# Refurbishment of small diameter nitrided spindles with laser based direct energy deposition

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**Abstract.** Laser based direct energy deposition is a process that is commonly used to refurbish worn components in the power generation sector. In this work the potential for refurbishment of nitrided spindles manufactured from AISI 420 SS, with a small diameter (20 mm), is evaluated. Firstly, the required material removal from the nitrided surface was established. Secondly, the distortion of the shaft was measured as a function of the length of the refurbished section, and the thickness of the added material. It was found that the shaft must be pre-machined to a depth of 0.4 mm to ensure a pore-free weld on AISI 420 SS subjected to a typical gas nitriding cycle. Furthermore, it was shown that the distortion of a 20 mm diameter shaft, with a length of 1000 mm, can be 0.12 mm, if a 200 mm long section of the shaft is repaired. Reasons for the distortion are discussed, and possible mitigation measures are proposed.

## 1 Introduction

Wear is one of the main causes of in-service damage to industrial components, whether in the form of friction, erosion, corrosion or cavitation. Refurbishment of worn components offers the option to restore the component to its original geometry and extend its service life. Various repair technologies exist, e.g. laser based directed energy deposition (LDED), thermal spraying and plasma transferred arc. In this study, LDED was investigated, with specific focus on the refurbishment of small diameter nitrided spindle components. Two problems are expected to occur when small diameter nitrided spindles are refurbished. First, porosity forms due to the presence of nitrogen at the surface. Second, distortion caused by the localized heating and cooling cycles at the melt pool during LDED processing. The low restraint of a small diameter shaft is expected to result in significant distortion.

Porosity forms when nitrided components are welded, because the nitrogen in the metal is released as a gas when the metal is melted. This has been reported by studies that

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investigated LDED refurbishment of nitrided components [16]. Across industry, many surface modification heat treatment methods are used to make metals more application suitable, and nitriding is one of these. Nitriding is a low-distortion, thermo-chemical treatment which entails the diffusion of nitrogen into the material surface. The added nitrogen combines with iron and other alloying elements in steel, to form hard metallic nitrides (compound layer). Underneath the compound layer, a diffusion zone forms which contains nitrogen in solid solution as well as stable metal nitrides [24]. This compound layer on the surface is also referred to as a 'white layer' and increases the wear resistance and fatigue strength of materials. Depending on the specific steel, nitriding method and process parameters, the achieved surface / compound hardness after nitriding is typically 60 - 70 HRC with a typical case depth of 50 - 200 μm [2,3,44].

The distortion that occurs due to the localized heating and cooling cycles at the melt pool during a welding process (of which LDED is a specific type) is influenced by several mechanisms [54]. Only two mechanisms are relevant to the current work. The first mechanism, called the thermal gradient mechanism, is applicable to regions that are not heated to above the melting temperature [66]. The heated region attempts to expand but is prevented from doing so by the adjacent cold metal, resulting in the heated region being compressed. Compression is elastic initially, but if a high enough temperature is reached plastic deformation occurs. When the heated region cools down as the heat conducts away from the weld, it shrinks to a size smaller than it was before the initial heating, resulting in it pulling the surrounding metal inwards. The second mechanism, called the shrinking of solidified metal mechanism, is applicable to regions heated to above the melting temperature [66]. Such regions do not exert any forces while molten, but after solidification it shrinks upon cooling. The result is also that it pulls the surrounding metal inwards.

In this work, porosity in overlays produced by LDED on base metal from which the nitrided layers were ground off is investigated first. Thereafter, the distortion caused by LDED on a shaft with a geometry similar to that of a typical spindle is investigated.

## 2 Experimental methods

All overlays were produced with LDED with Metco 42C powder, which has a chemical composition by weight of 17 % Cr, 2% Ni, 0.18% C, Fe-balance. The powder had a particle size range between 45 and 90 μm. All overlays were produced with a fiber laser with a wavelength of 1073 nm. The processing head was set up so that a spot size of 2 mm was achieved at the workpiece. Laser power of 1 kW was used. Powder was fed at a rate of 8.2 g/min with Argon carrier gas. The heat source moved at 1.5 m/min relative to the surface being refurbished. The resulting layer had a thickness of approximately 0.55 mm.

### 2.1 Characterization of nitrided material and overlays produced on material from which nitrided layers were ground off

The Carbon and Sulphur content of the as-received AISI 420 SS base material was determined by combustion analysis with an ELEMENTRAC CS-i ELTRA instrument. The rest of the elements present in the material were determined by Inductively Coupled Plasma (ICP) analysis with a Spectro Green ICP instrument.

