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The effect of manufacturing processes on the fatigue lifetime of aeronautical bolts

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Abstract

Many aeronautical fastners are exposed to cyclic stresses during service. Therefore, such parts are usually designed for limited fatigue lifetime. Various combinations of process type and sequence may be employed to produce threads, each resulting in different fatigue properties. Specifications of aircraft bolts often require production of threads by heat treatment followed by rolling, in order to improve the fatigue properties. Unfortunately, these specifications are not always followed to the letter. Therefore, for either quality assurance or failure analysis purposes, it is important to be able to determine unambigiously the process by which threads were produced. The objectives of this work were to study the effect of varied thread manufacturing process type and sequence on the mechanical properties of AISI 4340 stud bolts, and to develop a laboratory procedure for distinguishing between them. Threads were produced on heat-treated and non-heat-treated stud bolts either by machining or cold-rolling. The non-heat-treated bolts were subsequently heat-treated. All bolts were then subjected to mechanical testing (static tensile, dynamic fatigue, hardness and microhardness tests), metallographic and fractographic examinations. While the fatigue properties were significantly affected by the manufacturing process used, no effects on the tensile strength of the bolt were observed. Metallographic inspection and microhardness testing, but not fractographic inspection, were found to be effective for distinguishing between different manufacturing procedures. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Many aircraft fasteners are exposed to cyclic stresses during service, which might lead to fatigue failure; hence, such parts are usually designed for limited fatigue lifetime. Various types of processes may be employed to produce fastener threads. Machining is economically advantageous for small quantities and complicated geometries. However, defects (e.g., microcracks and grain boundaries) which form at the surface during this process serve as preferred sites for fatigue crack initiation. Thus, machined threads often exhibit only limited fatigue properties. Rolling, on the other hand, is advantageous for large throughput. During this process, grains are being aligned in the rolling direction ('mechanical fibering') and compressive residual stresses are introduced into the material. Consequently, both the initiation and propagation of fatigue cracks are hindered.

The sequence of processes may also affect the fatigue properties of threaded bolts. It has already been reported [1] that fatigue properties are markedly enhanced by rolling the threads after, instead of before, heat treatment. If heat treatment is conducted after rolling, decreased fatigue lifetime results from grain growth at the surface of the threads, anhilation of residual stresses, and accelerated propagation of microcracks that were introduced during thread processing. However, for machined threads, the influence of machining/heat treatment sequence is not evident, but mainly depends on the material and the machining parameters. In high-strength steel, for example, microcracks that had been formed at the thread root during machining were found to propagate during heat treatment, thus reducing the fatigue lifetime [2]. On the other hand, after heat treatment the high-strength steel is less plastic, exhibiting a higher tendency to cracking during machining [3].

Due to the aforementioned considerations, specifications of aircraft bolts that are exposed to dynamic stresses during service often require the manufacturing of threads by heat treatment followed by cold-rolling. Quality assurance of such bolts involves strict requirements of the material and manufacturing processes, form and dimensions of threads, microstructure (e.g., shape of grain flow and defects), mechanical properties (e.g., ultimate tensile strength, ultimate double shear, hardness, fatigue strength), surface roughness, etc. [4].

Naturally, manufacturers prefer to produce threads (either by rolling or machining) before heat treatment in order to reduce the roller/tool wear and to facilitate the process. Hence, for either quality assurance or failure analysis purposes, it is important to be able to determine unambigiously the type and sequence of processes by which threads were produced. Unfortunately, it is sometimes difficult to determine this from inspection of one batch of bolts. To the best of the authors' knowledge, no publication has provided a comprehensive comparison between the microstructure and mechanical properties of bolts manufactured by various combinations of process type and sequence. The aim of this work was to study the effect of thread manufacturing on the mechanical properties and microstructure of stud bolts, while developing a laboratory procedure for distinguishing between different manufacturing processes.

