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Evaluation on fatigue strength of AISI 4340 steel aluminum coated by electroplating and IVD processes

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Abstract In spite of toxicity, hydrogen embrittlement susceptibility, and environmental issues, cadmium electroplating is usually applied on high strength AISI 4340 aeronautical steel due to its efficient protection against electrochemical corrosion. Ion vapor deposition (IVD) process with pure aluminum also offers good protection against corrosion with the advantages of decreasing hydrogen embrittlement susceptibility and improving the fatigue strength of metallic components. In this research, the effects of aluminum electroplating and IVD aluminum coating on the rotating bending fatigue strength of AISI 4340 steel were evaluated in comparison with cadmium electroplated specimens. Experimental fatigue results showed that both aluminum electroplating and IVD aluminum coatings are possible alternatives to cadmium electroplating.

Introduction

Surface treatments have long been considered necessary to improve wear and corrosion properties of materials. As a real and critic process acting on aircrafts, by flowing with the time even on those not operational, the corrosion control is an important concern for the aerospace industry.

In general, the wear and corrosion processes on aircraft components are controlled by chrome plating or hard anodizing processes as related by Nascimento et al. [1]. However, Nascimento et al. [2] pointed that while producing improved abrasive wear and corrosion properties, chromium coatings reduce the fatigue strength of a component due to microcracking produced during electroplating process. Furthermore, as explained by Natishan et al. [3], the plating bath contains hexavelant chromium that is a health hazard and has environmental requirements restrictions.

Electroplated cadmium is a well-known and still widely used coating for high strength aeronautical steel components. Advantages as good corrosion resistance and interesting cost efficiency are eclipsed by technical drawbacks as: hydrogen embrittlement, as a consequence of the plating process; cadmium embrittlement at elevated operating temperatures; environmental issues and health effects. The search for alternatives to cadmium has resulted in processes with superior corrosion resistance and nontoxic properties, capable to protect metal with the application of aluminum coatings, such as metal spraying, cladding, and electroplating [4].

Among these processes the ion vapor deposition (IVD) offers corrosion protection at temperatures up to 510 °C with the application of a uniform coating of pure aluminum.

In complement to protection against oxidation, and impossibility of hydrogen embrittlement, the IVD coating process does not decrease the fatigue strength of steel or titanium parts. The shot peening effects are also not reduced by the IVD process [5].

On the fatigue viewpoint, it is also important to mention that IVD coatings are used to replace anodization on critical aluminum structures, due to the detrimental influence of anodization on the fatigue strength [6].

The objective of this research is to analyze the influence of cadmium electroplating, aluminum electroplating, and IVD aluminum coating on the fatigue strength of AISI

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4340 steel. S–N curves were obtained in rotating bending fatigue tests for the base material (BM), BM cadmium low hydrogen embrittlement (LHE) electroplated, BM cadmium electroplated; BM aluminum electroplated and BM IVD aluminum coated. The fatigue experimental program was performed with specimens quenched from 815 to 845 °C and tempered in the range of 520 ± 5 °C for a period of 2 h to obtain hardness of 39HRc-42HRc. Scanning electron microscopy techniques and optical microscopy were used to observe the fatigue crack origins sites and the existence of a uniform coverage on substrates.

Experimental procedures

Mechanical properties

The fatigue experimental program was performed on rotating bending fatigue specimens machined from quenched and tempered hot rolled bars, according to Fig. 1.

The chemical composition of AISI 4340 steel was 0.41C–0, 73Mn–0.8Cr–1.74Ni–0.25Mo, and 0.25Si in wt%.

Mechanical properties, obtained by means of quenching from 815 to 845 °C to 20 °C (in oil) followed by tempering in the range 520 ± 5 °C for 2 h, are 39HRc-42HRc, yield stress of 1260 MPa (0.2% offset), and ultimate tensile strength 1350 MPa. After final preparation, samples were subjected to a heat-treatment at 190 °C for 4 h to reduce the residual stresses induced by the machining process.

