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The effect of thick nickel coatings on the mechanical and fatigue properties of a turbine-disc steel

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SYNOPSIS

This paper reports and discusses experimental work carried out on heavy nickel-electroplated turbine-disc steel. Mechanical and fatigue tests were used to determine whether the coating was suitable for turbine-disc applications. It was concluded that dehydrogenation treatment is necessary in order to produce compatibility of the coating and substrate.

SAMEVATTING

Hierdie referaat doen verslag oor en bespreek eksperimentele werk wat in verband met swaar vernikkelde turbineskyfstaal uitgevoer is. Meganiese en vermoeidheidstoetse is gebruik om te bepaal of die laag geskik is vir turbineskyfaanwendings. Die gevolgtrekking was dat 'n dehidrogeneringsbehandeling nodig is om die laag en die substraat saamvoegbaar te maak.

Introduction

The engineering applications of electroplated nickel are well recognized and fairly widespread. This metal coating is used for aesthetic appeal, wear resistance, the building up of over-machined or worn components, and protection against corrosion.

Research into the influence of thick nickel coatings on the mechano-electrochemical properties of turbine-disc steel[1] led to a study of the effects of such coatings on the mechanical and fatigue properties of these types of steel. Previous research work had shown that thin nickel-electroplated layers tend to reduce the fatigue life of steels[2-4]. It was therefore necessary to establish whether this is true for thicker electroplated layers of nickel and, if so, to investigate methods of overcoming the problem. As a result, research was undertaken on the influence of heat, i.e. baking treatments, on the mechanical and fatigue properties of the nickel-electroplated low-alloy steel used for turbine discs.

Selection of a Plating Bath

The choice of a nickel bath depends primarily on the desired mechanical properties of the deposits, and to a lesser extent on such factors as deposit smoothness, tendency towards nodule formation, internal stresses, plating speeds, and ease of process control. For this type of service, only Watts and sulphamate baths were considered and, after preliminary screening tests on coated samples, it was decided to use only the sulphamate bath for electroplating the nickel. The main advantage of the nickel sulphamate bath is the low residual stress in the deposit, which is important for components that are to be subject to severe service stresses. As these internal stresses in a deposit from a sulphamate solution are less tensile than those obtained in a deposit from a Watts solution, sulphamate solution is possibly superior for components exposed to fatigue loading conditions. A further advantage of the sulphamate bath is its superior throwing power when compared with the Watts solution. It also has higher tensile strength and hardness values, which are therefore more compatible with those of quenched and tempered turbine-disc steels.

Experimental Procedure

The actual composition of the bath and the plating conditions developed are given in Table I.

TABLE I
EXPERIMENTAL CONDITIONS

Pre-treatment
Hand polish to a 1 μm finish
Anodic clean in inhibited 10% NaOH for 1 minute at 10 A/dm^2
Rinse in distilled water
Acid clean in 50% HCl for 30 seconds
Rinse in distilled water
Rinse in 5% sulphamic acid
Plating solution
80 g/l nickel as nickel sulphamate
40 g/l boric acid
2 g/l chloride
Plating conditions
Temperature 55°C ± 3°C
pH 4 to 4,5
Current density 3 A/dm^2 to give a plating rate of 0,01 μm/s
Mechanical agitation

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The samples to be coated took the form of undersized Hounsfield tensile and Wöhler fatigue specimens, which were then plated back to standard size by the application of 300 μm of nickel. The chemical composition of the low-alloy steel used in this investigation is given in Table II.

TABLE II
COMPOSITION OF STEEL USED
26NiCrMoV145

Element	%	Element	%
C	0,25	P	0,014
Ni	3,51	Si	0,09
Cr	1,46	Ti	0,01
Mn	0,33	Cu	0,10
Mo	0,43	Co	0,03
V	0,11	W	0,02
S	0,016		

The heat treatment given to the original turbine-disc material was as follows:

(1) austenitized at 880°C and oil quenched,
(2) tempered at 630°C, and
(3) stress relieved at 580°C and furnace cooled.

