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Influence of Plasma electrolytic Polishing on the surface morphology of additively manufactured Ni-Ti-parts investigated on the basis of smart springs

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Abstract
Additive manufacturing enables the fabrication of parts in a single process step – largely independent of the complexity of their geometry. This is particularly interesting when conventional manufacturing technologies (e.g. casting, forming, machining) are associated with extreme effort and usually only allow simple component shapes, as it is the case with Ni-Ti alloys. These not only have excellent mechanical properties and a high resistance to corrosion and wear as well as outstanding biocompatibility, but also exhibit a characteristic phase transformation in the solid state resulting in the shape memory effect and superelasticity. If an additive manufacturing approach is chosen for a Ni-Ti component, thus enabling the fabrication of complex and even intentionally porous components in one process step, post-processing of the surface becomes inevitable. Plasma electrolytic polishing (PeP) shows particular potential for this application due to its ability to achieve low roughness and high gloss levels within short processing times. The influence of PeP on the surface morphology of additively manufactured Ni-Ti components was investigated using corresponding compression springs, so-called smart springs. Using PeP, a structured morphology unimpaired by powder adhesions as well as a considerably smoother and glossy surface could be successfully achieved after five and fifteen minutes processing time, respectively, on Ni-Ti samples additively manufactured by Selective Laser Melting (SLM).

PeP, Nitinol, SLM, Additive Manufacturing

1. Introduction

Additive manufacturing enables the fabrication of parts in a single process step – largely independent of the complexity of their geometry. This is particularly interesting when conventional manufacturing technologies (e.g. casting, forming, machining) are associated with extreme effort and usually only allow simple component shapes, as it is the case with Ni-Ti alloys [1]. These not only have excellent mechanical properties and a high resistance to corrosion and wear as well as outstanding biocompatibility [2–4], but also exhibit a characteristic phase transformation in the solid state resulting in the shape memory effect and superelasticity. If an additive manufacturing approach is chosen for a Ni-Ti component, thus enabling the fabrication of complex and even intentionally porous components in one process step, post-processing of the surface becomes inevitable. Otherwise, powder adhesions can become detached during operation leading, for example, to increased abrasion or short circuits and thus need to be removed. In addition, a smoother surface with regard to roughness is usually preferable in terms of mechanical performance. However, it could be shown that retaining the underlying Selective Laser Melting (SLM) structure can enhance biocompatibility of the components [5]. The influences of the respective processing technologies on the surface morphology of Nitinol are, to date, largely unresearched. Plasma electrolytic polishing (PeP) shows particular potential for this application due to its ability to achieve low roughness and high gloss levels within short processing times. Here, the workpiece is immersed in a cathodically contacted electrolyte bath with a material-specific, aqueous salt solution and anodically contacted. With potential *u* (typically in the range of 180 V to 400 *V*) and current density *J* (approx. 0.2 A/cm²) within a specific process window, a vapour skin forms around the workpiece in which a plasma stabilises. Here, an interplay of electrochemical and physical mechanisms occurs, which remove material preferentially at protruding contours and thus eliminate burrs and reduce roughness peaks. On milled surfaces, a roughness of $R_a < 0.2$ µm can be achieved within a few minutes, although the significantly higher initial roughness of additively manufactured metal surfaces usually requires longer processing times. The influence of PeP on the surface morphology of additively manufactured Ni-Ti components was investigated using corresponding compression springs, so-called smart springs. Their function is based on the unconventional mechanical behaviour of martensite, which results in a 50 % to 75 % drop in spring rate compared to austenite [6]. Thus, they react to a change in temperature by performing work and are therefore simultaneously sensors and actuators.

2. Methodology

For this investigation, smart springs with a wire diameter *d* of 2.0 mm and a spring length *l* of 25.0 mm were designed. The pitch *p* corresponds to three times *d*, as shown in Figure .

