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Metallurgical Failure Analysis of Fasteners in an Impeller Assembly

L.R. Curtis

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This paper examines a failure analysis of the bolts from a failed joint between an impeller blade and a rotating assembly unit. The bolts failed due to poor thread manufacture and installation. Sharpened thread roots led to high stress concentrations that favored crack initiation. An oddly shaped thread profile allowed friction between mismatched thread surfaces. Poor installation procedures allowed for the possibility of overtightening to nucleate cracks in the head-to-shank interface (which had a smaller radius and therefore a higher stress concentration) and possibly also in the thread roots. Each of these influences contributed to crack initiation in the bolts. After cracks had formed, bending fatigue then propagated the nucleated cracks to final fracture. The failure analysis also recommended using bolts with rolled threads, which allow a more complete fit between mating male and female threads, and assuring that an appropriate preload is placed on bolts during installation.

Keywords: austenitic stainless steel, EDS, fasteners, fatigue failure, fractography, metallography, SEM

Introduction

A company with multiple divisions (the organization and employees of which will be referenced hereafter as the client) has been operating ammonium sulfate crystallizers as part of its processing stream. An impeller assembly at the bottom of each tank provides mixing action for hot, concentrated ammonium sulfate solution. The assembly consists of three blades attached to 25.4 mm thick support plates on a rotating shaft unit. Each blade is secured by ten fasteners (bolts in blind holes) arranged in a parallelogram configuration, with five bolts above the blade and five bolts below the blade. The client has experienced occasional failures in these fasteners over the years and in October 2005 requested assistance in investigating its most recent failure.

The client installed the failed bolts in August 2005. Two types of 19.1 mm diameter bolts were in use. All ten of the bolts from the failed joint were type 1 bolts and were manufactured by the client. Because these bolts had previously experienced repeated failures, the client began purchasing type 2 bolts from an outside vendor and installing them in impeller blade assemblies, in the hope of solving the failure problem. Type 2 bolts were observed to have longer service lives than type 1 bolts; however, these bolts also experienced failures. The client sent all ten type 1 bolts from the October 2005 failure for analysis and requested identification of the root cause of failure. The client also sent two used type 2 bolts and requested a comparison of the manufacturing differences between the two bolt types. These type 2 bolts were installed in August 2005 and removed in October 2005. During that time, they were among ten type 2 bolts that connected one of the other two impeller blade support plates to the same shaft hub. In order to facilitate the comparison, two new, unused type 1 bolts were requested and received from the client.

During installation of all bolts, the client tightened each bolt as much as possible with an ordinary wrench. Applied bolt torques were not measured, nor were any washers used. After tightening, the head of each bolt was secured in place with a tack weld. After the failure event, the remaining shank pieces were removed and collected without noting their location in the parallelogram configuration. The client recovered only eight bolt heads, and these

L.R. Curtis, The M&P Lab, 2210 Technology Drive, Schenectady, NY 12301. Contact e-mail: curtisl@the-mandp-lab.com.

pieces were matched to shank areas by visual inspection (1×) of fracture surfaces. All ten bolts received an arbitrarily assigned letter of the alphabet (A-J) as identification. Because no effort was made to record which bolt pieces came from which holes, a correlation of fracture features with bolt location could not be ascertained.

Initial Examination

Calipers were used to measure the shank lengths of headless fractured bolt pieces (in essence, the distance between the end of the bolt and the fracture surface). Table 1 lists the results. Table 1 also lists the distance to the fracture surface, which is the distance from the contact face of the bolt head to the fracture surface as calculated from these measurements, with the assumption that the bolt head measures 12.7 mm in thickness and that the total bolt length measures 63.5 mm. The two type 2 bolts were also measured. The first measured 68.1 mm in total length, with a bolt head thickness of 12.0 mm. The second measured 68.0 mm in total length, with a bolt head thickness of 12.1 mm.

Fracture Surface Examination

Bolt fracture surfaces were initially observed at magnifications up to 35×. Fatigue fracture patterns were identified on each fracture surface, which universally showed signs of bending fatigue, with mild to severe stress concentrations.[1] Figures 1 and 2 show the fracture surfaces observed in bolts D and B, respectively. Likely points of crack initiation were identified for each bolt head, except for bolts I and J, for which the shank was used because no corresponding bolt head had been received. In some cases, scanning electron microscopy (SEM) was used to identify and/or confirm likely locations for fatigue crack initiation. Ductile fracture features (dimples) were prominent near thread roots. Fatigue striations could be observed at higher magnifications, as shown in Fig. 3.