The resulting microstructure was mainly tempered martensite, with some bainite in the thicker sections.

Baking treatments were carried out on the plated specimens in a muffle furnace for 2 hours at various temperatures within the range 250 to 500 °C. The fatigue specimens were polished to a 1 μm finish before and after electroplating in order to remove any surface asperities left by the machining and plating.

Wöhler rotating-beam fatigue tests were carried out in air.

Results and Discussion

The S-N curves obtained for the various samples are given in Fig. 1. These curves demonstrate that the nickel coating drastically decreases the fatigue life of a component in the as-plated condition. The effect is illustrated in the fractograph in Fig. 2, which is a scanning electron micrograph (SEM) of a failed as-plated fatigue specimen. Clearly, the crack initiated in the apparently brittle coating. The coating thus has a limited critical defect size and would be expected to fail rapidly. The sharp crack in the coating acts as a stress raiser for the substrate, resulting in easy initiation of fatigue cracks, followed by ductile failure of the steel. It is thought that the decohesion of the coating, seen in this micrograph, occurred during the final ductile fracture of the specimen, since the fatigue crack observed appears to have propagated from the coating to the substrate in a continuous fashion.

The fatigue performance of a specimen baked at 250 °C appears to be no different from that of the as-plated specimen. However, at a baking temperature of 300 °C, an increase in the fatigue or endurance limit with respect to the as-plated specimen is obtained. This behaviour more or less approximates that of the uncoated specimen. In this test, there was no apparent difference between the nickel and the substrate as regards fatigue behaviour and final ductile failure, as can be seen by the SEM fractograph in Fig. 3. It was concluded that, under these conditions, the fatigue crack propagated uniformly from the nickel into the substrate without a discontinuity or change in mechanism.

At baking temperatures in excess of 300°C, a progressive decrease in fatigue life was observed, with the fatigue fracture surface exhibiting considerable ductility, as shown in Fig. 4. These results are summarized in Fig. 5. This shows a plot of fatigue limit versus baking

