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A REVIEW ON THE MACHINING OF NICKEL-TITANIUM SHAPE MEMORY ALLOYS

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Abstract. In this review paper the machining performance pertaining to the processing of Nickel-Titanium shape memory alloys is presented. High accuracy products for specialized applications need to be machined in order to be shaped to their final form. However, shape memory alloys are characterized by poor machinability due to the same properties that make them unique. Superelasticity and shape memory effect are discussed in order to obtain an insight on the transformation mechanisms of shape memory alloys. Furthermore, tension and shearing are considered. In the last part, conventional machining such as turning, milling and drilling and non-conventional machining for the processing of shape memory alloys are studied. A discussion on machinability, tool materials, tool wear, cutting fluids, cutting conditions and the effect of material properties on the final product is included.

1. INTRODUCTION

Shape memory alloys (SMAs) have attracted the interest of the scientific community mainly due to their exquisite properties that make them ideal materials for applications in automotive, aerospace and biomedical sectors while the areas of interest are constantly expanding and numerous commercial applications already exist. Properties such as superelasticity (SE) and shape-memory effect (SME) that give these materials their characterisation as smart materials are in the forefront of the studies related to them. Most of the research is referred to Nickel and Titanium intermetallic compounds, also known as NiTi or Nitinol alloys, which occupy the majority of the shape memory products market.

Surveys indicate that a high percentage of all mechanical components value, manufactured in the world, comes from machining operations and that annual expenditure on machine tools and cutting tools are several billion euros for industrially developed countries [1,2]. Manufacturing technology is driven by two very important factors, which are closely interconnected, namely better quality and reduced cost. Modern industry strives for products with dimensional and form accuracy and low surface roughness at acceptable cost while, from an economic point of view, machining cost reduction achieved through the increase of material removal rate and tool life without compromising surface integrity, especially for hard-to-machine materials like SMAs is highly desirable. Applications refer mostly to actuators and implants, but there have been more than 10,000 SMA related patents in the USA only and more than 20,000 worldwide, in various industrial areas [3]. Most applications refer to the micro-world regime for state-of-the-art products requiring accuracy, surface integrity and complex shapes at acceptable cost. Machining can provide all these characteristics and perform better compared to other manufacturing processes. However, there are limitations connected to materials and tools properties

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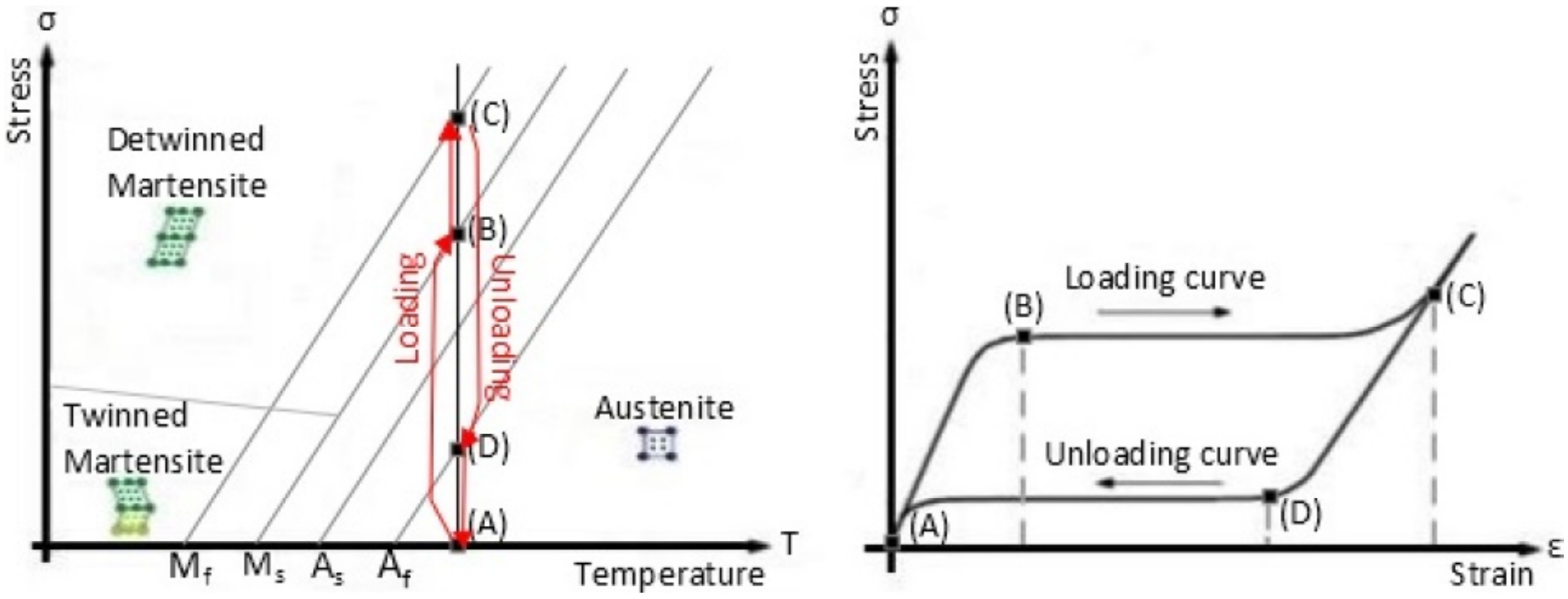