Average superficial roughness in the reduced section of the specimens was Ra ≈ 2.75 μm and standard deviation of 0.89 μm. The rotating bending fatigue specimens were tested with $R = -1.0$ load ratio, at a frequency of 50 Hz, at room temperature. Fatigue strength was considered either complete fracture of specimens or 10^7 load cycles. For all coated and uncoated specimen groups, the number of specimens used to obtain S × N curves were in accordance with ASTM E739 standard. The fracture planes of the fatigue specimens were examined using an SEM model Jeol JSM 5310, in order to identify the crack initiation points. Optical microscopy was used to observe the existence of a uniform coverage on the specimens, thickness regularity, and adhesion coating/substrate. The equipment employed was a microscope Nikon APOPHOT 200.

Fatigue specimens preparation: surface treatments

The following specimen groups were prepared to draw the S–N curves from the rotating bending fatigue results:

1. 12 smooth specimens of BM;
2. 12 smooth specimens of BM cadmium electroplated (CdE);
3. 12 smooth specimens of BM cadmium electroplated and thermally treated at 190 °C for 8 h to avoid hydrogen embrittlement (HT-CdE);
4. 12 smooth specimens of BM low hydrogen embrittlement cadmium electroplated (LHE-Cd);
5. 12 smooth specimens of BM aluminum electroplated (Al-E);
6. 12 smooth specimens of BM IVD aluminum coated (IVD-Al).

The cadmium electroplating process was carried out according to the following parameters: 20–30 g/L cadmium salt, 90–200 g/L of Na CN, 10–20 g/L of NaOH, ratio CN/Cd in the range 4:1–6:1, at room temperature with a current density from 1 to 5 A/dm^2 and a speed of deposition from 0.2 to 1.5 μm/min.

In this study, all the coatings were performed in accordance to LIEBHERR/ELEB specifications. The thickness of the coatings was evaluated by cross-sectioning the polished specimens and applying an image analysis technique. Before aluminum electroplating process, the fatigue specimens were coated with a thin nickel interlayer to improve chemical interlocking between electrolytic aluminum and AISI 4340 steel.

Microhardness measurement for each aluminum coating was obtained using a Vickers indenter applied in three regions on the top surface of polished cross section: (1) at coating (25 g); (2) at interface (100 g), and (3) at substrate (100 g). Each region was indented three times and the average values are listed in Tables 1 and 2.

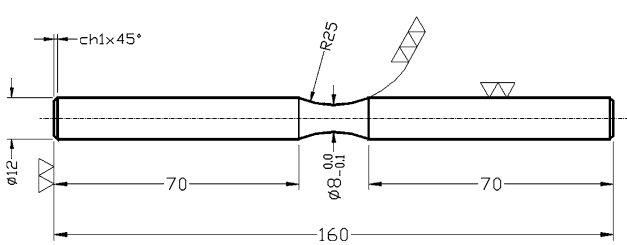


Fig. 1 Rotating bending fatigue specimen

Table 1 Microhardness: electroplated aluminum

Regions	Hardness average (HV)	SD (HV)
1	75	6
2	668	10
3	665	6

Table 2 Microhardness: IVD aluminum

Regions	Hardness average (HV)	SD (HV)
1	138	9
2	622	18
3	607	13

Results and discussion

Tables 1 and 2 show the microhardness values for electroplated and IVD aluminum coatings, respectively.

For both coatings, a similar tendency is observed, i.e., the lower values near coating surface, reaching a maximum value close to the interface coating-substrate and decreasing again inside substrate.

The thicknesses of the aluminum coatings, as shown in Fig. 2, were measured along the cross section of the specimens, resulting an average value and standard deviation equal to 17.94 ± 2.71 μm for the electroplated aluminum (Al-E) and 20.99 ± 4.49 μm for the ion vapor deposition of aluminum (IVD-Al).

From Fig. 2a, we can also observe that for nickel interlayer the average thickness and standard deviation were equal to 2.66 ± 0.63 μm. The Al-E and IVD-Al coating morphologies are represented in Figs. 3 and 4, respectively.