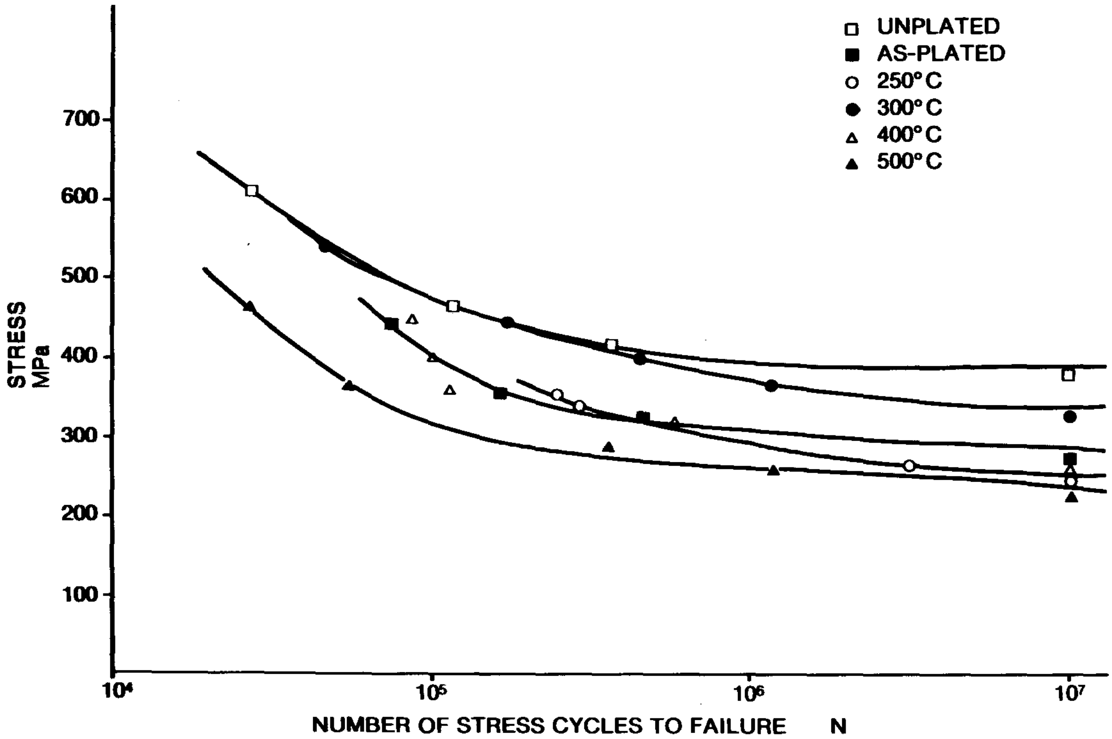

Fig. 1—S-N curves for the various samples

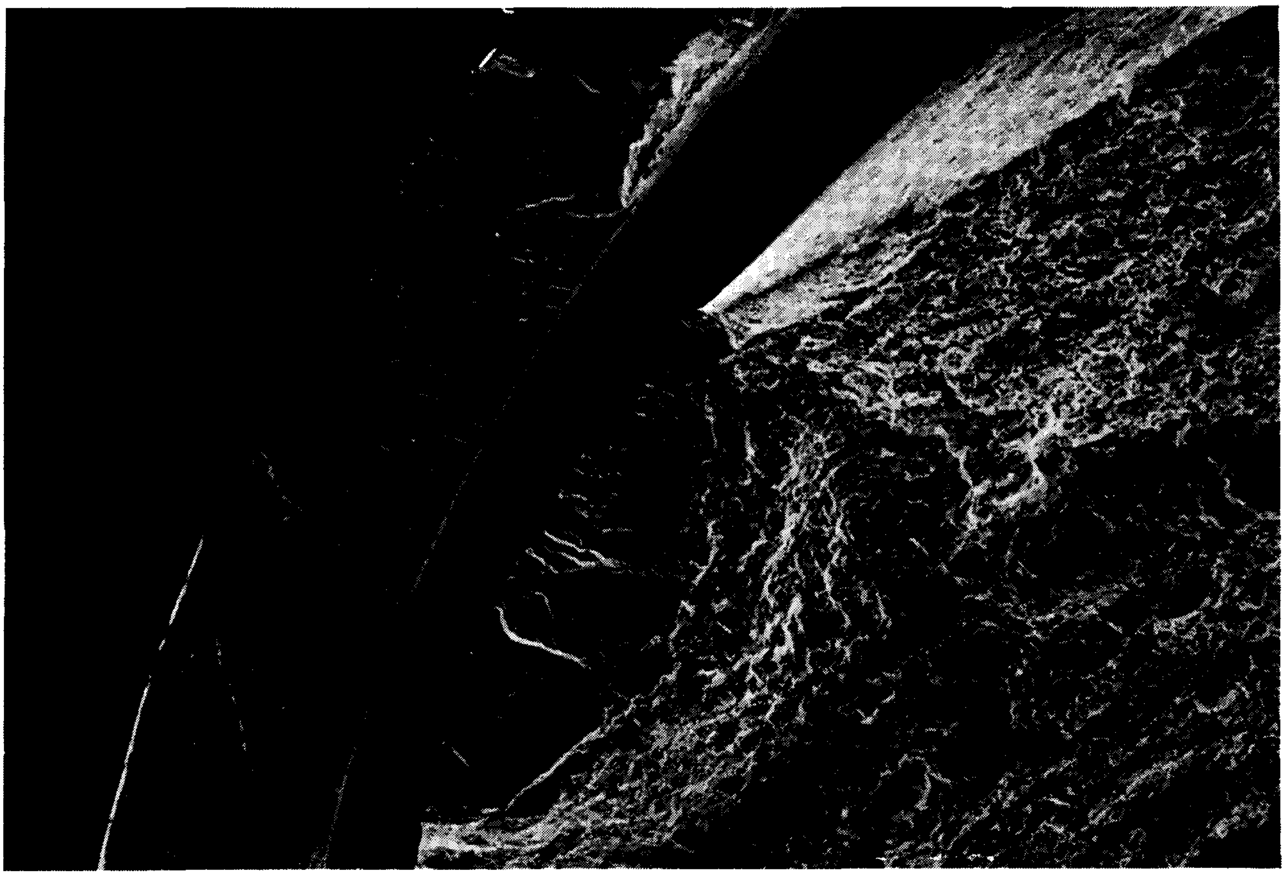

Fig. 2—SEM of a failed specimen (fatigue fracture surface: as plated 50X)

