principle of the Delta Gage method.

Hydrogen embrittlement rate (%) = (L0-L) 100 / L0 …(I)

Where,

L0: Vise travel distance to breaking point for test specimen not pickled (no hydrogen embrittlement) in mm.

L: Vise travel distance to braking point for pickled test specimen with hydrogen embrittlement.

Prevention of Hydrogen Embrittlement

Steps that can be taken to avoid hydrogen embrittlement include reducing hydrogen exposure and susceptibility,baking after plating (mandatory and as soon as practical) and using test methods to determine if a material is suspect. Other options that could help in avoiding hydrogen embrittlement include the use of lower strength steels (not always viable), the avoidance of acid cleaning, the utilization of low hydrogen plating techniques and the reduction of residual and applied stress.

If any of these factors are not present, the chances of the failure being confirmed as hydrogen embrittlement are unlikely.

1. Do not electro-plate inch socket head metric property class 12.9 bolts or screws.
2. If customers insist on using electro-plated bolts and screws, suggest they consider using a Grade 8 or property class 10.9 part of a slightly larger diameter instead of using the socket head cap screw or property class 12.9 part.
3. If the customer insists on using an electro-plated socket head cap screw or property class 12.9 part, specify that the parts must be baked at 190 ^{o} -200^{o} C within one hour after plating for at least four hours. Also, conduct one of the recognized hydrogen embrittlement tests on every lot of parts to provide you the opportunity to catch hydrogen embrittlement before it is exhibited in the user's application.
4. If you must electro-plate any type of tapping screw, specify to the heat treater that the core hardness of the screws must not exceed 32 HRC.

VI. Alternative Suggested

Uncoated Fasteners: Fasteners must be oil hardened & oil tempered with minimum or no scale, coming from oil tempering, least possibilities of rusting. But, after discussing with design team they need zinc passivated fasteners for avoiding metal corrosion.

Grade 10.9 (Tensile Strength 1040 N/mm^2) and 12.9 (Tensile Strength 1220 N/mm^2) grade Fasteners are not recommended for Zinc Plating as they may absorb Hydrogen during the coating process, which then causes embrittlement of the bolts.

Baking Parts (Hydrogen De-embrittlement) after coating will reduce the risk of failure, but this process can never be assumed to be 100% effective.

Solution: If electroplating is still desired, ensure that the plater uses the proper procedures and bakes the fasteners correctly based on the Hardness of the fastener. For the requirement of Plating on Fasteners, we suggested Grade 8.8. In general, if the hardness of the fastener is less than 32 HRC, there will probably be little difficulty with hydrogen embrittlement. However, if the fastener has hardness above 32 HRC, problems are more likely to occur.

Result: Usage of uncoated fasteners is one of the best cost effective engineering solution however zinc passivation to be given up to some extent due to working condition.

Low grade fastener for Zinc passivation reduced the fastener failure by Approx 98%, rest 2% failure is found because of

- Tightening methods
- Thread lubrication
- Corrosion
- Galling

VII. CONCLUSIONS

Hydrogen embrittlement remained as the only probable cause of the failure observed. Unlike stress corrosion cracking and quenching cracks, cracks caused by hydrogen embrittlement usually do not branch neither show oxidized surfaces. Typical features of hydrogen embrittlement were observed on the fracture surfaces of both bolts. Bolts had been zinc electroplated, which is one way to introduce hydrogen into metals, and baking treatment.

If any of these factors are not present, the chances of the failure being confirmed as hydrogen embrittlement are unlikely. Unhardened fasteners or those of Grade 5 or Property Class 8.8 or lower do not fail due to hydrogen embrittlement. Parts that are cleaned by mechanical processes instead of acid are highly unlikely to fail due to hydrogen embrittlement. Failures that occur while parts are being installed are not due to hydrogen embrittlement.

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