Adequate substrate surface preparation is fundamental if good adhesion is to be achieved. In order to minimize surface contamination, specimens were blasted with aluminum oxide mesh 90, prior to vacuum coating.

The excellent adhesion IVD-Al coating-substrate is associated to a mechanism called sputtering, in which substrate atoms and surface contaminants are removed during the operation [4].

From Fig. 2a, b, we can observe the uniform thickness for Al-E and IVD-Al coatings, respectively.

Figure 3 shows aluminum electroplated morphology. It is possible to observe that aluminum coating grew uniformly. Figure 4 shows a columnar structure of IVD coating, as related in literature [5, 7].

Figures 5 and 6 represent the conventional cadmium (Cd-E) and the LHE cadmium (LHE-Cd) morphologies, respectively.

The presence of microporous can be observed in the LHE Cd coatings, which is responsible for the heat treatment success in avoiding hydrogen embrittlement. As a result of the conventional cadmium plating process, atoms of hydrogen generate high local stress and, consequently, reduce the fatigue resistance of high strength steels. Considering that LHE Cd coatings do not retain hydrogen atoms, fatigue resistance is not affected.

EDS analyses on Al-E and IVD-Al coatings indicate that Al and Cr were found, as expected. The atomic and mass percentages for Al-E coating are 92.99 and 87.31%, respectively. Thus, for the chromium element, the resulting percentages were 7.01 and 12.69%. At a region closer to the fracture the results were for aluminum 92.21 at.% and 86.00 mass%; and for chromium 7.79 and 14.00%, respectively. For the IVD-Al coating, the results were 82.85 at.% and 71.48 mass%, and for chromium 17.15 and 28.52%. In a second trial, also closer to the fracture, the atomic and mass percentages were 81.10% Al/69.01% Cr, and 18.90% Al/30.99% Cr, respectively. EDS analysis confirmed coating chemical composition and the absence of impurities, which could reduce specimens fatigue life.

Table 3 lists the S–N fatigue data of S–N curves showed in Fig. 7 for the rotating bending fatigue tests for the BM, BM cadmium electroplated (Cd-E), BM cadmium electroplated heat treated to avoid hydrogen embrittlement (HT-CdE), and BM cadmium LHE electroplated.

From Fig. 7, it is possible to observe reduction in the fatigue strength of AISI 4340 steel associated to the HT-CdE coating. For LHE-Cd coated specimens, the S–N curves in Fig. 7 show performance very close to that of BM, certainly due to the presence of microporous in the interlaced coating morphology (Fig. 6b).

Figure 8 illustrates the fracture surfaces from rotating bending fatigue specimens cadmium electroplated. In Fig. 8a, maximum stress applied was 1047 MPa, corresponding to 12,000 cycles to fracture. Electroplated cadmium thickness measured is 11.24 μm. Figure 8b shows a

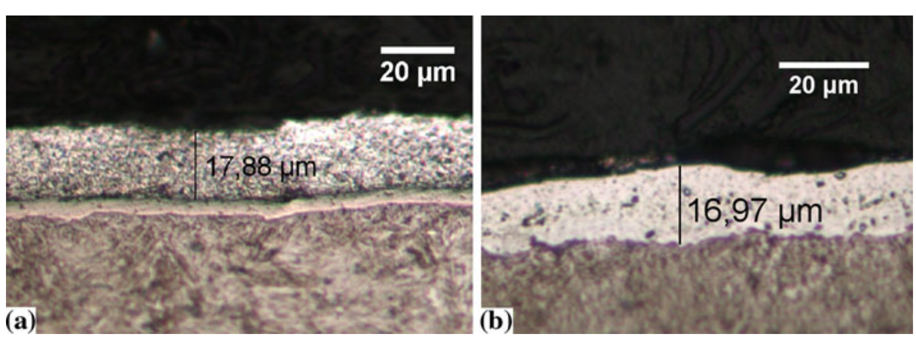


Fig. 2 Cross section of aluminum coatings at 500× magnification. **a** Electroplated; **b** IVD