Metallurgical Evaluation

One of each bolt type was submitted for metallographic analysis after ultrasonic cleaning in a light detergent wash. Each cleaned bolt was sectioned longitudinally, and one-half of each bolt was submitted for evaluation of chemical composition by energy-dispersive X-ray spectrometry (EDS) analysis. The results of this evaluation appear in Table 2, which lists the semiquantitative estimated weight percents of each constituent element in each bolt. Elements listed as "trace" did not produce significant peaks in the respective EDS spectrum.

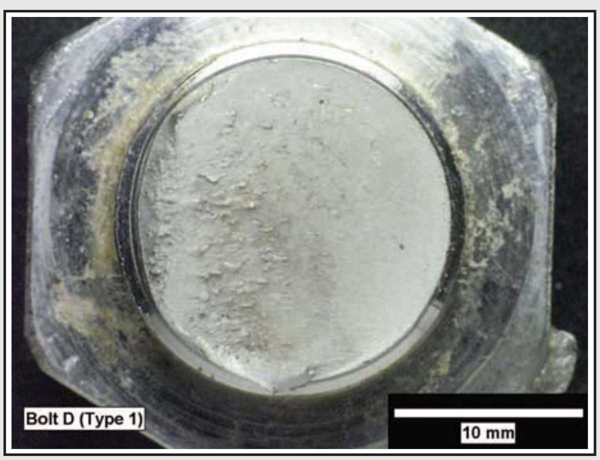

Fig. 1 *Fracture surface of bolt D (type 1 bolt)*

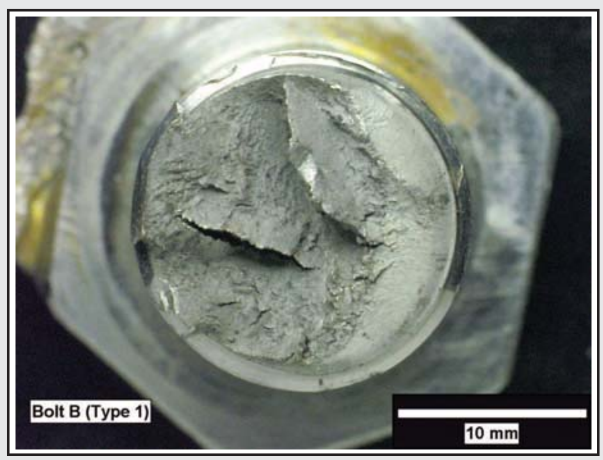

Fig. 2 *Fracture surface of bolt B (type 1 bolt)*

Table 1 Fractured Bolt Shank Measurements

Bolt	A	B	C	D	E	F	G	H	I	J
Length, mm (measured)	26.4	24.3	27.0	47.6	48.2	53.8	47.3	48.5	48.1	47.1
Distance to fracture, mm (calculated)	24.4	26.5	23.8	3.2	2.6	-3.0	3.5	2.3	2.7	3.7

In addition, the detection sensitivity for nitrogen by EDS is poor,[2] and therefore, nitrogen concentration determination by the semiquantitative EDS method was not possible. Because the client anticipated the material for type 2 bolts to conform to the limits for Nitronic 50 stainless steel, Table 2 also lists the chemical composition of Nitronic 50 stainless steel to facilitate comparison.

The other half of each bolt was metallographically mounted, polished, and then examined, using a reflected light microscope at magnifications up to 100×. In the as-polished condition, the type 1 bolt showed cracking in head-to-shank interfaces on both sides of the bolt (away from and toward the tack weld). The type 2 bolt showed no cracking at these same locations. Head-to-shank corner radii were also measured. The type 1 bolt measured 620 μm, and the type 2 bolt measured 850 μm.