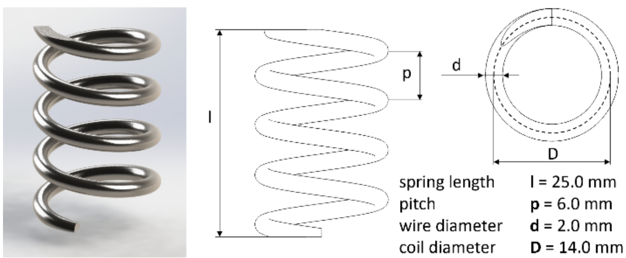

Figure 1. CAD-rendering and design parameters of the samples

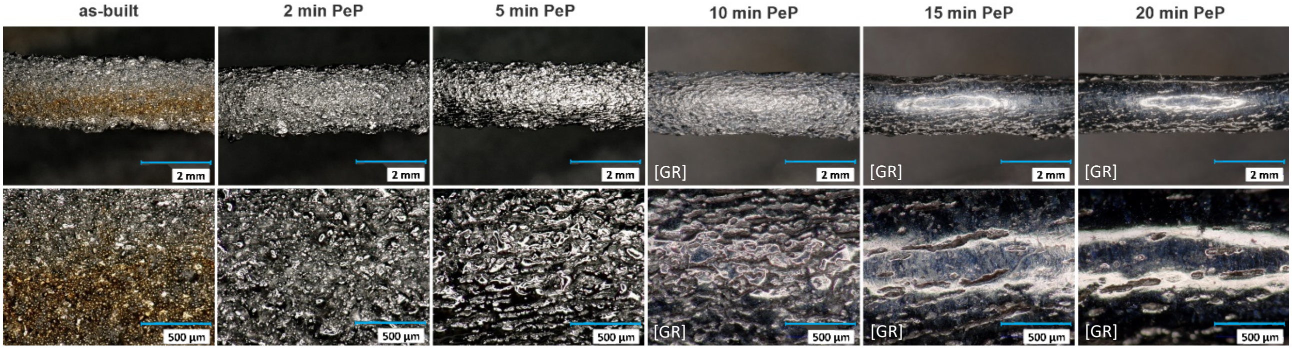

Figure 2. Optical micrographs of the lateral spring surface (centre coil) after different PeP times; [GR] recorded with active gloss reduction

Nine samples (#1 to #9) were then additively manufactured by SLM using a powder with the chemical composition shown in Table 1 along with the process parameters listed in Table 2.

Table 1. Chemical composition of the SLM powder in wt%

Ni	Ti	Fe	C	O + N
56.570	43.325	0.021	0.009	0.043

Table 2. SLM process parameters

Laser power	Laser speed	Layer thickness	Hatch distance
150 W	900 mm/s	60 µm	90 µm

Subsequently, the samples were PeP polished in a material-specific electrolyte for two minutes (#4 – #6), five minutes (#9), ten minutes (#7), fifteen minutes (#8) and twenty minutes (#1) at u = 330 V while being turned over after half of the processing time. In comparison to the initial as-built condition (#2, #3), the processing objectives were defined as the removal of powder adhesions while retaining the fissured SLM structure (T1) as well as its removal in order to achieve a smoother, uniform surface with lower rougness (T2). The evaluation of the investigated states was carried out by assessing the surface morphology using a Keyence VHX 900F optical microscope and determining the remaining sample mass using a KERN 572 precision scale.