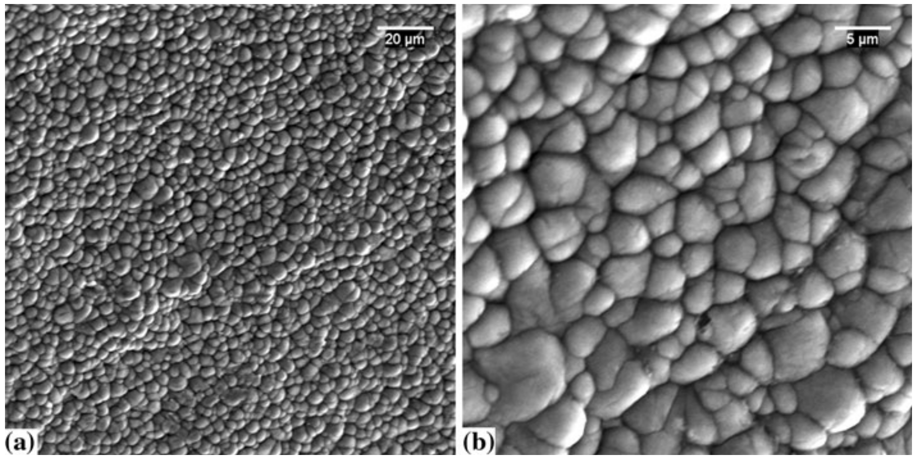


Fig. 3 Electroplated aluminum coating morphology. **a** 1000×; **b** 7500×

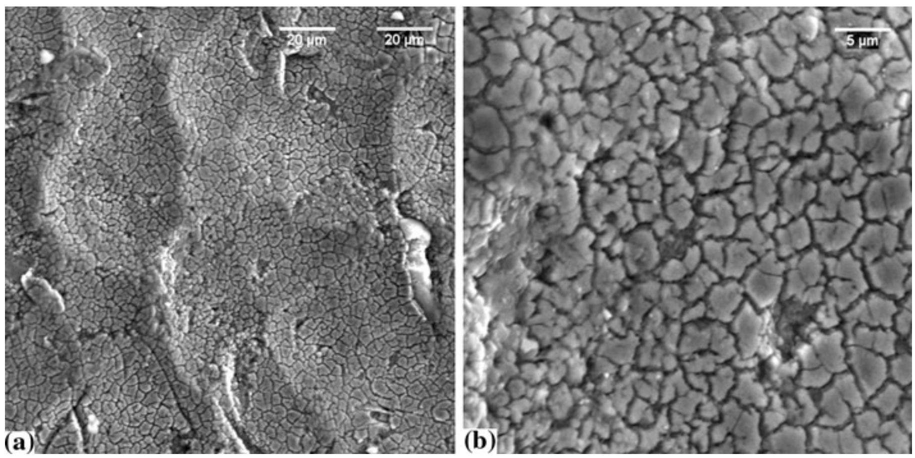


Fig. 4 IVD aluminum coating morphology. **a** 1000×; **b** 7500×

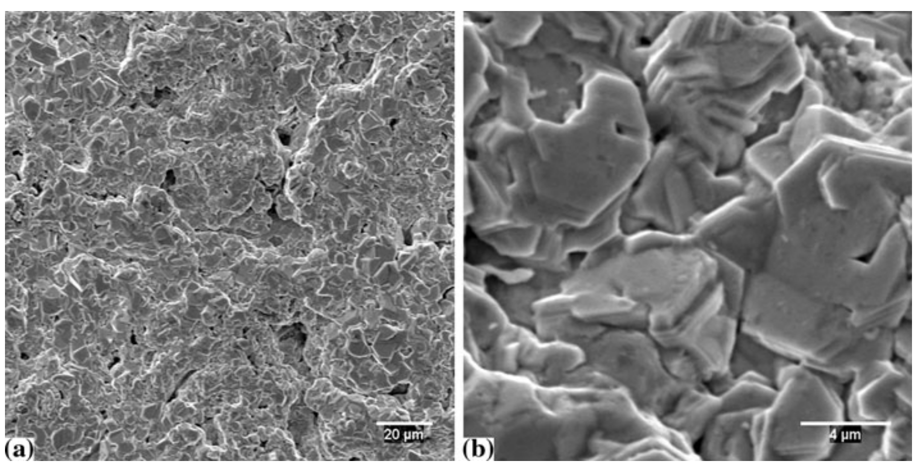


Fig. 5 Conventional cadmium morphology. **a** 1000×, **b** 7500×

fatigue specimen fracture surface tested at 871 MPa and corresponding to 28,000 cycles to failure. The cadmium coating thickness is 8.6 μm.

In Fig. 8a, b, it is possible to observe that the electroplated cadmium process resulted in uniform coverage of the substrates. From the analyses of Fig. 8, one can see cracks starting from the interface coating/subtracted and propagating inside BM.

