Review on EDM and Wire-EDM machining of TiNi Shape Memory Alloys

Dr. V. B. Jaware¹, A.M. Takale²

1. Professor, Department of Mechanical Engineering, J.S.P.M.s Rajashree shahu College of Engineering, Pune, Maharashtra, India.
2. Research scholar, Department of Mechanical Engineering, J.S.P.M.s Rajashree shahu College of Engineering, Pune, Maharashtra, India. And Assistant Professor, Department of Mechanical Engineering, Sharad Institute of Technology College of Engineering, Ichalkaranji, Maharashtra, India.

Abstract: Titanium-Nickel (TiNi) shape memory alloys (SMA) have wide applications in medical devices, actuators, aerospace, and automobile etc. TiNi Shape memory alloys are the developing advanced materials due to their unique mechanical properties including superelasticity, shape memory effect (SME), biocompatibility, high specific strength, high corrosion resistance, high wear resistance and high anti-fatigue property. However, the conventional machining of SMAs causes serious tool wear, time consuming and less dimensional accuracy due to severe strain hardening and pseudoelasticity. These materials can be machined using non-conventional methods such as laser machining, water jet machining (WJM) and electrochemical machining (ECM), but these processes are limited to complexity and mechanical properties of the component. Electrical discharge machining (EDM) and wire-cut Electrical discharge machining (WEDM) show high capability to machine SMAs of complex shapes with precise dimensions. The aim of this paper is to present the consolidated references on the machining of SMAs using EDM and WEDM and subsequently identify the research gaps. In support to these research gaps, this work has also evolved the future research directions.

Key words: Shape Memory Alloy, Electrical discharge machining, wire-cut Electrical discharge machining, Material removal rate, Surface Integrity.

1 Introduction

TiNi alloys are an important class of shape memory alloys (SMAs). In recent years, the materials such as titanium-nickel (TiNi) based shape memory alloys and other SMAs are commonly used in medical and several engineering applications. The medical applications include eyeglass frames, surgical stents, orthodontic arch wires, active catheters, The industrial engineering applications are functional devices such as fasteners, sealing and coupling, aerospace actuators, sensors, cellular phone antennas and fuel injector [1].

TiNi alloys are mainly used owing to their high strength at low to moderate temperature, shape memory effect (SME), high wear resistance, high corrosion resistance, light weight, great ductility, good fatigue property, high bio-compatibility and so on[2]. The microstructure characteristic of TiNi alloy is that it is in a martensitic phase at lower temperatures, but in an austenitic phase at elevated temperatures [3].
Machinability study of TiNi shape memory alloy has become an important aspect of the manufacturing sector. The machining of titanium materials is extremely difficult because of low thermal conductivity and high chemical reactivity. The productivity and surface integrity are identified as important phenomena in the process of machining[4]. Higher productivity can be achieved by using high cutting speed. The machining of these materials at higher cutting speed is very difficult due to greater tool wear (rapid chipping at cutting edge, plastic deformation of the cutting edge), higher surface hardness, severe microstructure alteration and poor surface quality[5].

In the past few years, SMAs are used in many engineering applications with different shapes like tubes, foils, tapes and in medical application guide wire for catheter. The machining of SMAs is relatively important and integral part in the production of components for utilizing in engineering applications. During conventional machining of these materials, higher tool wear and lower surface quality are commonly observed phenomenon, due to their higher strain hardening effect, pseudoelastic behavior and high toughness. Thus, they can be effectively machined by non-conventional machining processes such as laser machining, Water Jet Machining (WJM), Electro Discharge Machining (EDM) and Wire-EDM (WEDM)[6,7].

The application of EDM and WEDM process includes automotive, aerospace, mould, tool and die making industries. EDM and WEDM applications can also be found in the medical, optical, dental, jewellery industries and R & D areas. Another popular application for EDM and WEDM is the machining of extrusion dies[8].

Complex shapes of TiNi shape memory alloys are difficult to machining by conventional machining, in such a situation EDM and WEDM is preferred and in EDM and WEDM very accurate, precise and irregular intricate shapes can be manufactured. EDM and WEDM has been acquiring wide acceptance for the machining of various conductive materials used in real applications such as metals, ceramics, silicon and metal matrix composites[9].

2 EDM and WEDM machining of SMAs

This section provides the basic principle of the EDM and WEDM process.

2.1) EDM and WEDM of SMAs

EDM and WEDM is an electro-thermal process in which the material is removed by electro-discharges occurring between the workpiece and tool electrode immersed in a liquid dielectric medium. These electro-discharges melt and vaporize minute amounts of the work-piece, which are then swept away by the dielectric. Therefore, EDM and WEDM is a versatile technique in machining the stubborn materials, which are difficult to machine by conventional techniques.