The type 1 bolt showed cracking in every thread root on the side farthest from the tack weld on the bolt head. Figure 4 shows typical cracking. Cracks were also observed on the side closest to the tack weld, but these cracks were not as pronounced or extensive. Also visible in Fig. 4 was the unusual thread form of the type 1 bolt, which featured sharpened and asymmetrical roots. In contrast, the type 2 bolt had a thread form with rounded thread roots, as seen in Fig. 5. Some thread roots in the type 1 bolt had elongated features resembling pits in the thread roots directly above the fracture area

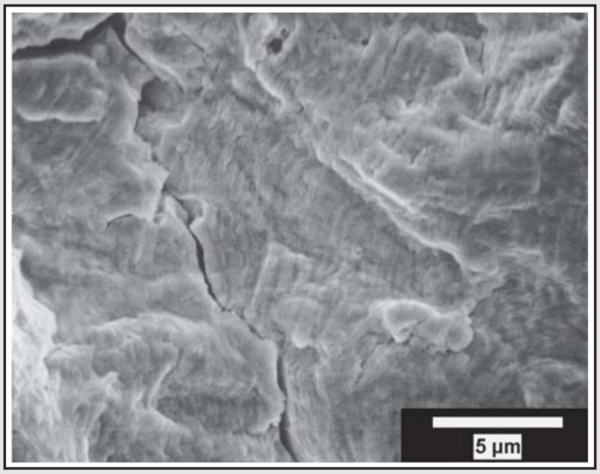

Fig. 3 *SEM micrograph of fracture surface in bolt B (type 1 bolt)*

Table 2 Estimated Semiquantitative Bolt Compositions in Weight Percent

Element	Type 1 Bolt	Type 2 Bolt	Nitronic 50
C	Trace	Trace	0.06 max
Cr	21.10	22.18	20.50-23.50
Cu	0.88	0.31	N/A
Fe	58.48	57.33	bal
Mn	4.76	4.17	4.00-6.00
Mo	2.14	1.82	1.50-3.00
N	Not determined	Not determined	0.20-0.40
Nb	Trace	1.00	0.10-0.30
Ni	11.90	12.11	11.50-13.50
P	Trace	Trace	0.04 max
S	Trace	Trace	0.03 max
Si	0.59	0.96	1.00 max
V	0.16	0.12	0.10-0.30

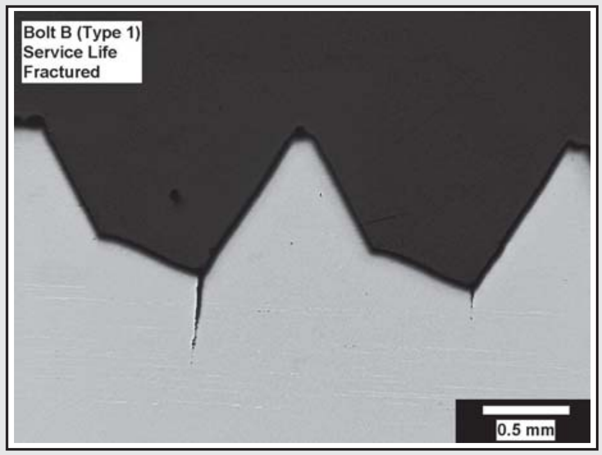

Fig. 4 *Thread profile in bolt B (type 1 bolt) showing cracks in thread roots and irregular shape of thread form*

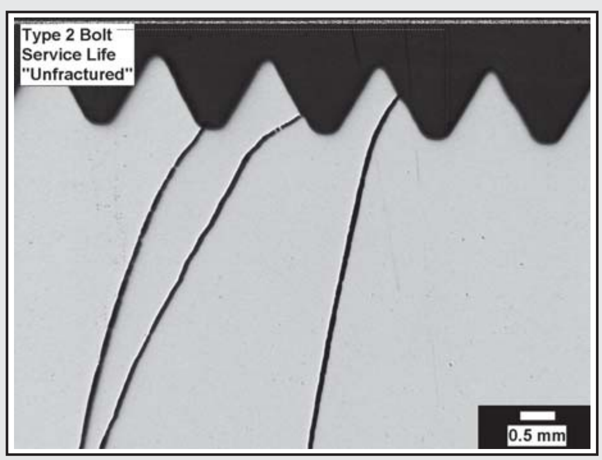

Fig. 5 *Thread form profile in type 2 bolt. The three cracks seen here were the only ones in the bolt and extend almost across the entire diameter.*

on the side closest to the tack weld. These features were elongated in the direction of the thread roots. The extent of these features increased with proximity to the fracture area.

The type 2 bolt showed cracking that initiated at or near thread roots in three locations. One of the three nucleated cracks joined with an adjacent crack; thus, only two crack ends were visible. One of the crack ends appeared pointed, similar to that of a fatigue crack; the other crack end appeared blunted and rounded, similar to that of a corrosion-assisted crack. Each of the cracks extended across almost the entire diameter of the bolt and initiated in thread roots toward the side of the bolt with the tack weld.