Figure 9 represents the fracture surface of a rotating bending fatigue specimen HT-Cd electroplated.

It is interesting to observe cracks also starting at the free coating surface and propagating inside substrate.

Rotating bending fatigue S–N curves tests of the BM, Al-E, and IVD-Al groups are presented in Fig. 10.

Figure 10 shows that the effect of aluminum coating on the rotating bending fatigue test is to slightly decrease the

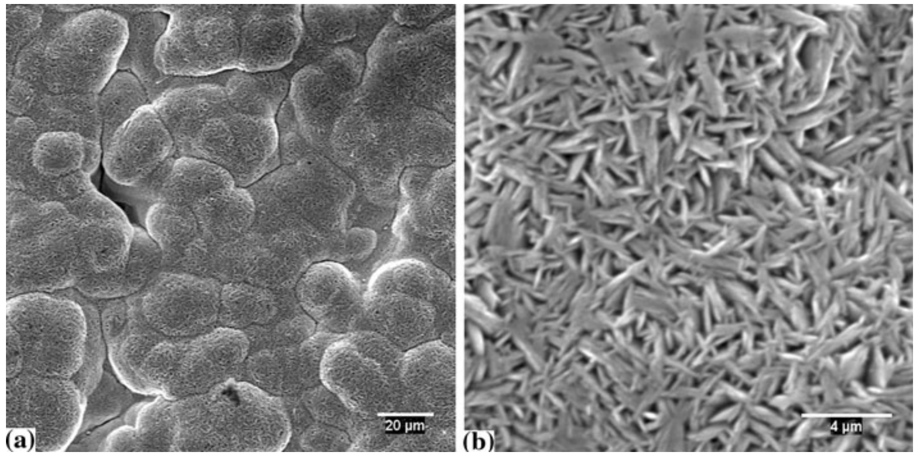


Fig. 6 LHE cadmium morphology. **a** 1000×, **b** 7500×

Table 3 S–N fatigue data of BM and BM with cadmium LHE, cadmium whit and without dehydrogenation, aluminum electroplated, IVD aluminum coated