Fig.1. Stress-temperature (left) and stress-strain (right) curves that describe the SE behaviour.

and thus it is imperative to further study the machining of SMAs.

In this study, the superelasticity and shape memory effect are described and the basic deformation mechanisms in connection to SMAs are considered. Then, a survey on the most commonly used conventional and non-conventional machining processes used for SMAs is presented. Aspects of the processes, e.g. cutting tools and cutting conditions are investigated and the findings of relevant researches are presented.

2. SUPERELASTICITY AND SHAPE MEMORY EFFECT

Superelasticity, also termed as pseudoelasticity, refers to a phenomenon that certain materials possess. Superelastic materials can return to their initial shape when the applied deformational stress is removed, which leads to a subsequent recovery of the deformation strain, thus the material returns to its original shape. This phenomenon is attributed to the reversible transformation occurring from the austenite to martensite phase, also termed as stress induced martensite. In order to better clarify the SE mechanism, Fig. 1, depicting a stress-temperature curve and a stress-strain curve, is presented. The temperatures shown in the stress-temperature curve are characteristic for each material and are described below:

- M_s: martensite phase transformation start temperature upon cooling;
- M_f: martensite phase transformation finish temperature upon cooling;
- A_s: austenite phase transformation start temperature upon heating;
- A_f: austenite phase transformation finish temperature upon heating;

As shown from the curves in Fig. 1, the material from point (A) is stressed at a constant temperature, while being in a stable austenite phase. The resulting deformation is elastic until a certain point (B), where the material reaches the state that the martensitic transformation begins. From this point on, the transformation that takes place is accomplished under a constant stress, while the strain continues to increase, until a maximum strain level at point (C); maximum strain level varies according to the material. The curve section between points (B) and (C) is termed as stress plateau. At this point the phase transformation from austenite to martensite is completed and the curve that describes the behaviour of the material is different. This new behaviour usually presents a small temperature hysteresis, $\Delta T = A_f - M_s$, whereas the parent martensite interfaces present some mobility. In needs to be noted, that the level of the stress plateau is depended on the applied temperature [4]. Further stressing the material from point (C) will only lead to elastic deformations of the detwinned martensite. Finally, after the stress is removed, the material begins to return to its stable austenite phase, until it fully transforms this phase, point (D), thus the cycle can be repeated.

SE is different from the regular elasticity of bulk materials, as the mechanisms of the two phenomena differ. Unlike the mechanism of the SE described above, the mechanism of the regular elasticity is attributed to the variation of the interatomic spacing within the material, as described by Hooke's Law. Typical values of regular elasticity can be up to 0.5% for most bulk materials, whereas the value of SE in Fe-based SMAs can be up to 13%. In single crystal materials it can even reach values of 15% or more [4].

