

THE EFFECT OF ELECTRODEPOSITED CHROMIUM ON THE FATIGUE STRENGTH OF LOW ALLOY STEEL

1. INTRODUCTION

This Item provides information on the effects of chromium plating on the fatigue strength of low alloy steels. The effects of various pre- and post-plating treatments are also discussed.

2. NOTATION

Both SI and British units are quoted but any coherent system of units may be used.

E	modulus of elasticity	N/m ²	lbf/in ²
f_t	tensile strength of material	N/m ²	lbf/in ²
N	endurance		
S_a	alternating stress based on net area	N/m ²	lbf/in ²
$S_{a0}(N)$	fatigue strength at endurance N when $S_m = 0$	N/m ²	lbf/in ²
$S_{a0}(\infty)$	fatigue limit when $S_m = 0$	N/m ²	lbf/in ²
S_m	mean stress	N/m ²	lbf/in ²
S_R	residual tensile stress in chromium electrodeposit	N/m ²	lbf/in ²
$\Delta S_{a0}(\infty)$	change in $S_{a0}(\infty)$	N/m ²	lbf/in ²

Suffixes

c	indicates that the property belongs to the chromium
s	indicates that the property belongs to the steel

3. THE CHROMIUM PLATING PROCESS

In addition to protecting against corrosion, electrodeposited chromium provides a surface that has excellent wear-resisting properties. These properties make the electrodeposition of chromium suitable as a salvage process for worn components. Other applications of chromium plate exploit the following properties.

- i) Low coefficient of friction.
- ii) Anti-stick capability.
- iii) Good load bearing ability.
- iv) Good anti-fret properties.
- v) High reflectivity.
- vi) Good corrosion resistance.

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During the electroplating process the component to be plated is made the cathode in a low voltage electrolytic cell. Normally, insoluble lead anodes are employed with the electrolyte being an aqueous solution of chromic oxide and sulphuric acid. Chromium for wear resistance is typically deposited under the conditions shown in Table 3.1 to a coating thickness of between 0.01 and 0.5 mm (0.0004 and 0.02 in).

TABLE 3.1 Typical chromium plating conditions

Bath composition	CrO ₃	250 g/litre H ₂ O	2.5 lb/gallon H ₂ O
	H ₂ SO ₄	2.5 g/litre H ₂ O	0.025 lb/gallon H ₂ O
Current density		4.0 kA/m ²	2.6 A/in ²
Voltage		6 – 7 V	6 – 7 V
Temperature		50 – 60°C	122 – 140°F
Deposition rate		25 μm/h	1.0 × 10 ⁻³ in/h

4. MECHANISMS OF FATIGUE FAILURE OF AN ELECTROPLATED COMPONENT

When a fluctuating tensile load is applied to an electroplated component, stresses will be induced in both the chromium and the steel. The stresses are determined by the magnitude of the load, the moduli of elasticity of the chromium and the steel and any residual stresses present as a result of the plating process or any pre- or post-plating treatments.

If, as is usual, the fatigue strength of the chromium is less than that of the steel, fatigue cracks will initiate in the chromium. Typically the fatigue limit $S_{a0}(\infty)$ of chromium is approximately 340 MN/m² (49×10^3 lbf/in²) (see Derivation 3).

Conventionally electrodeposited chromium is normally found to possess a residual tensile stress, which is additive to stresses induced under tensile loading. This is responsible for producing minute cracks in the chromium. This feature adversely affects the fatigue strength of chromium electroplated steel components. Tests have shown that chromium deposited from the conventional solution operated under normal conditions usually contains internal residual stresses in the range 60 MN/m² to 120 MN/m² (9×10^3 to 18×10^3 lbf/in²).

If the stress intensity factor range at the tip of a crack through the chromium is above the threshold values for the particular steel, then the crack will continue to propagate under fatigue loading into the steel and fatigue failure will eventually follow. In this respect chromium plating is especially detrimental where there is a high local stress on the surface, such as occurs adjacent to cross-drilled holes in shafts or at the radius under a bolt head. Plating of such areas should be prevented by suitable masking-off.

Some low strength steels have a fatigue strength less than that of the chromium plate, and in these cases fatigue cracking may initiate in the steel.

5. FATIGUE TEST DATA

Results of fatigue limit tests in air on chromium electroplated low alloy steel specimens are shown in Figure 1 as a plot of tensile strength of the steel substrate against the change in fatigue limit of the plated component. Most of the data were obtained from tests on either rotating or reverse bend specimens. Two lines appear on the figure. Line A is the mean curve plotted through all the data. Line B predicts the maximum loss of fatigue limit that might be expected from conventional electroplating as a result of developing the maximum residual tensile stress in the chromium. It can be seen that this line gives a good lower bound to the experimental data.

In the construction of line B the following assumptions were made.