Stress (MPa)	AISI 4340		Cadmium LHE		Cadmium with dehydrogenation		Cadmium without dehydrogenation		AI-IVD		AI-electrodeposition	
	Cycles average (*N*)	SD (*N*)	Cycles average (*N*)	SD (*N*)	Cycles average (*N*)	SD (*N*)	Cycles average (*N*)	SD (*N*)	Cycles average (*N*)	SD (*N*)	Cycles average (*N*)	SD (*N*)
1200.8	27300	19940	11150	4737	7000	0	6500	2121	9050	353	7050	70
1100.8	96500	–	42350	16475	–	–	–	–	–	–	–	–
1046.8	–	–	47150	4171	34500	9192	26500	20506	22300	3252	34500	8626
1020.8	–	–	80150	49851	–	–	–	–	–	–	–	–
1000.8	113300	63665	242600	–	43000	15556	19500	12020	47600	1697	42500	15556
990.8	–	–	10000000	0	403000	–	–	–	36800	–	223550	254063
980.8	–	–	–	–	44000	–	–	–	–	–	–	–
970.8	–	–	10000000	0	140000	153326	17000	–	130000	–	–	–
950.8	111000	–	10000000	0	5680000	6112231	27000	–	434850	422213	248600	96307
910.8	686200	–	–	–	–	–	–	–	–	–	–	–
870.8	–	–	–	–	–	–	24500	4949	–	–	–	–
820.8	–	–	–	–	–	–	162000	182428	–	–	–	–
800.0	10000000	–	–	–	–	–	–	–	10000000	–	10000000	–
770.8	–	–	–	–	–	–	10000	–	–	–	–	–

fatigue strength of AISI 4340 steel. The tendency is observed for low number of cycles (10^4), high number of cycles (10^5), and close to the fatigue limit, 10^7 cycles, which we may consider as the same ($\approx$800 MPa) for the three conditions presented in Fig. 10.

From Fig. 11, which represents fracture surfaces from a rotating bending fatigue Al-E specimen, one can see the coating homogeneity, strong adhesion substrate/coating, and microcracks distributed along thickness in a radial shape.

From Fig. 11, it is possible to observe that cracks start from free coating surface and grow perpendicular to the interface coating/substrate. Fatigue crack coalescence and propagation inside substrate are preceded by crack growth at interface. It is well known that the fatigue crack growth through the interface between different solid materials is associated to the direction in which the crack approaches the interface and the mechanical strength of materials involved [2].

In the case of brittle layer and ductile substrate, fatigue crack may propagate through interface inside base metal. In the case of aluminum electroplated on AISI 4340 steel, whose average hardness are 102 HV and 505 HV, respectively, the fatigue crack may deflect at interface coating/substrate. In Fig. 11a, b, it is clearly shown that microcracks in the electroplated aluminum coating deflect at interface coating/substrate and grow at interface before coalescence and propagation inside base metal.

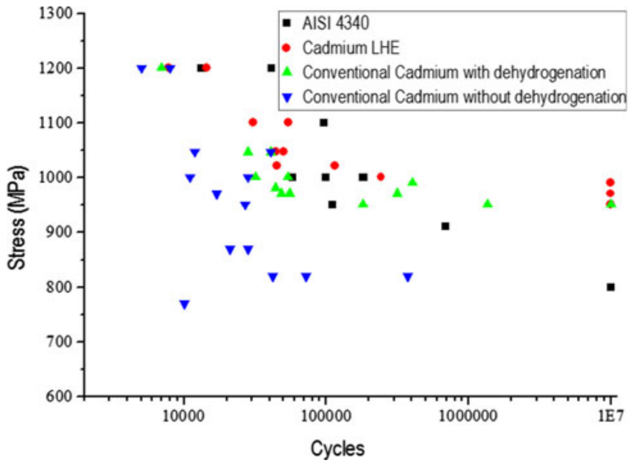


Fig. 7 S–N comparative curves. BM, BM cadmium electroplated, BM cadmium electroplated heat treated at 190 °C/8 h and BM cadmium LHE electroplated

Figure 12 shows the fracture surfaces of rotating bending fatigue specimens of IVD-Al coated AISI 4340 steel.

The same observations about the mechanical strength of materials involved (coating/substrate) are herein considered, i.e., IVD aluminum coating average hardness are 105 HV and 519 HV for the substrate.

On the other hand, it is interesting to observe in Fig. 12a lower microcracks density in IVD aluminum coating in comparison to electroplated aluminum and intense crack propagation at interface coating/substrate.

Figure 12b shows strong interface adhesion between IVD aluminum coating and substrate. It also indicates the important role played by the interface with respect to crack nucleation and propagation at interface and inside base metal.