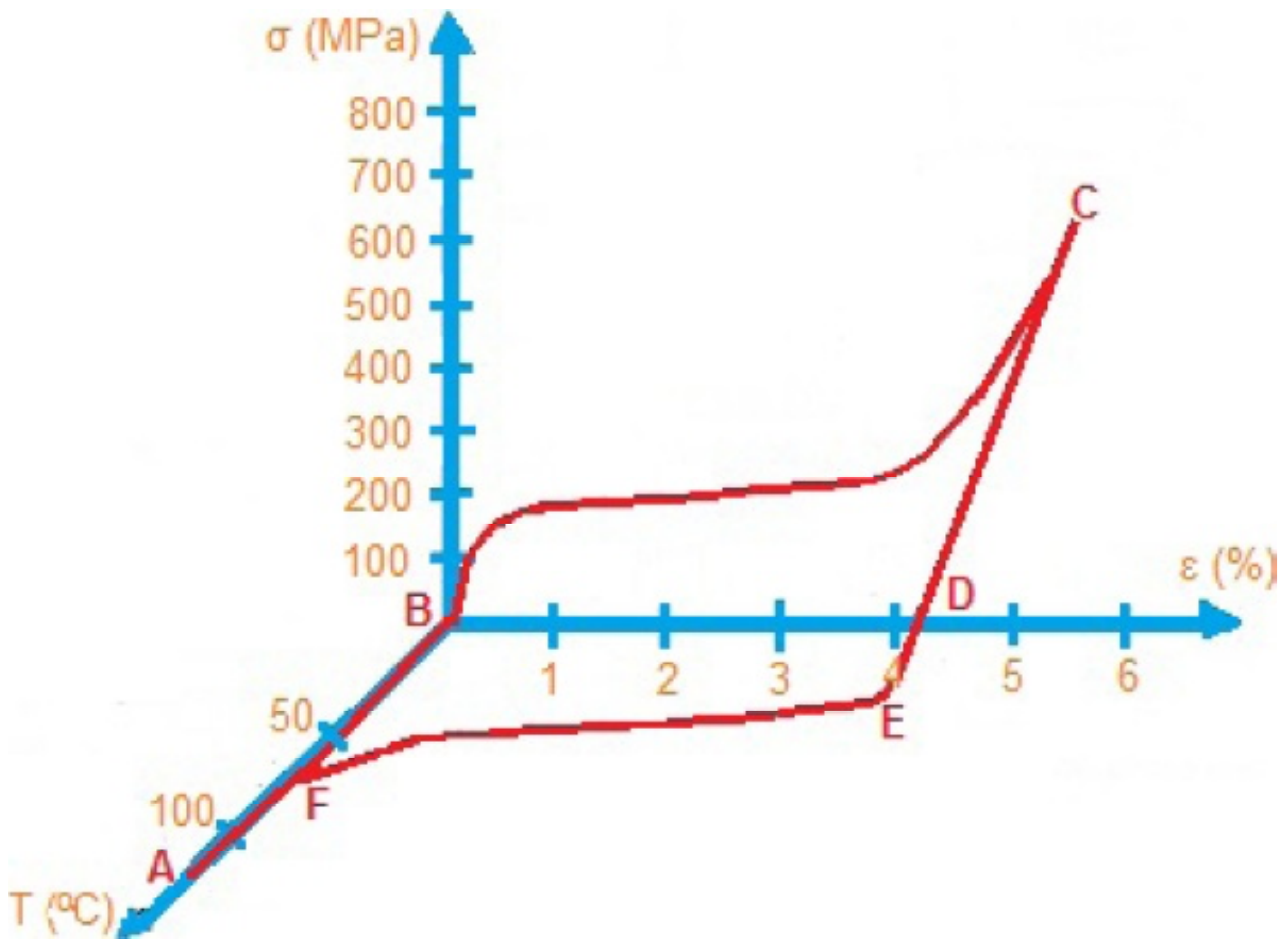

Fig.2. Uniaxial loading path of a typical NiTi SMA, in a stress-strain-temperature graph.

The shape memory effect refers to the recovery of plastic strains in an initially deformed in low temperature material, through the mechanism of austenite-martensite phase transformation. The shape in which the material returns to, after the phase transformation, can be memorized by the material through its deformation in high temperature, at austenite phase. Thus, a material deformed in the martensite phase can recover its plastic strain and return to its high-temperature shape via heating to the austenite phase. In other cases, the material can return to its low-temperature shape from the austenite phase via cooling to the martensite phase. In order to clarify the SME mechanism, Fig. 2 is given. In this graph a thermo-mechanical loading path in a stress-strain-temperature space is presented. It is worth noticing, that the below described phenomenon is the simplest case of the SME, termed as one-way shape memory effect or SME for short. The data for the graph of Fig. 2 represent the SME mechanism of a typical NiTi wire, tested under uniaxial loading.

As shown in the graph, the test begins with the material being in the austenite phase in point (A), it is cooled to a temperature below the material's forward transformation temperatures, where a twinned martensite is formed, point (B). After the material is completely in the martensite phase, the uniaxial loading begins. The applied load continues to advance until the start stress level is surpassed. Beyond this point, the grains of the material begin to re-orientate, leading to certain martensitic variants with a favourable orientation to grow at the expense of other less favourable variants. It needs to be noted, that the stress needed for this process is far lower than the plastic yield strength of the martensite. This process, termed detwinning, is completed at a final stress level corresponding to the end of the stress plateau in point (C). The next step is the elastic unloading of the material, where its state remains unchanged, point (D). After the material is completely unloaded, a heating process leads the material to begin transforming to austenite. This process begins at point (E), above temperature A_s, and it is completed when the material reaches a temperature above its A_f temperature in point (F). With only the parent austenitic phase remaining, the material regains its original shape, point (A), due to the absence of the permanent plastic strain of the detwinned martensitic phase. The strain recovered as a result of the martensite to austenite phase transformation is termed as transformation strain (ε^t). Cooling the material from this point will result in a twinned martensitic phase, which will bring no change to the shape of the material, thus the above explained cycle can be repeated [5].