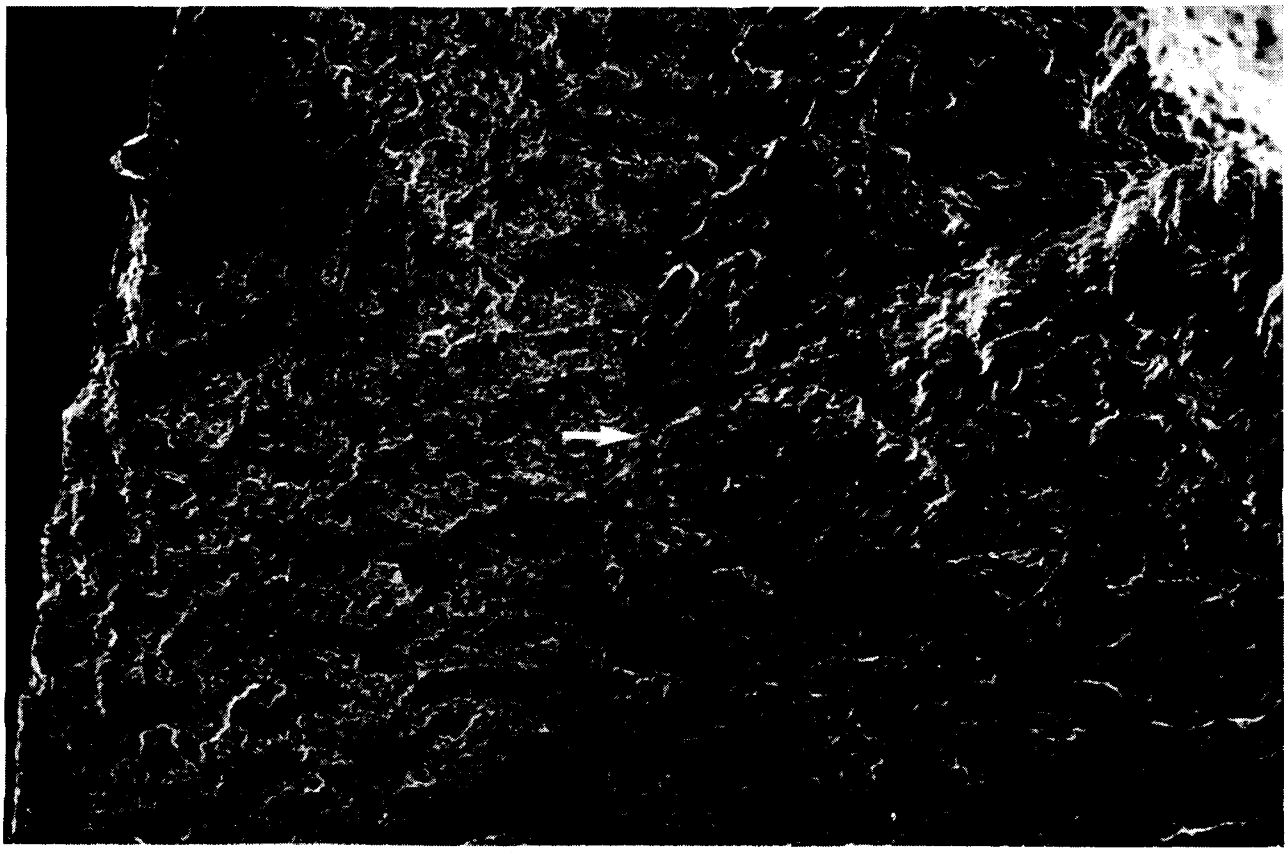

Fig. 3—Uniform propagation of a fatigue crack from the nickel into the substrate (fatigue fracture surface: plating–substrate interface 300°C 200X)