2. Experimental procedure

All bolts were fabricated from the same rod (19 mm-diameter) of AISI 4340 alloy steel. The raw material was examined and found to satisfy the requirements of AMS 6415 [5]. The chemical composition of this material is shown in Table 1. The fabrication of the bolts followed the requirements of military standard MIL-B-7838C (for 160–200 ksi bolts expected to serve under high dynamic stresses) [4], except that the bolts were manufactured without a forged head (i.e., stud-type bolts). This modification resulted from both economic and time-schedule considerations. It was also thought that since this work was aimed to study the effects of thread manufacturing only, the fabrication of the head

Table 1
The chemical composition (wt%) of the studied AISI 4340 steel, as obtained by optical emission spectrometer. The requirements of the AMS 6415 standard are also shown for comparison

	C	Ni	Cr	Mn	Mo	Si	S	Fe
Steel studied	0.41	1.88	0.87	0.76	0.27	0.33	0.022	Rem.
AMS 6415	0.38–0.43	1.65–2.00	0.70–0.90	0.65–0.85	0.20–0.30	0.15–0.35	0.025 max	Rem.

could be ignored. Various combinations of process type and sequence were used for the manufacturing of bolts (see Table 2), three of which were not in accordance with the requirements of MIL-B-7838C. All heat treatments (quenching and tempering to obtain hardness within the range 37–41R_C) followed the requirements of MIL-H-6875 [6]. All threads were of type $\frac{3}{4}$-16 UNF 3A. Finally, cadmium plating was applied in accordance with the requirements of QQ-P-416 Type II Class 2 [7]. This plating, while providing corrosion resistance, has almost no effect on the fatigue properties of the bolt [8].

Various characterization techniques were used in this work. Mechanical testing (both tensile and fatigue tests) was conducted at room temperature, using a standard 50-ton servo-hydraulic MTS load frame. Fatigue tests were performed in accordance with MIL-STD-1312-11A [9]. Sinusoidal wave loading with a maximal stress (σ_{max}) of 29,200 lb, a stress ratio (R) of 0.1, and a frequency τ of 10 Hz, was employed. Static tensile tests were performed at room temperature in accordance with MIL-STD-1312-8A [10], using a constant loading rate of 44,000 lb/min to fracture. All mechanical tests were followed by both visual and microscopic examination of the fracture surface, using stereomicroscopy, optical microscopy (OM) and scanning electron microscopy (SEM).

Representative cross-sections along the bolt axis were prepared for each group of bolts. The macro- and microstructure were examined before and after chemical etching in Nital solution (3% HNO_3 in ethanol), using both OM and SEM. The hardness of the bulk material was measured by means of the Vickers method under a load of 10 kg. In addition, microhardness measurements were conducted perpendicular to the thread surface by means of the Knoop method under a load of 500 g.

3. Results and discussion

Comparative tests were performed using bolts from each of the four groups described in Table 2. Firstly, quality assurance tests were conducted according to the specifications for the raw material [5], heat treatment [6] and cadmium plating [7]. These tests confirmed that all bolts were of high quality, with no deviations from standard requirements. Secondly, mechanical properties of the bolts were evaluated, as described in Section 2.

Table 3 summarizes the results from fatigue, tensile, hardness and microhardness tests. Both mean

Table 2
Manufacturing procedures for the four groups of stud bolts studied

Group index	Thread manufacturing method
R/HT	Cold-rolling before heat treatment
HT/R	Cold-rolling after heat treatment
M/HT	Machining before heat treatment
HT/M	Machining after heat treatment

and standard deviation values are presented. It should be noted that bolts from group HT/R (Rolling following heat treatment) withstood almost 40,000 cycles before fracture in fatigue testing. This value is about four times larger than the values obtained for the other three groups. It should also be noted that although these specific numerical values relate to the particular specimen geometry, processing and test conditions employed in this work, the general trend may apply to other conditions as well.