In most cases, the trigger that causes the phase transformation is heating the material above its A_f temperature, the so called thermo-responsive shape memory effect. However, this is not the only case; other possible effects that can cause this transformation are the direct application of light, termed photo-responsive shape memory effect, the exposure of the material to a certain chemical substance, called chemo-responsive shape memory effect, the application of a mechanical load, described as pressure-responsive shape memory effect or the application of a magnetic field, identified as magnetic-responsive shape memory effect [6].

The repeating thermo-mechanical cycle described above, either to induce SE or a thermal phase transformation in a SMA, both under applied load, can lead to a premature fatigue of the material. The fatigue behaviour of a SMA is generally attributed to a variety of factors, like the processing of the material, the working conditions, environmental factors and transformation induced microstructural modifications. By repeatedly loading the material, both mechanically and thermally, microstructural changes occur. These microstructural changes gradually degrade the SMA behaviour.

3. DEFORMATION MECHANISMS

In manufacturing processes, high stresses are applied on the material. The overall process may include a combination of many different loading modes and for this reason tension and shear mechanisms are described below.

The most basic loading mode is tension; in this mode the material is axially loaded and the stress is distributed uniformly inside the volume of the

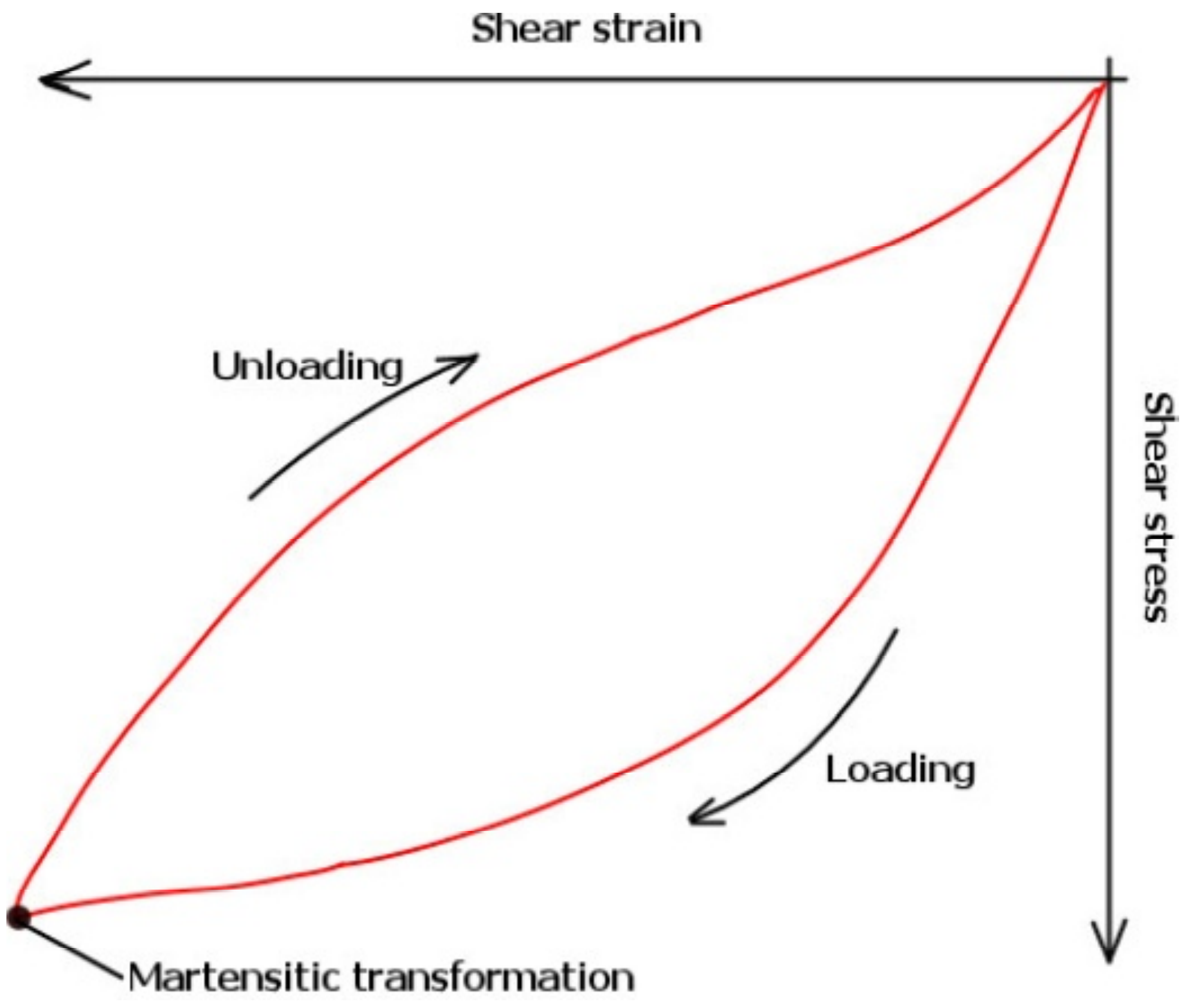

Fig.3. Typical shear stress-shear strain curve.

material. Thus, the material is uniformly transformed resulting in the optimal efficiency in transformation energy. However, the range in which the material can move is fairly low. It needs to be noted, that in this loading mode the normal stress is directly proportional to the applied force. The behaviour of a SMA in tension mode is shown in the material's characteristic stress-strain curve. In other words, the curve that characterises the superelastic behaviour during the loading cycle, also presents the material's behaviour in tension.

Shearing is the dominant mechanism occurring during the machining of a component. In order to research the effects that the shear mechanism brings to superelasticity and shape-memory effect of the SMA materials, various studies have been performed. The difficulty faced in most of the cases lies with the fact that a pure shearing of a material is considered to be rather difficult [7]. However, various techniques have been employed in order to maximize the effect of shear deformation, compared to other types of deformation [8,9]. Daly et al. [7] performed a shearing test in Nitinol samples, in order to define the effects of shear