Each mounted sample was etched with Kalling's reagent and examined at magnifications up to 1000×. Features that had been observed in the as-polished condition were also observed in the etched samples. The inclusion content of the type 1 bolt was high; elongated oxides and sulfides littered the matrix material. The material of the type 2 bolt was much cleaner, with occasional precipitates scattered throughout the matrix. The material flow lines were also noted for each bolt. For both the type 1 and type 2 bolts, the flow lines ran parallel to one another along the longitudinal direction of the bolt. They did not conform to the shape of the thread, thus suggesting that the threads were machined rather than roll formed. The material flow lines in the type 1 bolt followed this pattern throughout the bolt profile, including the head. In contrast, the material flow lines in the type 2 bolt followed this pattern only in the area below the head; the flow lines in the head conformed to the shape of the head profile, suggesting a forged head on the type 2 bolts.

Mechanical Testing

For each bolt, Knoop microindentation hardness measurements were taken in three areas: just below the thread root on the side away from the tack weld, at the center of the bolt diameter, and just below the thread root on the side toward the tack weld. Each of these areas was located approximately 25 mm below the bottom of the bolt head. With a 500 g load and 15 s dwell time, three microindentations were made in each area. Table 3 reports the averages for each area in each bolt. Indentations were measured at 400× magnification.

The ultimate tensile strength (UTS) was also measured for an unused type 1 bolt and a used type 2 bolt. Each bolt exhibited necking before final fracture. Necking was observed in the type 1 bolt at approximately 222 kN and in the type 2 bolt at approximately 214 kN. These values were used to calculate a UTS[3] for each bolt (1115 MPa for the unused type 1 bolt and 1071 MPa for the used type 2 bolt). These values compare well with the client-specified UTS value of 1000 MPa for type 2 bolts.

Discussion

The hardness values obtained from both bolt types compare well with one another, except in the area away from the tack weld. The significantly lower average value of the type 1 bolt in this area can be explained by the cracking observed in every thread root on that side of the bolt. Although care was taken to place indentations away from visible cracking, indentations may have been made where an unobserved crack lying beneath the surface influenced the results.

The bolts generally conform to the client-supplied composition specification for Nitronic 50 stainless steel, although the nitrogen content could not be analyzed by the EDS method used to characterize the alloys. The type 1 bolt also appeared to contain more inclusions than did the type 2 bolt. However, the evidence collected appears to suggest that the larger problem leading to final failure in the bolts relates to the manufacture and installation of the bolts.

The fractured bolt length calculations in Table 1 are based on the assumptions that the bolt head is 12.7 mm thick and that the total bolt length is

Table 3 Knoop Microindentation Hardness Values (HK 500 gf)

Bolt Area	Type 1	Type 2
Away from tack weld	331	417
Center of bolt diameter	432	432
Toward tack weld	423	423

63.5 mm. The three type 1 bolts noted to have been the last to fracture (A, B, and C) all failed approximately where the 25.4 mm (1 in.) thick support plate meets the rotating shaft assembly. The other type 1 bolts appear to have fractured near the bolt head in the vicinity of the head-to-shank radius.

These results, combined with the cracking seen in the head-to-shank interface both toward and away from the tack weld in type 1 bolts, suggest that the bolts were likely overtightened during installation. However, cracking was not observed beneath the head of the type 2 bolt; thus, some bolts may not have been overtightened. The unknown torque applied during installation certainly may have contributed to the cracking observed in the type 1 bolt, but without knowing those torque values, the possibility of overtightening cannot be confirmed.

Bending fatigue was clearly the means by which a crack propagated through the material. The fatigue crack patterns on the bolts (Fig. 1 and 2 are examples) are all consistent with bending fatigue occurring in mild-to-severe stress concentrations. This observation suggests that, once initiated, the fatigue cracks propagated under high stress levels.[1] Fatigue is also confirmed by the striations viewed with the SEM, as seen in Fig. 3.