To evaluate the influence of nitrogen that is present close to the surface in a nitrided metal, a 60 mm diameter shaft of AISI 420 SS was nitrided at 560 °C for 3h. The microstructure and micro hardness at various depths below the surface of the nitrided material was characterized. Thereafter, overlays were produced on as-nitrided material and material from which 100 μm, 250 μm, 400 μm, 550 μm were ground off respectively. Finally, cross sections of the overlays were made and prepared for metallographic evaluation. Preparation for metallography consisted of cutting and mounting, followed by manual grinding. Grinding started with SiC paper with a 120 grit size, followed by 320 grit size and finally 9 µm diamond suspension. The sample was ground until all scratch marks were in one direction after which the sample was rotated by 90° and ground again until all scratches were in one direction. Polishing was performed automatically with 3 µm diamond suspension followed by 0.04 µm colloidal silica suspension. When desired, samples were etched with Kalling's No.2 etchant.

## 2.2 Distortion investigation

Overlays were produced with laser based directed energy deposition on small diameter shafts to investigate distortion. The length of the overlays and number of layers were varied in order to identify trends.

### *2.2.1 Fabrication of overlays for distortion analysis*

The dimensions of the shafts used to investigate distortion are shown in Fig. 1. Each shaft had a flat surface on one end which was used to align the CMM data obtained before and after fabrication of the overlays. To produce a layer, the shaft was spun at a set revolutions per minute. The required revolutions per minute were calculated so that the tangential speed on the surface of the shaft was 1.5 m/min. Once the rotational speed of the shaft was stable, the laser beam was switched on and the directed energy deposition head was guided along the axis of the shaft by a robotic arm. This resulted in the metal being deposited as a helix [7]. The speed at which the head traversed was calculated so that the pitch of the helix was 1 mm.

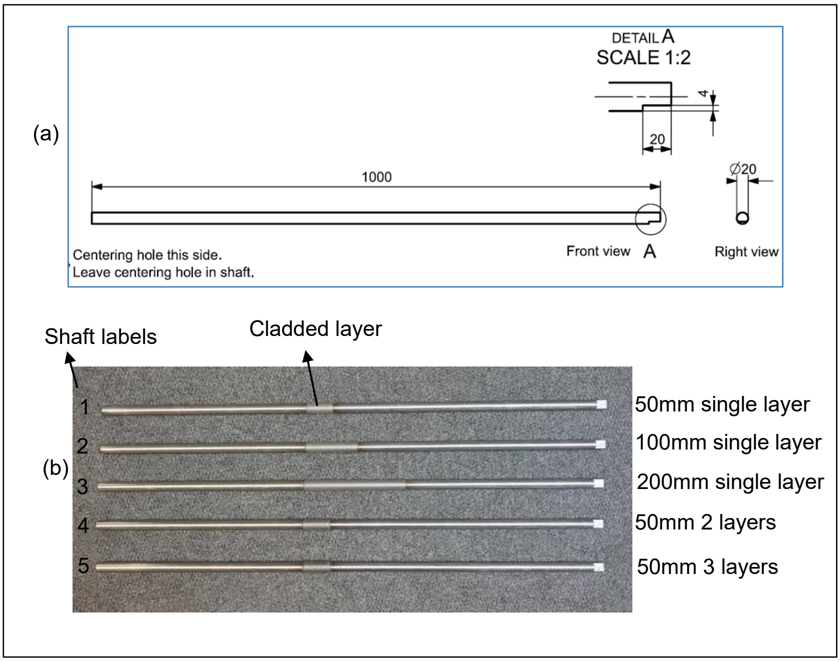


**Fig. 1.** (a) Dimensions of shafts used to investigate distortion. (b) Photograph with the length and number of layers corresponding to each shaft label indicated.

#### *2.2.2 Distortion characterization*

In order to measure the distortion that occurred during LDED, each individual shaft's geometry was characterized before and after processing. The geometry was characterized by a Coordinate Measuring Machine (CMM). The following geometrical information was captured on each shaft: the midpoints of the ends, the coordinates of several points on the flat surface, the coordinates of points spaced 2 mm apart on the top, bottom and sides of the cylindrical portion of the shaft. See the illustration in Fig. 2.
The CMM data, captured in an IGS file, was imported in MATLAB to be processed. The geometrical information of each shaft before and after LDED was aligned with the following procedure: the midpoints of the ends were placed on top of each other, data was rotated so that the flat surfaces aligned, the centre before and after was determined by fitting a circle at each 2 mm increments along the length of the shaft. The distance between the middle of the shaft at each 2 mm increment before and after LDED, was taken as the distortion at that position. CMM data at positions where the overlays were produced was excluded from the analysis.