stresses in NiTi based shape-memory alloys, both in small scale, during the stress-induced phase transformation, and in large scale, during the plastic deformation of each sample. The results from the small scale shearing showed that the shear deformation induced was fairly homogenous, thus hindering the formation of differentiating bands of deformation. This attitude is opposite to the one observed during the tension of Nitinol. Furthermore, whether a phase transformation occurs or not during shearing, has not been thoroughly clarified. Similar results were presented by Huang et al. [9]. Although, the method used for inducing shear stresses was different in this case, the final deformation distribution in the NiTi samples appeared homogenous in this case as well. Moreover, the effect of strain rate was discussed, where it was noted that a lower strain rate leads to an increase in the maximum value of the critical shear strain. A typical shear stress-shear strain curve can be seen in Fig. 3. It needs to be noted though, that depending on the parameters of the actual shearing, the morphology of the curve may differentiate; the final unloading step may finalize in a residual strain value different than zero, as a result of the deterioration of the material's superelasticity.

One of the most important factors for the morphology of the occurring stress-strain curve in the shearing of SMAs, is proven to be the shearing temperature. In a study performed by Orgéas and Favier [10], the dependence of the critical stresses for the stress-induced phase transformation, as well as, the material's superelasticity on the temperature of the material at the beginning of the shearing, was discussed. The results showed an increase of the critical stress for higher values of temperature, while the superelastic attitude of the material showed a progressively deteriorating pattern with the increase of temperature. The relation between the critical stresses and the temperature showed a transition from linear to non-linear above a certain temperature value. This behavior indicates that the plastic deformations occurring above that point, have a greater impact on the material's attitude. It is worth mentioning, that in the intermediate range of temperature values, the curve is considered to obey the Clausius-Clapeyron equation [11]. Moreover, the deterioration in the superelasticity of the material is also considered to be a result of the increased plastic deformation occurring at higher temperatures.

In large scale shearing, the deformation distribution seems to become more inhomogeneous, as a result of the combination of plastic deformation and the material's phase transformation. While large scale shearing seems to enhance the inhomogeneity of the material, the developing strain hardening, due to the plastic deformation, has been proven to be relatively low [7].