- (i) The unnotched fatigue limit of a low to medium strength steel, $S_{a0}(\infty)$, is approximately half its tensile strength. (See Figure 2 of Data Item No. 88008*.) This approximation is valid for steels having a tensile strength less than or equal to 1400 MN/m^2 ($203 \times 10^3 \text{ lbf/in}^2$).
- (ii) The moduli of elasticity, E_c and E_s , of chromium and steel are 248 and 207 GN/m^2 (36×10^6 and $30 \times 10^6 \text{ lbf/in}^2$) respectively.
- (iii) Once the layer of electrodeposited chromium contains a fatigue crack through its full depth, the stress intensity factor range at the crack tip will exceed the threshold value for the steel substrate and the crack will continue to propagate.
- (iv) The maximum residual tensile stress in the chromium, S_R , is 120 MN/m^2 ($18 \times 10^3 \text{ lbf/in}^2$) (see Section 4).
- (v) The fatigue limit of the chromium, $S_{a0}(\infty)$, is 340 MN/m^2 ($49 \times 10^3 \text{ lbf/in}^2$) (see Section 4).

Line B is then given by the equation

$$\Delta S_{a0}(\infty)_{(s)} = \frac{f_{t(s)}}{2} - \frac{E_{(s)}}{E_{(c)}} (S_{a0}(\infty)_{(c)} - S_R) \quad (5.1)$$

6. ALLEVIATION TREATMENTS

The detrimental effects of chromium electroplating on the fatigue limit of steels may be alleviated by pre- or post-plating processes. These are described in the following sections. More specific process details can be found in Derivation 12.

6.1 Pre-plating Treatments

6.1.1 Shot peening

All experimental results are consistent in showing that the residual compressive stress induced in the surface of the steel by shot peening before chromium plating improves the fatigue strength.

Figure 2 presents $S-N$ curves giving a comparison of fatigue strengths of unplated, chromium plated, shot peened, and peened and chromium plated steel specimens. The tensile strength of the steel was 620 MN/m^2 ($90 \times 10^3 \text{ lbf/in}^2$). The specimens were peened to give an intensity of 0.006 to 0.008 A2 as measured by the Almen Standard. The specimens were of the rotating beam type, and the plated specimens were not baked before being tested.

Because shot peening roughens the surface of the steel, sliding or running parts must be lightly ground, either before or after plating, or both. Careful control of the grinding process is required to ensure that:

* Data Item No. 88008 "Fatigue limit of unnotched steels (related to tensile strength)".

- a) before plating, residual compressive stresses induced by shot peening are retained in the surface layer of the steel.
- b) after plating, no cracks are initiated and that excessive heat, which may soften the chromium, is not generated. See also Section 6.2.2.

6.1.2 Rolling

Rolling before chromium plating is beneficial because (as with shot peening) a residual compressive stress that will resist the propagation of a fatigue crack is induced in the surface of the steel. Rolled and chromium plated steels may be baked in the range 100°C to 300°C (210°F to 570°F) without any lowering of their as-plated fatigue limit.

6.1.3 Nitriding

Nitriding the steel before plating induces a high compressive stress in the surface layer so improving the fatigue strength of the chromium plated steel. Fatigue strengths approaching or equal to that of the unplated steel have been obtained by this method (Derivation 1).

6.2 Post-plating Treatments

6.2.1 Baking

The electroplating process can cause hydrogen embrittlement of some steels, and this reduces their static strength under sustained load. To avoid this, chromium plated components are baked and this disperses the hydrogen absorbed by the steel during the plating process. This baking process has an effect upon the fatigue strength and care must be taken to ensure that the correct baking temperature is used. This is because of the complex changes that occur when heating a chromium electrodeposit on a steel base. Figure 3 shows the effect of baking for three thicknesses of chromium plate on steel*.

The effect of baking on fatigue strength can be summarised as follows.

1) Low temperature baking

Baking in this temperature range induces a permanent contraction in electroplated chromium. On cooling, this increases the residual tensile stress in the chromium, hence further lowering the fatigue strength of the component.

2) High temperature baking

At these temperatures the chromium softens and stress relief occurs. Owing to the differential contraction between chromium and steel (the coefficient of linear expansion for chromium being approximately half that of steel) the chromium experiences a compressive stress when cooled to room temperature, to a degree dependent on the maximum temperature attained during baking.

The low tempering temperature of some high strength steels prevents the use of high temperature baking as a means of stress relieving the chromium plate. Such steels are often especially prone to hydrogen embrittlement and so must be baked to remove the hydrogen at a temperature in the range 100°C to 300°C (210°F to 570°F). Baking a chromium electroplated component in this temperature range would normally cause a lowering of its as-plated fatigue limit. The loss of fatigue strength due to baking appears to be highly

* BS En 25, currently designated 826 M31 in BS 970.