Comparison between rotating bending fatigue experimental data in Figs. 7 and 10 confirms aluminum coatings (electroplated/IVD) as an alternative to cadmium electroplating.

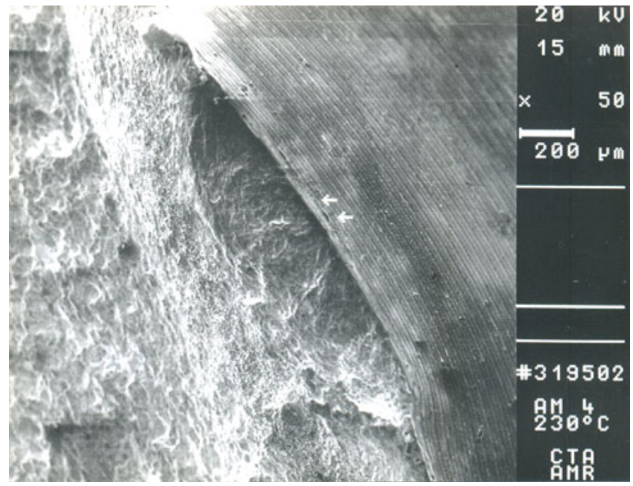


Fig. 9 Fracture surface of a specimen cadmium electroplated heat treated to avoid hydrogen embrittlement

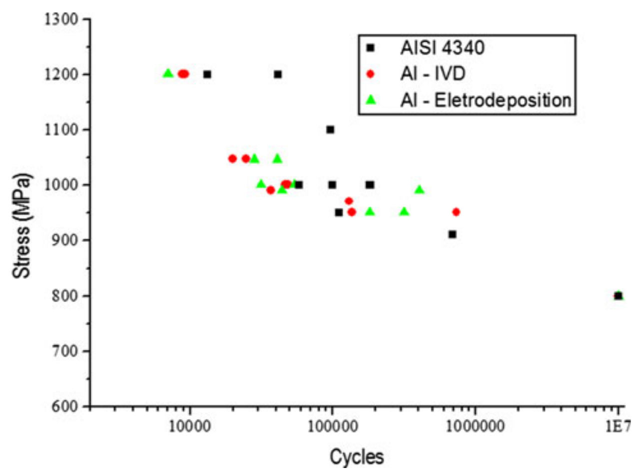
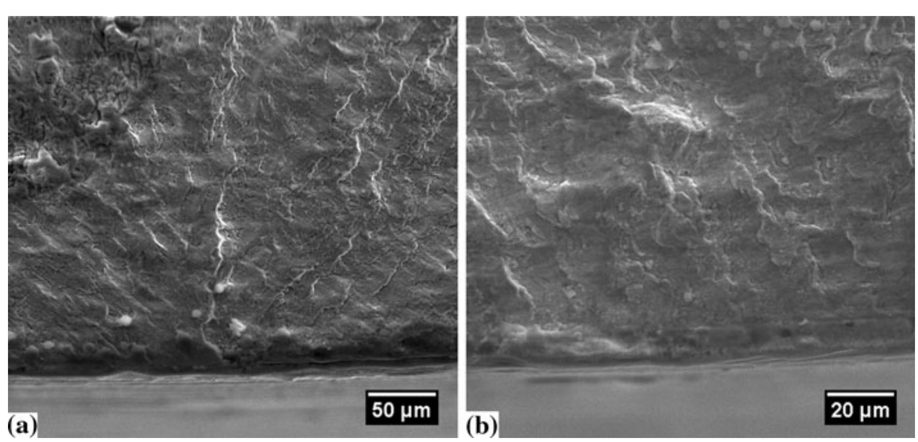


Fig. 10 Rotating bending fatigue S–N curves. BM, BM aluminum electroplated, and BM IVD aluminum

Fig. 8 Fracture surface from a rotating bending fatigue specimen cadmium electroplated. **a** $s_{max} = 1047$ MPa; **b** $s_{max} = 871$ MPa