4. MACHINING OF SMA

The term machining is used to describe processes that shape parts by removing unwanted material, which is carried away from the workpiece usually in the form of a chip; evaporation or ablation may take place in some machining operations. The more narrow term cutting is used to describe the formation of a chip via the interaction of a tool in the form of a

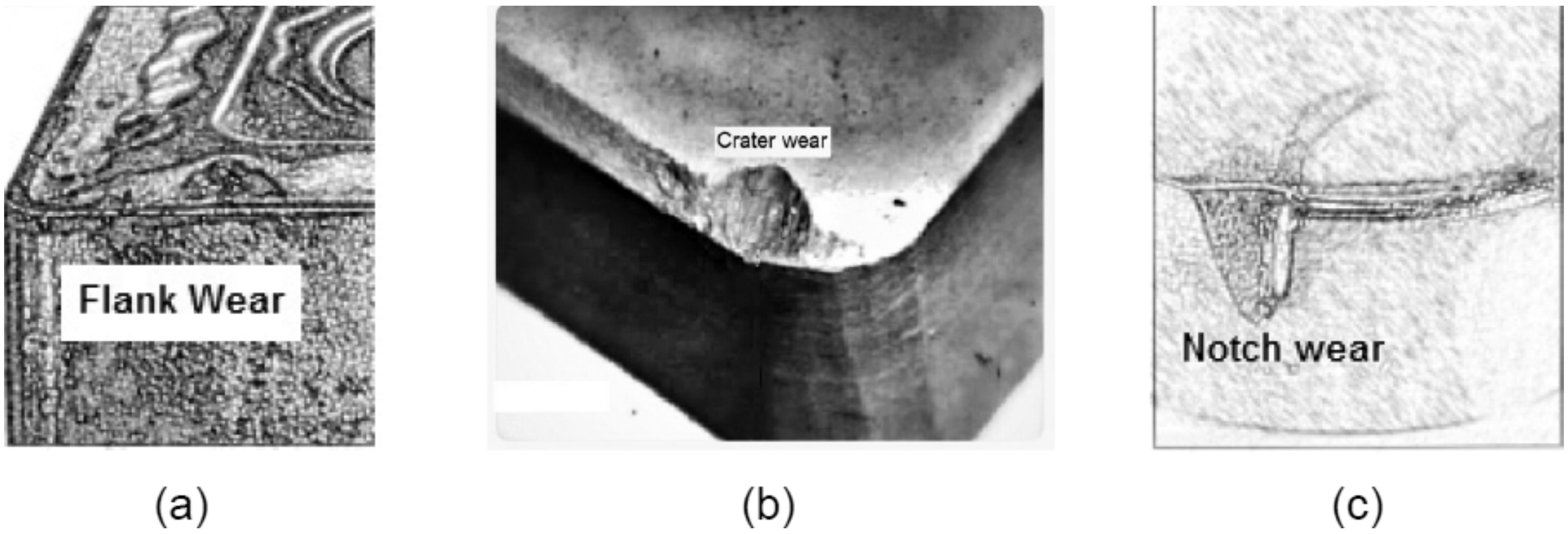

Fig.4. Sketches of (a) flank, (b) crater and (c) notch wear on cutting tools.

wedge with the surface of the workpiece, given that there is a relative movement between them. These machining operations include turning, milling and drilling among others and are usually referred as conventional machining processes. Abrasive processes such as grinding are also part of cutting processes of great importance in contemporary industry. Other non-conventional machining operations that may or may not include physical contact between cutting tool and workpiece or may not have a cutting tool in the same sense as conventional processes or utilize thermal or chemical energy for removing material from workpiece, are electrodischarge machining, laser machining, water jet machining and electrochemical machining just to name some.

When machining hard–to–machine materials such as Titanium and Nickel alloys obstacles pertaining to the machinability of these materials are imposed. The quality and cost goals are not easily achieved due to work hardening, phase transformations and in the case of SMAs due to phenomena closely connected to SMA characteristics. Low material removal rates and high tool wear are commonly observed. In the following paragraphs, conventional and non-conventional machining processes used in the case of SMAs are considered. Aspects of the processes, e.g. cutting tools and cutting conditions are investigated and the findings of relevant researches are presented.

4.1. Conventional machining

Most of the work conducted on the conventional machining of SMAs pertains to NiTi or ternary alloys of NiTi thus the information presented revolve around these materials. A first look at the machinability characteristics of Titanium and Nickel alloys can give an insight on the phenomena that take place when NiTi SMAs are considered. Titanium's reactivity with the cutting tools, low heat conductivity, high strength at elevated temperatures and low elastic modulus result in increased temperatures at the tool-chip interface, high dynamic loads, workpiece distortions and rapid tool wear [12]. Nickel based alloys and super-alloys, similarly to Titanium alloys, also present high strength and are considered hard-to-machine materials. Additionally, due to their austenitic matrix, nickel superalloys work harden rapidly during machining and tend to produce continuous chip which is difficult to control during machining [13,14]. The results of the above characteristics lead to accelerated flank wear, cratering and notching, depending on the tool material and the cutting conditions applied, see Fig. 4. A review on abrasive adhesion/attrition, diffusion and chemical wear as well as plastic deformation of cutting tools employed in the machining of Nickel super-alloys can be found in [15]. To avoid premature failure of the tool, low cutting speeds, proper tool materials and cutting fluids are required [16].