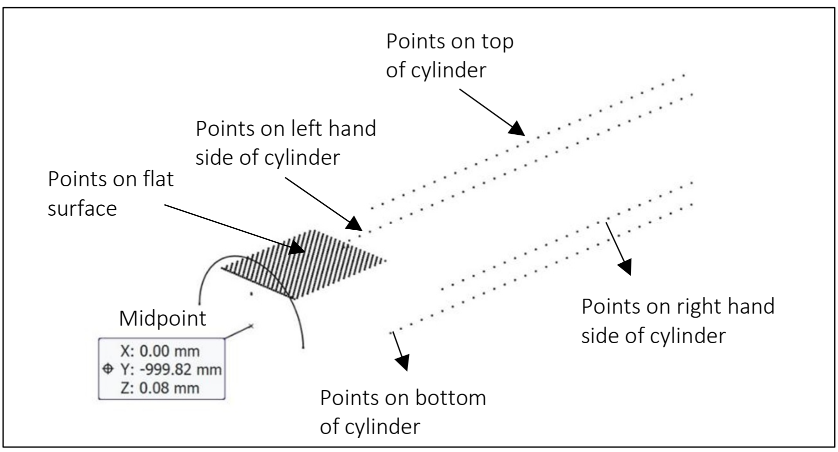


**Fig. 2.** Geometrical information gathered from each shaft by CMM.

## 3 Results

### 3.1 Chemical composition and microstructure of base metal

The chemical composition by weight of the base metal was measured to be 0.317% C, 0.025% S, 0.78% Mn, 0.019% P, 0.5% Si, 13.1% Cr, 0.05% Mo, 0.05% Cu, 0.05% V, 0.03% Nb, 0.02% Co, Fe-Balance.

The microstructures of the AISI 420 SS base material viewed from two planes are shown in Fig. 3 (d) and (e). Note that the microstructure was homogenous martensite when viewed cross sectionally, but in the axial view stringers that could be delta ferrite or manganese sulfide were seen. Stringer-type manganese sulfide inclusions can cause lamellar tearing when a component is welded, if it exceeds allowable levels [8]. Fig. 3 (a) is a photograph of the bar which shows its black color after nitriding. In Fig. 3 (b) the 70 μm deep nitride ceramic layer (typical of nitrided materials [24]) of an unetched sample is shown, note that some small pores are present. Fig. 3 (c) shows the hardness at various depths of the nitrided sample. Within the nitrided layer it was approximately 832 HV (64 Rockwell C), which is within the range of hardness reported for alloyed steels in the literature [4,88]. The hardness of the base metal was unaffected by nitriding at depths exceeding 120 µm, suggesting that removing 150 µm from the surface of this nitrided material should be sufficient to prevent it from influencing an overlay.

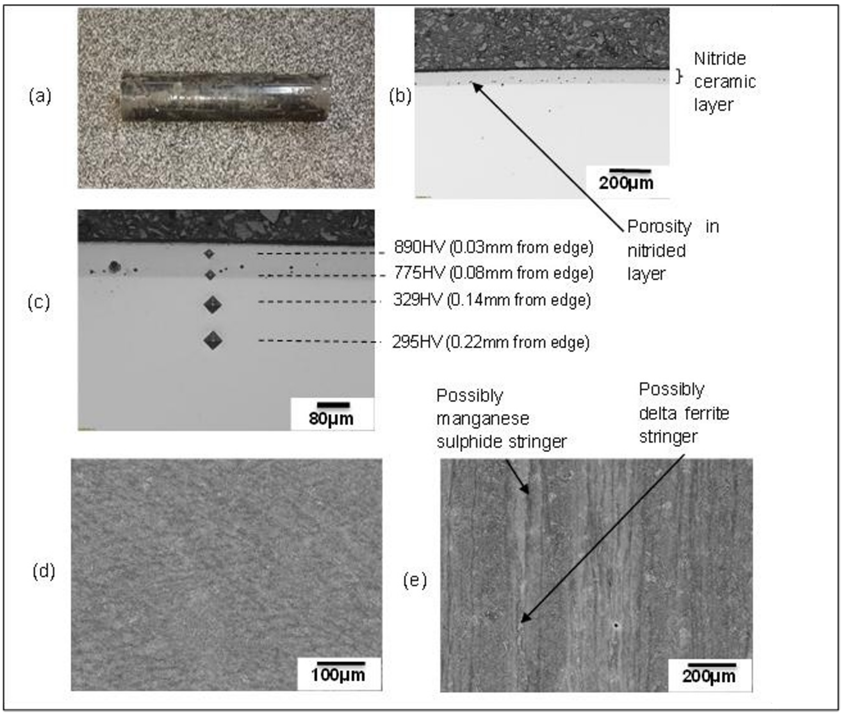


**Fig. 3.** (a) Photo of nitrided bar. (b) Cross section of bar at the surface. (c) Hardness of nitrided bar at various depths. (d) Cross sectional view of bar's microstructure. (e) Axial view of bar's microstructure.