It is clear that the fatigue lifetime of the bolts can be significantly increased by rolling the threads after heat treatment. This behavior may be explained as follows. Machined threads usually contain microcracks and other microdefects, and can sometimes exhibit poor surface roughness; characteristics that typically lead to reduced fatigue lifetime. Cold-rolling, on the other hand, causes the material to plastically deform and spread laterally in the thread root area. Since such motion is constrained by the bulk elastic substrate, compressive residual stresses develop at the thread root. In addition, the cold-rolling-induced enlargement of the thread root radius brings about reduction in stress concentration. Finally, the fracture toughness of the bolt material is enhanced by the favorable grain flow pattern produced by cold-rolling, where the flow lines are oriented parallel to major stress trajectories and normal to the path of a potential crack. Cracks can thus deflect from their normal plane and direction of growth at grain boundaries, flow lines and inclusions. The combination of these three factors is expected to lead to improved fatigue lifetime in cold-rolled fasteners [11]. The results of this work support this expectation; fatigue properties of cold-rolled threaded bolts were improved in comparison to machined ones (when both processes were done following heat treatment). Table 3 also reveals that if heat treatment is done after rolling, the benefit of rolling in increasing fatigue lifetime is almost completely diminished.

Following fatigue tests, the fracture surfaces of the bolts were examined by means of both stereomicroscopy and SEM. In spite of the observed difference in fatigue lifetime of bolts from different groups, the microscopic characteristics of all fracture surfaces were identical. Figs. 1 and 2 show typical macroscopic and microscopic characteristics, respectively, of the fracture surface of a bolt from group HT/R. The fracture surface is composed of three distinct regions: (i) crack origin at the center of curvature of (ii) beach markings, and (iii) overload regime representing the final rupture. Thus, it may be concluded that fractographic observations cannot be used to distinguish between bolts fabricated by different type and sequence of processes.

In contrast to the results from fatigue tests, results from static tensile tests show (Table 3) approximately the same rupture strength for all four groups, independent of the type and sequence of processes used. It should be recalled that the tensile properties depend on the whole cross-section of the bolt. Hardness tests and metallographic examinations, to be presented later, reveal that only the outer surface and the material just beneath it are affected by rolling. Therefore, the increase in the local

Table 3
Summary of results from tensile, fatigue, hardness and microhardness tests[a]

Group #	σ_f (GPa) [ksi]	N (cycles)	Hardness (VHN) [R_C]	Microhardness (KHN) [R_C]	d (mm)
R/HT	1.29 [187]	$13{,}667 \pm 1528$	363 ± 8 [37 ± 1]	456 ± 33 [44 ± 2]	0.1
HT/R	1.33 [193]	$39{,}000 \pm 7550$	368 ± 16 [37 ± 1]	468 ± 32 [45 ± 2]	0.4
M/HT	1.33 [193]	$10{,}100 \pm 854$	378 ± 7 [38 ± 1]	405 ± 10 [40 ± 1]	–
HT/M	1.33 [193]	9500 ± 1670	375 ± 8 [38 ± 1]	399 ± 16 [40 ± 1]	–

[a] σ_f is the static rupture stress, N the number of cycles to fatigue failure, and d the depth of the hardened surface layer (if this exists). Hardness values relate to the bulk of the bolt; microhardness values relate to the thread surface. Indexing of groups is in accordance with Table 2.

hardness near the surface has little effect on tensile measurements on the bulk material. However, for other bolt designs, in which the ratio of surface (or threaded) area to overall cross-section area is much larger, one might expect an improvement in the static tensile strength of rolled threaded bolts in comparison to machined ones.

As evident from Table 3, the material hardness in the bulk of the bolts was approximately the same for all four groups. This is likely due to the application of similar heat treatments in all four cases; i.e., quenching and tempering under the conditions required to obtain hardness between 37 and 41 R_C. In contrast to the bulk hardness results, microhardness tests reveal distinguishable characteristics of the four groups of bolts. The hardness at the surface layer of cold-rolled threads was much higher in comparison to the bulk bolt hardness or the hardness of the surface layer of machined threads. While the depth of the hardened surface layer was measured to be 0.4 mm for bolts that had been rolled following heat treatment, it was found to be only 0.1 mm for bolts that had been rolled before heat treatment. No hardened surface layer was observed at the surface of machined threads. The microhardness results are in accordance with the results of fatigue tests previously mentioned. Moreover, they can be correlated to the density and depth of the plastic flow region at the root of the thread, as observed by OM and described hereafter.