Identifying a single cause of failure, however, is more difficult. Of the two bolts observed metallographically, the type 2 bolt appeared to resist cracking better than did the type 1 bolt. The type 1 bolt had cracks in every thread root on the side opposite the tack weld. Only three crack roots were observed in the type 2 bolt. In addition, the type 2 bolt had higher crack resistance at thread roots because these areas were generously rounded, as opposed to the pointed thread roots of the type 1 bolt. The sharper thread roots created higher stress concentrations that favor crack initiation.[4] Additionally, the type 2 bolt had a larger head-to-shank radius, which lessened the stress concentration experienced just below the head, and the type 2 bolt head was formed by upsetting, which provided a favorable grain flow[3] and hence further resistance to cracking by overload or fatigue. Finally, the type 2 bolt had a more traditional thread shape; it appears likely that the thread shape of the type 1 bolt would not have fit completely when initially mating with female threads.

This mismatch, combined with the bending moment on the bolt in service, permitted friction between mating threads, leading to damage at thread roots. This damage is evident in the "pitting" effect observed during the metallurgical examination. These features were not observed in the type 2 bolt. Fretting is a possible explanation for this damage, although surface rupture at these locations is more probable. Surfaces damaged by fretting usually display a layer containing a mixture of the materials from the contacting surfaces;[5] no such layer was observed in any of the "pitting" areas of the type 1 bolt. Therefore, these areas appear more likely to have been formed by ductile rupture during plastic deformation. Fretting, however, could still exist as a possible crack initiation mechanism. The attendant layer of mixed material from contacting surfaces could be revealed in the same bolt by examining another metallographic plane. Examining an entirely different bolt may also reveal fretting damage.

The possibility of overtightening the bolts provides an additional complicating influence in the failure process. The cracking underneath the bolt head in the type 1 bolt, combined with client-supplied information regarding installation procedures, suggests that the bolts were in fact overtightened. The type 1 bolt did have a smaller head-to-shank radius than the type 2 bolt, providing an added concentration of stress that could lead to cracking under the application of excessive torque. Cracking in thread roots could also have initiated from overtightening, although this is unlikely for this very ductile austenitic stainless steel.

The bolts may have been overtightened, but not enough to produce cracking in thread roots or even underneath the head. The cracking would then be the result of stress concentrations at the head-to-shank radius and sharpened thread roots. Another possibility is that some cracks may have initiated due to overtightening and others due to thread shape, and one of these cracks then led to final fracture. An additional possibility is that the tack weld provided stress relief on one side of the bolt, allowing that side to be loosened enough to permit fretting. With no knowledge of what torque was applied to each bolt during installation, and multiple influences toward crack initiation, no single influence can be distinguished as more responsible for final failure than any other.

Despite these difficulties, it is most likely that two or more of these influences operated simultaneously. Any overtightening would prevent application of the proper preload to the bolts, resulting in a loosening of the bolts and allowing more freedom for bending stresses to produce fatigue. The mismatched thread shape is also highly suspect. Additionally, the sharpened thread roots produced higher stress concentrations at those locations, which contributed to crack formation. Once cracks initiated, bending fatigue propagated them to final fracture. Each fractured bolt caused the load to be redistributed among the remaining bolts until the load was too great to bear, at which time all of the bolts fractured, releasing the impeller blade from the assembly.

A final point regarding manufacturing differences deserves attention. Both bolt types have cut threads, as demonstrated by the material flow lines observed in the metallurgical examination. A rolled thread should display a material parting line at thread tips,[6] and parting lines were not observed in either bolt type. The grain flow patterns in each bolt confirm that the threads in each bolt were cut.[3] Observations of the material flow lines throughout each mounted bolt indicate that the type 1 bolt appears to be machined entirely from bar stock, whereas the type 2 bolt appears to be machined from an upset-forged blank, which undoubtedly increased its resistance to crack formation. However, a rolled thread would provide added resistance to crack formation in thread roots, because the rolling action would impart a layer of compressive residual stress.[7] With cut threads, no such compressive stress layer exists.

Recommendations

The multiple factors that may have influenced crack initiation provide a basis for the following recommended actions to mitigate each of the possible influences:

- Bolts with a rolled thread should be used. The rolling action will impart a layer of compressive residual stress, which will provide resistance to fatigue crack initiation and fretting.
- The thread shape should provide a proper fit between male and female threads (to reduce the possibility of fretting), and thread roots should be rounded (to eliminate stress concentration points that can lead to crack initiation).
- An appropriate preload should be placed on each bolt. The absence of any control in this area can lead to fatigue crack nucleation as well as fretting; it also introduces the possibility of overtightening.

Additional measures, such as using bolts with a larger head-to-shank radius, may also be appropriate.

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