## 3.2 Distortion results

The measured distortion of 50 mm long overlays produced with one, two and three layers are shown in Fig. 4 (a). In all three cases little distortion occurred, the maximum distortion was ~0.035 mm. Scatter in the data points could be due to minor imperfections and scratches on the surfaces. Nevertheless, a clear trend occurred, being that adding more layers increased the distortion. The distortion of shafts of which 50 mm, 100 mm and 200 mm long portions were overlaid are shown in Fig. 4 (b). A maximum distortion of 0.12 mm was observed when the clad was 200 mm long, indicating that distortion is indeed a problem when refurbishing large sections of the shafts. Clearly, an increase in distortion occurred when the length of the overlaid portion was increased.

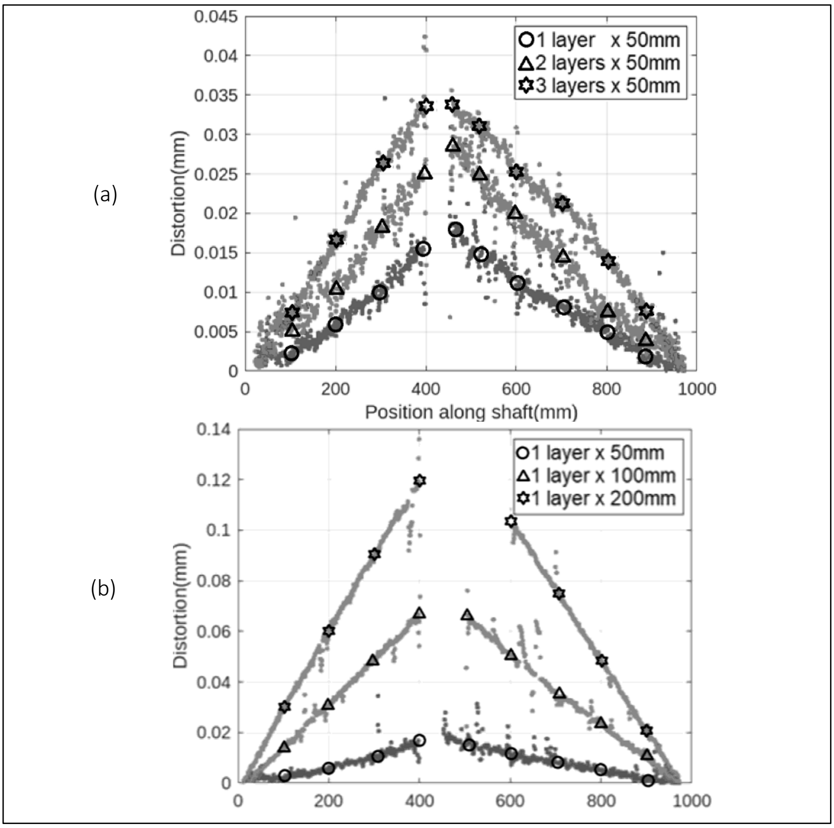


**Fig. 4.** (a) Distortion of shafts on which different amounts of layers were overlaid. (b) Distortion of shafts on which overlays of different lengths were produced.

### 3.3 Microstructure of base metal and overlays produced on a nitrided bar from which different amounts were ground off

Micrographs of the nitrided material from which various amounts were ground off are shown in Fig. 55. Note that severe porosity formed when the overlay was made directly on the nitrided surface. Furthermore, note that removing material to a depth of 250 µm was not sufficient to avoid porosity, thus indicating that the nitrogen penetrated deeper into the material than the nitride ceramic layer observed in Fig. 3 (b). Removing material to a depth of 550 µm, was observed to be sufficient to prevent pores from forming in the overlay, see Fig. 55 (e), thus indicated that an insignificant amount of nitrogen diffused into the material to a depth of 550 µm. Note that the depth reported is specific to the material used and the parameters of the nitriding procedure, according to the literature the diffusion zone can be up to 0.8 mm thick [2].