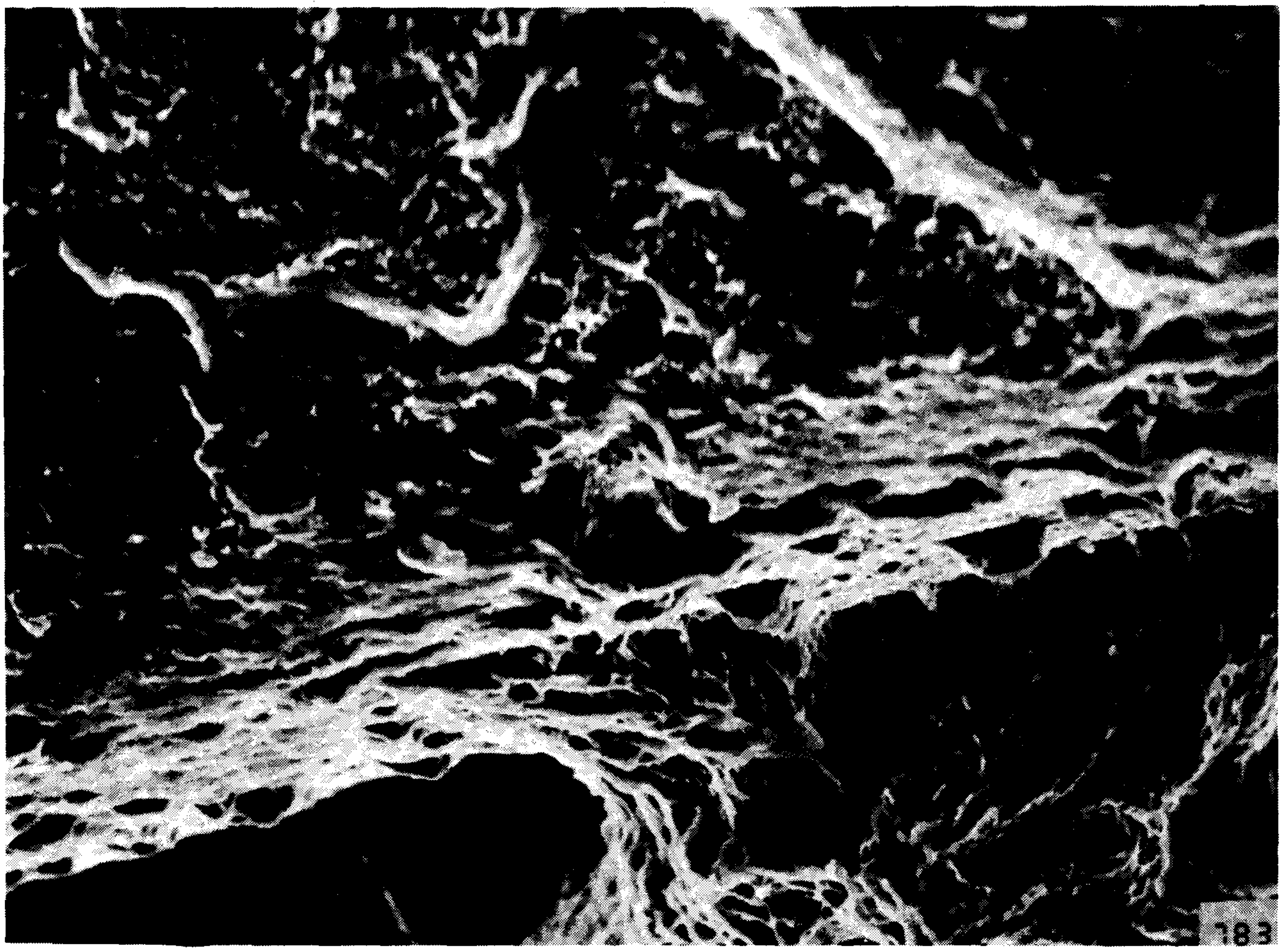

Fig. 4—A progressive decrease in fatigue life (fatigue fracture surface: 400°C 1000X)

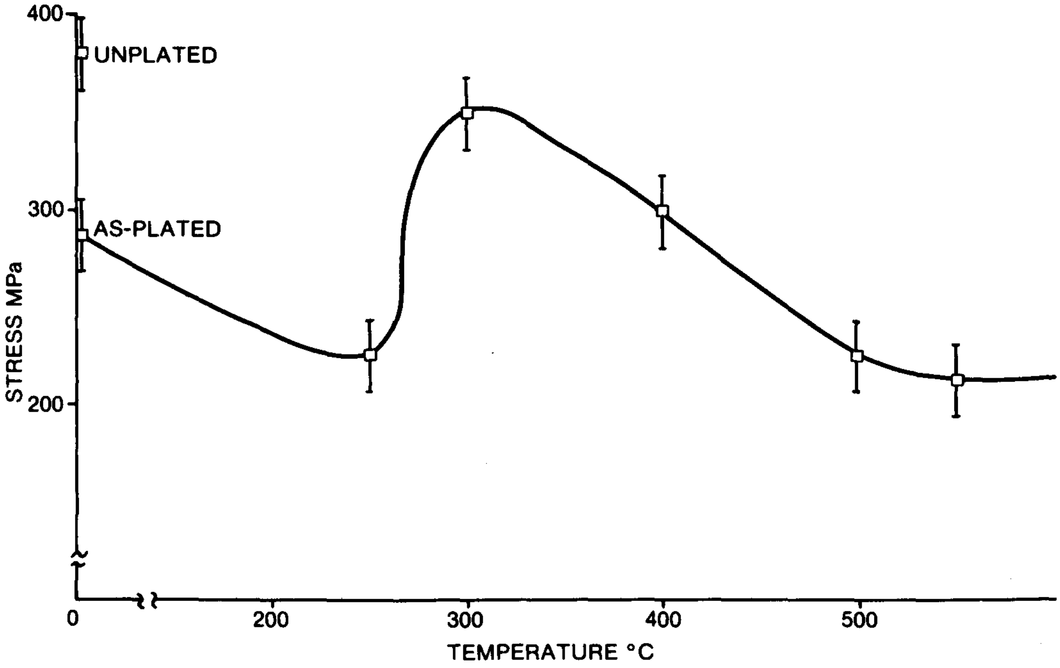

Fig. 5—Fatigue limit versus baking temperature

temperature with a peak at 300°C, which approximates the fatigue limit for the uncoated sample.

Fig. 6 shows a plot of baking temperature versus tensile properties for the plated and unplated samples. It can be seen that there is a small drop in the tensile strength of the material after plating. This as-plated specimen failed in a brittle manner, probably because the tensile strength of the nickel obtained from the sulphamate solution is slightly less than that of the substrates[5], with the brittle behaviour of the coating being attributed to the presence of small amounts of hydrogen in the coating. After a baking treatment, the coating became more ductile and failed in the same manner as the substrate. The ultimate tensile strength (UTS) remains constant until a baking temperature of 300 °C is reached, at which temperature it starts decreasing significantly, probably as a result of re-tempering of the steel substrate.