Metallographic cross-sections through the fatigue fracture origin, oriented perpendicularly to the fracture surface, were prepared. OM observations indicated regular mechanical failure in all four cases, with no evidence of special stress concentration risers. Following chemical etching, the typical microstructure of each bolt material was revealed (Fig. 3). Rolled bolts were characterized by metal flow along the thread surface. Bolts that had been rolled following heat treatment exhibited continuous and dense flow lines. On the other hand, bolts that had been rolled before heat treatment exhibited only few, discontinuous and less dense, flow lines. This observation is in accordance with the measurement of a thinner hardened surface layer in bolts cold-rolled before heat treatment in comparison to those rolled

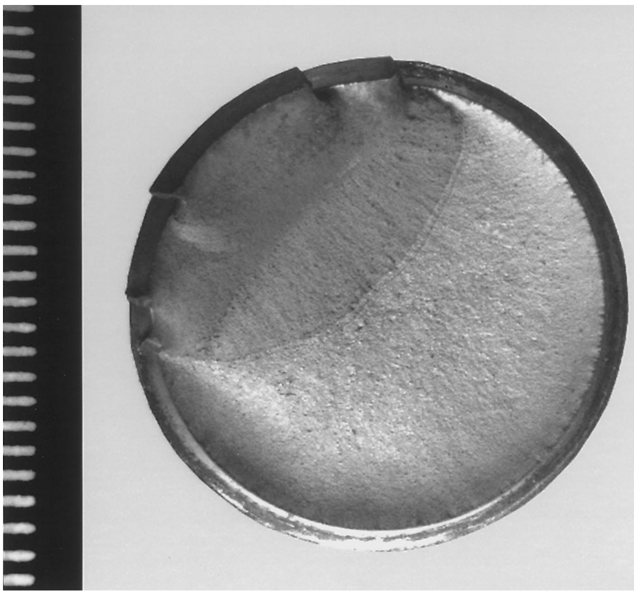

Fig. 1. Macroscopic view of fatigue fracture surface of a bolt from group HT/R. Similar fracture characteristics were observed for bolts from the other three groups.