All the difficulties reported for Titanium and Nickel alloys separately apply for NiTi alloys as well. Furthermore, key features of SMAs such as pseudoelasticity, pseudoplasticity and high ductility of NiTi alloys impose more difficulties when machining these alloys, leading not only to rapid tool failure but also to poor workpiece quality due to excessive burr formation, adhesions on the machined surface and microstructure alterations of the workpiece material. Machining of NiTi is connected to large strains, high strain rates and temperatures on the workpiece surface and the layers underneath it which in turn results in surface and sub-surface defects such as the formation of a white layer and the development of microcracks [17].

Turning of NiTi SMAs was the subject of the work presented by Weinert, Petzoldt and Kötter [18].

Different cutting tools, namely indexable coated and uncoated cemented carbide, PCD, CBN and ceramic inserts, were investigated. The research concluded that coated cemented carbide tools present reduced wear. More specifically, tools with eight alternating layers of TiCN and TiAlN were found to perform better even in comparison to tools with harder coatings like TiB_2; the latter exhibited cratering on the rake face due to tribo-chemical dissolving of the coating. Uncoated cemented carbide tools present extensive tool wear, ceramic cutting tools are not capable of machining NiTi alloys irrespective of the cutting parameters, PCD tools present notch wear which leads to sudden tool breakage and CBN tool wear is higher in comparison to coated cemented carbide tools and in combination to their high cost, they are not preferable. Regarding the cutting parameters it was concluded that for the machining of NiTi with coated cemented carbide tools, higher cutting speeds than those recommended by the relevant literature and the tool providers can be used. Tool wear was reduced and surface quality was improved at cutting speed of 100 m/min.

In another work by Weinert and Petzoldt [19] on turning of NiTi, the significance of cutting fluids is discussed. High wear of the cutting tool leads to significant friction and thus higher temperatures in the cutting zone. Dry turning of NiTi results in chip burning and very high cutting forces; the use of a cutting fluid as lubricant/coolant prevents the chip from burning. Other investigations propose cryogenic cooling as being advantageous in comparison to dry and minimum quantity lubrication conditions regarding tool wear and surface quality [20,21]. Weinert and Petzoldt [19] also discussed the effect of cutting fluids on chip breaking and the formation of burrs. Poor chip breaking in NiTi machining results in long continuous chip, which in turn results in tool wear and is not affected by the use of cutting fluids; chip breaking is noticed only in low cutting speeds where tool wear is excessive. Burrs, as a result of the high ductility of NiTi alloys, are reduced when an emulsion is used in comparison to dry cutting. Burrs are also favoured with small feed rates, which should also be avoided due to high tool wear.

Milling of a NiTi alloy used in biomedical applications (50.8 at.% Ni-49.2 at% Ti) was studied by Guo et al. [22]. The authors conducted quasi-static and Split-Hopkinson pressure bar compression tests to evaluate the mechanical properties of the material. The tests showed high strength of the material under static and dynamic conditions indicating that NiTi is more difficult to be machined than Ti or Ni based superalloys. For milling, coated carbide inserts were used and once again a shorter tool life in comparison to milling conventional metals was observed. Increase of feed rate leads to increase in surface roughness; however, very small feed rate presents high surface roughness and by correlation, increase in the flank wear of the tool increases surface roughness. Furthermore, high ductility of NiTi is responsible for large exit burrs. Finally, from the subsurface microstructure and microhardness investigation it may be said that smaller feed rate results to thicker white layer, indicative of the phase transformation due to excessive loading and temperatures.

Weinert and Petzoldt [19] investigated the drilling of NiTi tubes for the production of parts to be used in medical applications. They argue that the work hardening in the subsurface zone is of importance when this machining operation is considered. Hardness of the material is increased with low cutting speeds or high feed rate. Furthermore, it is argued that the use of coated instead of uncoated cemented carbide tools exhibit no advantage in the case of drilling. Drilling was also investigated by Lin, Lin, and Chen [23]. The observation of the drilled surface morphology reveals numerous wavy tracks that are the result of the action of a blunt tool, adhesion and abrasive deformation which lead to vibration and damage of the twist drill. Drilling chips are continuous and have a yellowish colour as a result of elevated temperatures and oxidation.

Some studies pertain to the production of micro-parts by micro-milling [24,25]. Micro-milling was selected as complex geometries required in micro-parts to be used for micro-actuators and medical applications can be achieved. The studies investigate the optimal cutting conditions and the characteristics of SMA machining like burr formation in the micro-scale; a direct down-scaling is impossible since phenomena may differ in comparison to the processes discussed in the previous paragraphs. It turns out that micro-machining is as difficult as conventional machining processes if not even more and the ranges for optimal cutting conditions are rather limited.