Fig. 7, which is a plot of coating hardness versus baking temperature, shows the same trend as for the UTS, i.e. the initial hardness of the coating closely approximates that of the substrate and remains constant until a baking temperature of 300°C is reached, at which point it decreases significantly.

It thus appears that 300°C is the critical temperature required for optimization of the properties of the coating and its substrate. Sunada[2] proposed a critical temperature of 250°C for thin nickel coatings (100 μm maximum). The existence of this critical temperature is thought to be governed by hydrogen diffusion processes, i.e. in this case complete effusion of the hydrogen dissolved in the coating takes 2 hours at 300°C. In thinner coatings such as those studied by Sunada, a lower temperature would be expected to be adequate for complete dehydrogenation within the same time period.

However, once the baking temperature exceeded 300 °C, a decrease in fatigue life was again observed. This phenomenon is probably due to the progressive relief of the low residual tensile stress within the coating. This results in a softer, more ductile coating as supported by the data on hardness and tensile strength reflected in Figs. 6 and 7. The reduced strength of the coating, and therefore of the entire plated composite, results in easier initiation of fatigue cracks. Such a crack, once it has formed in the coating, acts as a stress raiser for the substrate. Once again, there is easy initiation of substrate cracks, and thus reduced fatigue properties for the plated component. Further substrate weakening is possibly obtained by slight re-tempering at elevated temperatures.

It therefore appears that, under certain conditions, i.e. after dehydrogenation, the presence of low residual tensile stresses in the coating obtained from the abovementioned sulphamate bath is beneficial in the production of a coating that has suitable hardness and strength properties for the optimization of fatigue resistance.

Conclusions

(a) As-plated coatings obtained from sulphamate baths do not have mechanical or fatigue properties that are compatible with turbine-disc steel substrates, thus making a dehydrogenation treatment necessary.

(2) The baking temperature for optimization of the mechanical and fatigue properties in the case of heavy nickel-coated low-alloy steel is approximately 300°C. This treatment also produces mechanical and fatigue properties within the coating closely approximating those of the substrate.

(3) Baking of coated samples at lower temperatures facilitates the removal of hydrogen from the coating,