3. Results and discussion

The initial surface after SLM is characterised by the presence of spatters and partially melted powder adhering to the part. Furthermore, surfaces manufactured in hanging orientation exhibit a golden brown discolouration due to titanium oxide, which consequently ends at the centre of the lateral surface. As shown in Figure 2, it can be successfully removed after only two minutes of PeP polishing time. This is due to the dissolution of the oxide by complexing agents in the electrolyte. However, a glossy surface free of powder adhesion can only be observed after five minutes of processing time. Simultaneously, the underlying SLM structure is slightly rounded, but preserved. This stage can therefore be equated with target T1. With continued polishing time, the fissured morphology is further removed and, after fifteen minutes of PeP, transforms into a coherent and glossy surface with a roughness several orders of magnitude lower than the initial state. Despite a waviness visible in the light reflection and elongated notches located in the build plane, it thus approaches the desired geometry and achieves target T2. The notches can be reduced by further machining, but at the cost of additional material removal. However, it is more promising to counteract their formation by optimising the SLM parameters. The achievable results in this scenario are shown in Figure 3, which compares the upskin surface of the springs in the initial state and after twenty minutes of PeP.

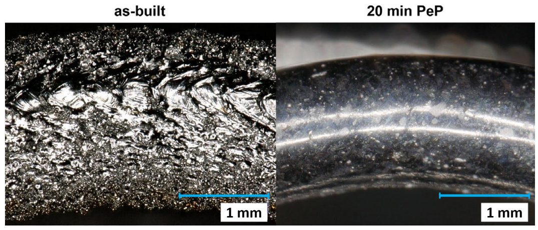

Figure 3. Optical micrographs of the upskin surface before and after PeP

This processing is accompanied by a corresponding material dissolution, which at a rate of approx. 45 mg/min reaches 6 % for target T1 and 18 % for target T2, as shown in Figure 4. This is significantly lower than the 25 % and 41 % reported for chemical etching by Jahadakbar et al. [7].

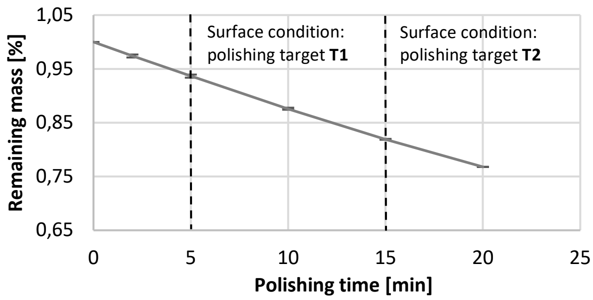

Figure 4. Remaining relative sample mass in relation to the PeP time

4. Summary

Using PeP, a structured morphology unimpaired by powder adhesions as well as a considerably smoother and glossy surface could be successfully achieved on SLM Ni-Ti samples after five and fifteen minutes processing time, respectively. The material removal required for this is significantly lower than with chemical etching as a researched alternative process. This demonstrates the potential of PeP for this application, although its influence on phase transformation and functional properties remains to be investigated.

References

[1] M. H. Elahinia, M. Hashemi, M. Tabesh, and S. B. Bhaduri, *Prog. Mater. Sci.*, **vol. 57**, pp. 911–946, 2012

[2] X. Wang, S. Kustov, and J. Van Humbeeck, *Materials*, **vol. 11**, no. 9, pp. 1683, 2018

[3] H. C. Lin, H. M. Liao, J. L. He, K. C. Chen, and K. M. Lin, *Metall. Mater. Trans. A Phys. Metall. Mater. Sci.*, **vol. 28**, no. 9, pp. 1871–1877, 1997

[4] J. Ryhänen, E. Niemi, W. Serlo, E. Niemelä, P. Sandvik, H. Pernu and T. Salo, *J. Biomed. Mater. Res*., **vol. 35**, no. 4, pp. 451–457, 1997

[5] I. V Shishkovsky, L. T. Volova, M. V Kuznetsov, and I. P. Parkin, *J. Mater. Chem.*, **vol. 18**, pp. 1309–1317, 2008

[6] D. Stoeckel and T. Waram, *Springs -The Mag. Spring Technol.*, **vol. 30**, no. 2, pp. 35–42, 1991

[7] A. Jahadakbar, M. Nematollahi, K. Safaei, P. Bayati, G. Giri, H. Dabbaghi, D. Dean, and M. Elahinia, *Metals*, **vol. 10**, pp. 1–15, 2020