Generally speaking, when machining SMAs, the combined action of strain hardening and fatigue hardening causes a severe hardening effect and impairs the cutting rate. As a result, the workpiece quality is poor and tool wear unacceptably high, even for optimised cutting parameters and suitable cutting tools. These effects may also influence the shape memory characteristics. Researchers have turned to the study of non-conventional machining processes with the aim to improve machining of SMAs.

4.2. Non-conventional machining

This category of machining processes refers to mechanisms of material removal that include no contact between the tool and the workpiece. This way tool wear is minimised or totally diminished but surface integrity may still be affected, mostly due to thermal loading. These processes are widely used in SMA machining, especially for components with very small dimensions.

Most non-conventional machining works pertain to electrodischarge machining (EDM) or wire electrodischarge machining (WEDM) of NiTi SMAs. Object of the studies is usually the surface and subsurface modifications that take place from the spark discharges during machining and the influence of various parameters on the material removal rate of the process. Studies on the influence of the machining conditions on the surface roughness [26,27] indicate that with increase of the working energy, surface roughness worsens; increase of working current, voltage and pulse on time results in thicker and more abnormal melting zone. Surface roughness also depends on the thermal properties of the workpiece material, namely melting temperature and thermal conductivity [28]. When cutting conditions are such that improve workpiece quality, changes in the subsurface of the workpiece material, due to excessive heat generation, may be observed [29]. In a comparison between milling and EDM investigations concluded that EDM produced higher surface roughness than that of milling [22]. Furthermore, a white layer was also observed that was less thick than that measured when milling was applied. It is argued by the authors that the white layer of EDM was produced by melting and rapid quenching while the white layer of milling was attributed to deformation induced phase transformation, making the nature of each white layer fundamentally different. The conducted investigation concluded that an increase in feed speed in milling results in thinner white layer and that the white layer formed in EDM is thinner than that of milling. Furthermore, for finish trim cut, the white layer is even thinner and crack-free. Material removal rate also increases with increase in working energy [26]. Similar results are reported when WEDM is considered [30]; surface roughness and material removal rate increase with increase in machining energy.

Laser machining of NiTi SMAs is also a promising process. As EDM, laser machining induces a heat affected zone on the workpiece material. NiTi alloys are sensitive to thermal influence and it is of interest to reduce the effect of excessive thermal loading when laser machining components made of SMAs. Femptosecond laser is used for the machining of NiTi alloys for the production of micro-devices [31]. Although the ultrashort pulses of this laser perform better than other lasers, still the thermal nature of the process and the high ablation rates cause a significant recast layer. The authors suggest a sideways-movement path planning that permits better quality finished micro-products. The femtosecond laser machinability of NiTi was also investigated by Huang, Zheng, and Lim [32]. On the processed surfaces a re-deposition layer and a heat affected layer were measured but were quite thinner than those observed from Nd:YAG laser machining, milling and EDM while the resulted surface roughness was similar to that of precision milling. The laser drilling of ferromagnetic SMAs was investigated by Biffi and Tuissi [33] and was concluded that laser machining of micro-features can be performed with limited thermal affection of the material.

Other works refer to abrasive water jet machining [34] and electrochemical polishing [35] of NiTi SMAs. Abrasive water jet machining for NiTi alloys exhibits no white layer but the material was difficult to be cut at straight kerf geometry. However, the authors' machining strategy indicated that this process can produce quality surfaces of NiTi SMAs.

5. CONCLUSIONS

The at hand paper highlighted the manufacturing processes used to fabricate shape memory products. In the first section of the paper, the mechanisms of superelasticity and shape–memory effect via the martensite to austenite transformation were described. The mechanism of the transformation induced fatigue in SMAs was also discussed in the same section. Then, some basic deformation processes were described, in order to better comprehend the mechanisms taking place in the machining of SMAs. The final part of the paper was dedicated to the main machining processes employed in manufacturing of SMA products. It was divided in two parts; the first part pertained to conventional machining processes, while the second one to non-conventional machining processes.

Nickel-Titanium SMAs are difficult-to-machine materials and special care needs to be given to the selection of cutting tools and cutting conditions for their processing. Several works for turning, milling, micro-milling and drilling are discussed, for the successful manufacturing of high quality products from SMAs. Works on non-conventional machining include processes such as EDM, WEDM, laser and water jet machining; these processes seem quite promising and are expected to further improve SMA products in the future.

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