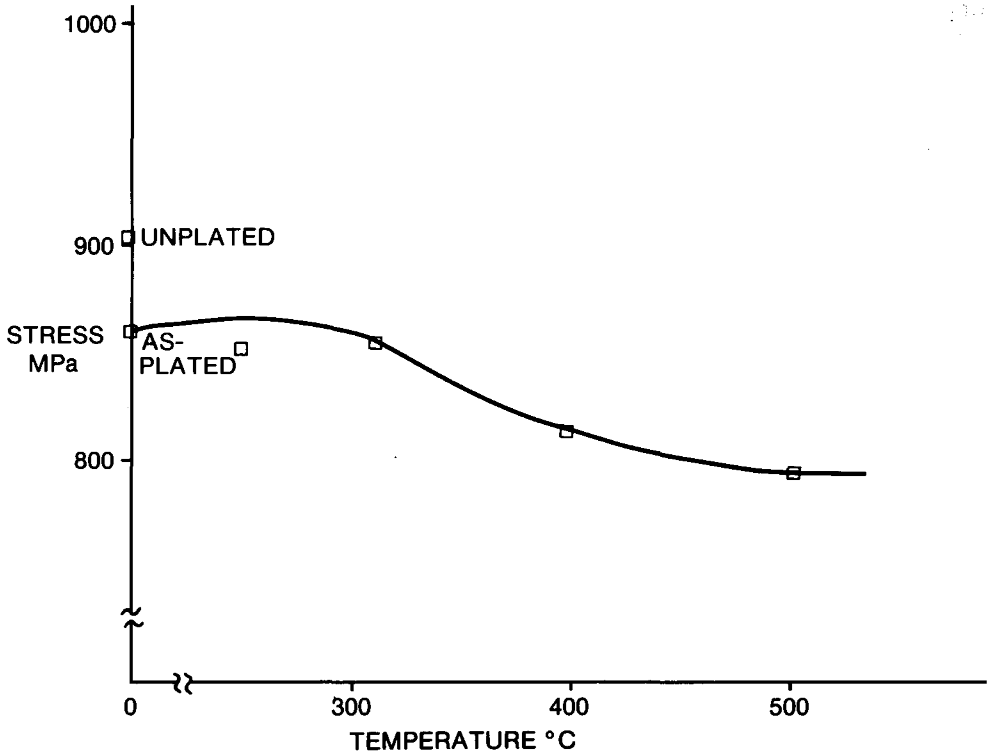

Fig. 6—Ultimate tensile strength versus baking temperature

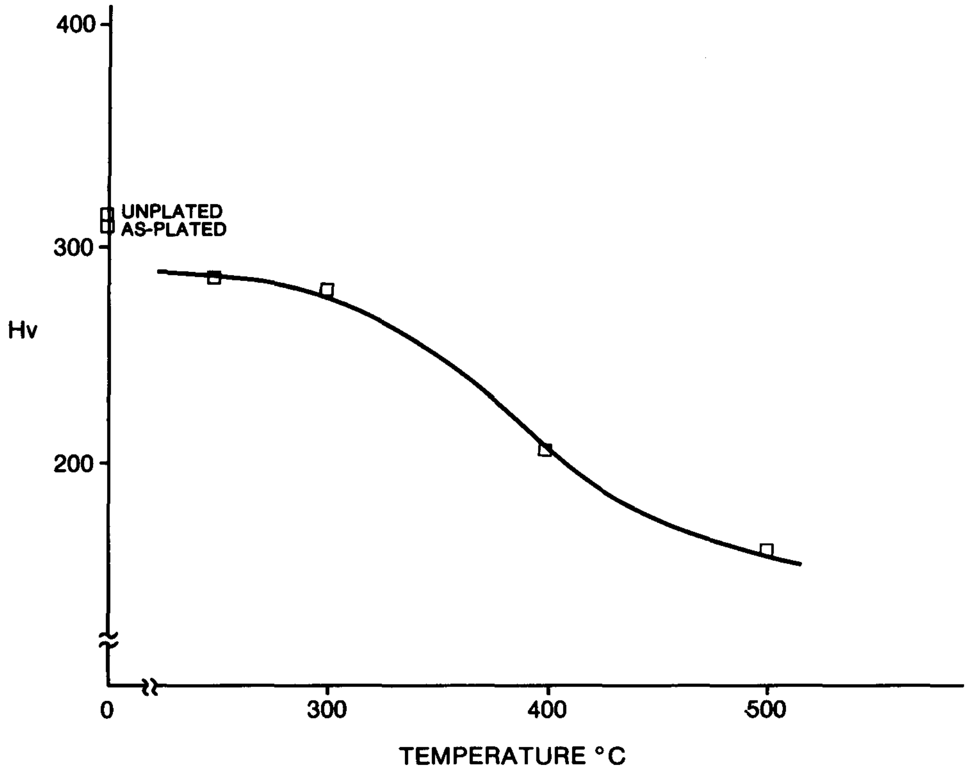

Fig. 7—Hardness of coating versus baking temperature

while baking at temperatures in excess of 300°C brings about a relief of residual tensile stresses within the coating.

(4) A nickel coating with the requisite mechanical and fatigue properties for turbine-disc service, involving exposure to stress corrosion and fatigue conditions, will be obtained if the coating is of sufficiently high quality, and if the appropriate dehydrogenation baking treatment is administered.

Acknowledgements

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