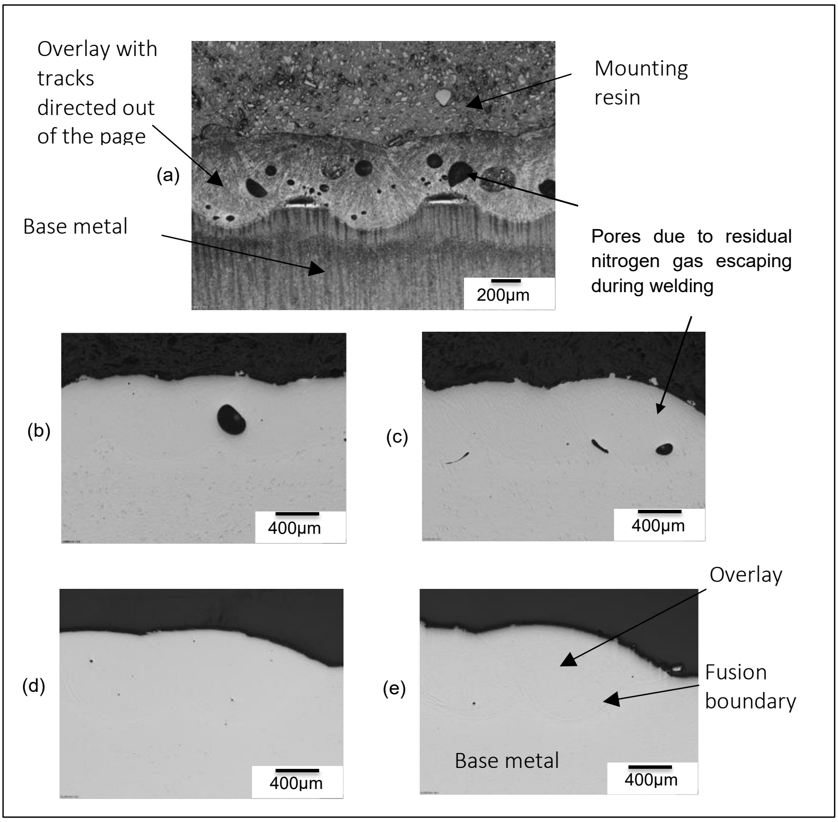


**Fig. 55.** (a) Micrograph of overlay produced on as-nitrided material. Unetched micrographs of overlays produced on nitrided material from which (b) 100µm, (c) 250µm, (d) 400 µm and (e) 550 µm were removed respectively.

## 4 Discussion

The results obtained on as-nitrided material clearly indicate the need for removal of the surface layers of a nitrided component before refurbishment. As expected, significant pores formed in the overlay when no grinding was performed. Furthermore, it is important to note that porosity formed even when the ceramic nitride layer was ground off. Indicating significant amounts of nitrogen diffused into the metal below the ceramic layer which could not be deducted from the hardness measurements or the optical metallography that was performed. Examining the microstructure with a Scanning Electron Microscope may reveal sub-micron sized nitrides in the diffusion zone [8], but such a study is beyond the scope of this work.

Distortion measurements confirms the validity of the “rule of thumb” regarding welding distortion [99], which states that reducing the volume of the weld metal (the volume of the overlay in this work) reduces distortion. The low distortion observed is due to the overlays being approximately axisymmetric and the use of LDED which is a low heat input welding process. A perfectly axisymmetric build-up will result in no distortion, because the influence from the track on one side is countered by the track on the opposite side of the shaft. The observed distortion in this work was most likely due to slight asymmetry in the overlays at the start and end points of the helix which formed the build-up. The observation that overlaying a larger portion caused more distortion could be due to an increase in the size of the heat affected zone occurring due to heat build-up. The heat affected zone contributes to distortion through the thermal gradient mechanism.

The accumulation of distortion observed when more layers were added (Fig. 4 (a)) can be reduced by taking note of the starting and ending points of the helix in consecutive layers. If the start and end points of a layer are placed on the sides of the shaft opposite to the start and end points of the previous layer, it will counter the previous layers distortion to some extent.

## 5 Conclusions

This study investigated the porosity in LDED overlays produced on nitrided material and the distortion of small diameter shafts. Based on the results obtained the following conclusions can be drawn:

- AISI 420 SS that underwent the nitriding cycle used in this work requires at least 0.4 mm to be ground off from the surface of the nitrided component to avoid the formation of porosity in the overlays.
- Despite minimal distortion that occurred when small portions of the shafts were refurbished, a maximum distortion of 0.12 mm was observed when a 200 mm long section was overlaid.
- Distortion increased when the length of the overlaid section increased or if more layers were added.

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