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. Super elasticity 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.

Keywords: Super elasticity, machinability, Nickel-Titanium Shape Memory Alloys, tool, tool wear, cutting fluids.

I. 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 super elasticity (SE) and shape-memory effect (SME) that give these materials their characterization as smart materials are in the fore- front of the studies related to them. Most of the re- search 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 propertie. thus it is imperative to further study the machining of SMAs.

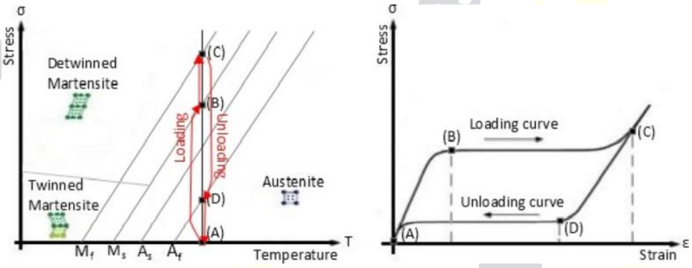

Fig.1. Stress-temperature (left) and stress-strain (right) curves that describe the SE behavior.

In this study, the super elasticity 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. 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

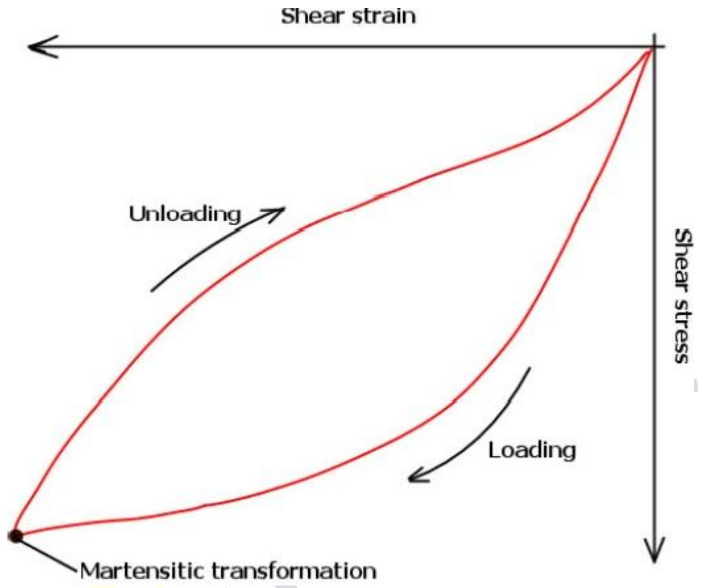

Fig.2. Typical shear stress-shear strain curve

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 behavior of a characteristic stress-strain curve. In other words, the curve that characterizes the super elastic behavior during the loading cycle.

Shearing is the dominant mechanism occurring during the machining of a component. In order to research the effects that the shear mechanism brings to super elasticity 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. More- over, 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.

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 tem the dependence of the critical stresses for the stress-induced phase transformation, as well as, 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 super elastic 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, 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 super elasticity 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 scale shearing seems to enhance the in homogeneity of the material, the developing strain hardening, due to the plastic deformation, has been proven to be relatively low [7].

3. MACHINING OF SMA

The term machining is used to describe processes that shape parts by removing unwanted material, which is carried away from the work piece 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 wedge with the surface of the work piece, 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 work piece or may not have a cutting tool in the same sense as conventional processes or utilize thermal or chemical energy for re- moving material from work piece, are electro discharge machining, laser machining, water jet machining and electrochemical machining just to name some

4. 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 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, work piece 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 super alloys work harden rap- idly 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 pseudo elasticity, pseudo plasticity and high ductility of NiTi alloys impose more difficulties when machining these alloys, leading not only to rapid tool failure but also to poor work piece quality due to excessive burr formation, adhesions on the machined surface and microstructure alterations of the work piece material. Machining of NiTi is connected to large strains, high strain rates and temperatures on the work piece 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 micro cracks [17].

5. NON-CONVENTIONAL MACHINING

This category of machining processes refers to mechanisms of material removal that include no contact between the tool and the work piece. This way tool wear is minimized 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 electro discharge machining (EDM) or wire electro discharge 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 resultsin thicker and more abnormal melting zone. Sur- face roughness also depends on the thermal prop- erties of the work piece material, namely melting temperature and thermal conductivity [28]. When cutting conditions are such that improve work piece quality, changes in the subsurface of the work piece 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].

CONCLUSIONS

The manufacturing processes used to fabricate shape memory products. 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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