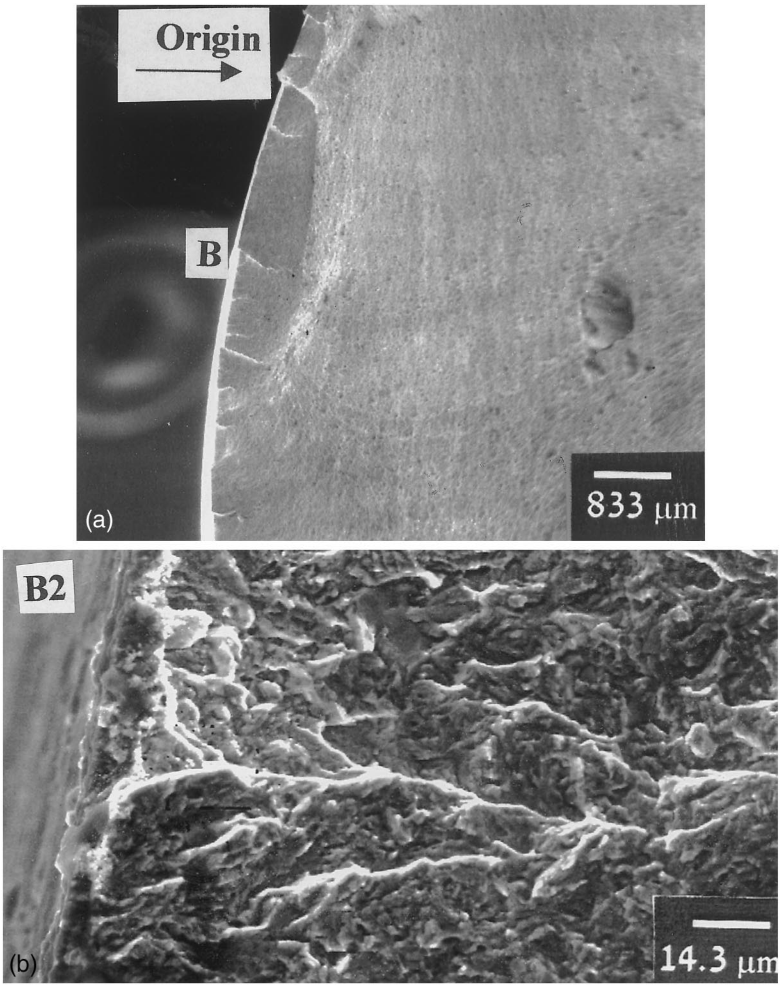

Fig. 2. SEM micrographs showing typical crack origin zone in a bolt from group HT/R following fatigue testing: (a) at low magnification; (b) at high magnification.

following heat treatment. Practically, it should be noted that in the case of bolts from group R/HT, heat treatment did not mask all flow lines that had been formed during cold-rolling, though it obviously blurred them. In contrast to the OM results aforementioned, the metallographic characteristics of machined bolts did not show clear dependence on the manufacturing process sequence. The parallel longitudinal flow lines observed in Fig. 3(c) were probably produced during the forging of the rod. As their emergence depends on both the process by which the raw material is shaped and the conditions of chemical etching, they can hardly be used as a criterion for quality assurance purposes.

4. Conclusions

1. In order to maximize fatigue lifetime, it is crucial to fabricate the threads by cold-rolling following heat treatment (in comparison to the other three combinations studied in this work).

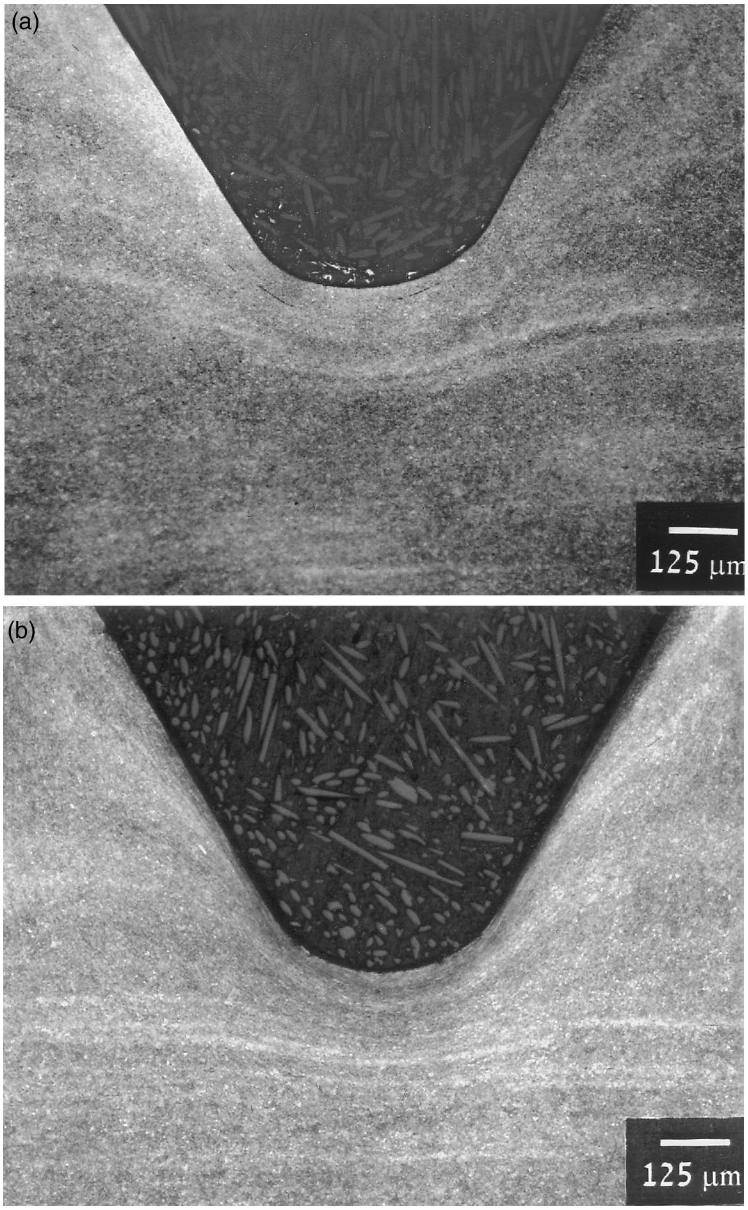

Fig. 3. OM micrographs showing the typical microstructure in the thread region of bolts: (a) cold-rolled before heat treatment; (b) cold-rolled following heat treatment; (c) machined before heat treatment; and (d) machined following heat treatment.