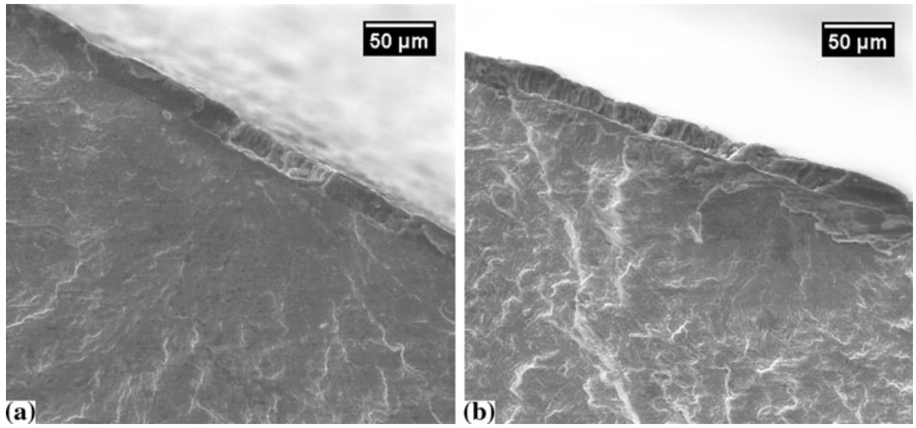


Fig. 11 Fracture surface from a rotating bending fatigue test specimen. **a** $s_{max} = 970$ MPa—250×, **b** $s_{max} = 970$ MPa—250×

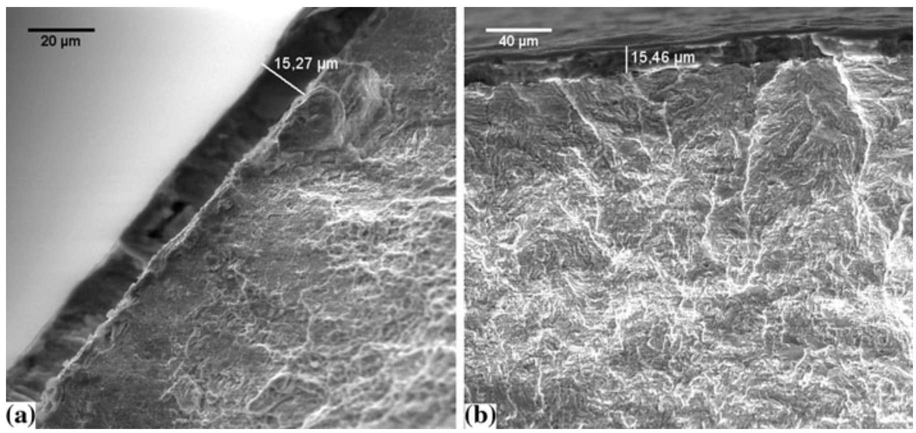


Fig. 12 Fracture surface from a rotating bending fatigue test specimen. **a** $s_{max} = 950$ MPa, **b** $s_{max} = 1047$ MPa, 300×

Conclusions

Based on the results obtained and presented, the following conclusions may be drawn:

1. Experimental results indicated a reduction in the rotating bending fatigue strength of AISI 4340 steel associated to cadmium electroplating without post heat treatment at 190 °C for 8 h.
2. Better performance was obtained with heat treatment after the cadmium electroplating process, to avoid hydrogen embrittlement and with the use of LHE cadmium coating.
3. Electroplated and IVD aluminum coatings slightly decrease the rotating bending fatigue strength of AISI 4340 steel.
4. The uneven mechanical strength of the solid materials involved (coating/substrate) was responsible for microcracks deflection and propagation at interface coating substrate.
5. In the electroplated aluminum coating, microcracks start at free coating surface and growth in a radial shape in direction to the interface coating/substrate. In the case of IVD aluminum coating, lesser microcracks density is observed in the coating and at the same time intense nucleation and propagation at interface and substrate occurred.
6. Fatigue experimental results confirm aluminum coatings as an alternative to conventional electroplated cadmium.

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