2. Fatigue lifetime tests, microhardness testing and metallographic examination may be used as laboratory tools to distinguish between bolts fabricated by cold-rolling following heat treatment and bolts fabricated by any of the other three procedures.
3. Static tensile tests, hardness tests and fractographic examination (using SEM) cannot be used as laboratory tools for such a distinction.
4. None of the characterization techniques mentioned above can be used to distinguish between bolts

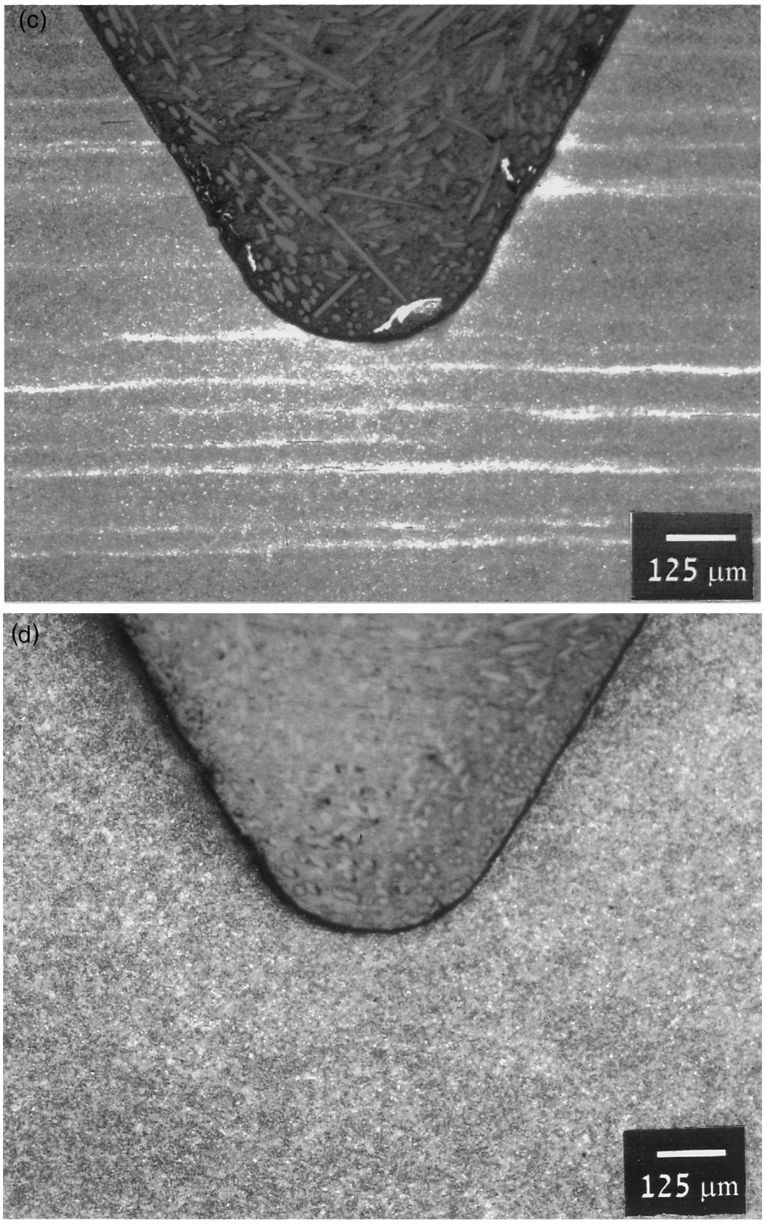

Fig. 3 (*continued*)

fabricated by machining before heat treatment and bolts fabricated by machining following heat treatment.

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