3 Survey of Work Done In Research Area

In EDM and WEDM, discharge sparks are utilized to melt and evaporate the material. The dielectric fluid is used as a medium between the electrode and workpiece. The highly complex shapes can be machined using EDM and WEDM with high precision.
3.1 Material Removal Rate (MRR) in EDM and WEDM

The MRR is a significant parameter which affects the productivity of any manufacturing industry. The MRR plays a vital role in increasing the productivity. MRR is the amount of material removed from the workpiece under the working time (mm$^3$/min or mg/min). It defines the characteristic efficiency of the machine [4]. The present survey is made on the MRR for TiNi shape memory alloy machined by EDM and WEDM at different machining conditions. The MRR is increased by the increase in discharge current. It is due to the strengthened discharge energy melts and removes the material more easily by the higher current density. The MRR will increases with a pulse on time duration also up to a particular point and then reduction takes place after that. This is due to the expansion of plasma channel. At high pulse duration, the localized temperature increases. It leads to decomposition of carbon that is bonded on the electrode surfaces. Hence the discharge energy of the electrode is reduced and lower MRR is attained at high pulse duration [5,11].

During the non-conventional machining the MRR is less compared to the conventional machining. However, the surface is relatively less affected by the phenomena such as defects, plastic deformation, cracks, work hardened layer, residual stresses compared to conventional machining. The machined components having good surface quality are required [6,12]. In the study is to determine the influence of some of the most important parameters implicated in the EDM process on Ti$_{50}$Ni$_{49.5}$Cr$_{0.5}$ ternary alloys including discharge current $I_P$ and pulse duration $\tau_P$. Fig. 3.1 shows the material removal rate (MRR) versus the pulse duration at various discharge currents for the ternary alloy (Ti$_{50}$Ni$_{49.5}$Cr$_{0.5}$). It is found that the MRR increases with the discharge current. It has been reported that a high discharge current can have a high current density [13]. This feature will obviously increase the material’s melting and evaporation and the impulsive force of expanded dielectric medium. Therefore, a higher MRR occurs at a higher discharge current during the EDM process. Besides, one can also find in Fig. 3.1 that the MRR initially increase with the pulse duration, reach maximum values, and then decrease to constant values for various discharge currents. It is expected that the MRR should increase with growing pulse duration, because its high accumulated electro-discharge energy will rapidly melt and evaporate the material. Moreover, an over-long pulse duration will reduce the energy density of the discharge spots by expanding the plasma channel [14]. The energy provided by the plasma channel melts the material, but it is insufficient to generate a high exploding pressure of the dielectric which can flush the molten materials away from the EDMed surface. As a consequence, the molten material cannot be swept away effectively by the circulative dielectric system, and hence the MRR decreases.

![Fig. 3.1 The material removal rate vs. pulse duration $\tau_P$ at various discharge currents $I_P$ for the Ti$_{50}$Ni$_{49.5}$Cr$_{0.5}$ alloy.][5]
3.2 Surface Integrity of SMAs

Surface conditions of a manufacturing/machining metal part directly influence the processing and end use of that part. The surface integrity of the final product is crucial in machining processes. In most applications, having the smoothest possible surface is desired, especially when the fatigue life of a machined part is important. Surface integrity is an intrinsic factor which is affected by the machining conditions and indicates the machined surface and subsurface. The surface integrity is a major contributing factor in processing and performance of the part [15].

Machining processes induce and affect various surface integrity attributes on the finished parts. These can be grouped as:
(a) Topography characteristics such as surface roughness.
(b) Mechanical properties affected such as microhardness and residual stresses.
(c) Metallurgical state such as microstructure and recast layer

The quality of surface is very much essential in performance, preventive, life costs, period of time and reliability of the products. Non-conventional machining is meant for the better surface integrity and higher productivity. This technique is rapidly growing in microcomponent manufacturing industries [16].

3.2.1) Surface Roughness

Surface roughness is an important parameter influence on the performance of the machined components. There are number of machining parameters which quantify the surface roughness such as the amplitude parameters that characterizes the surface topography. Surface deviation characteristic is most widely used parameter as the arithmetic mean average roughness [17]. The selection of EDM or WEDM parameters is an important criterion in achieving a better surface finish for TiNi shape memory alloys.

The surface roughness in an EDM is dependent on the intensity of the spark and the size of the crater produced during the machining at different range of pulse duration or discharge current. The surface roughness is significantly affected by the discharge current and pulse duration contributes to the surface roughness of the EDMed TiNiCr and TiNiZr ternary shape memory alloys [5,18]. From this it is clear that the surface roughness is mainly varied by the discharge current followed by the pulse duration. For the better surface roughness lower discharge current and lower pulse duration is required.

The machine feed also affects the surface roughness which in turn the wire tension and voltage significantly affects the surface roughness because of wire vibration during the machining and stronger electric field discharges spark at the same gap between the electrode and workpiece induces coarse surface. From this the better surface finish can be achieved with the lower machine feed [10,19].

As mentioned above, the electro-discharge energy mode in the EDM process, involving the discharge current $I_P$ and pulse duration $\tau_P$, can also affect the work material’s surface roughness. Fig.3.2 depicts the roughness of EDMed surface versus the pulse duration at various discharge currents for Ti$_{50}$Ni$_{49.5}$Cr$_{0.5}$ alloy. These features demonstrate that the higher discharge current and pulse duration will have higher roughness of EDMed surface. As the discharge current increases,
discharges strike the surface of the work-piece more intensely, and the resulting worsened erosion effect leads to a deterioration of the surface roughness. Furthermore, an extended pulse duration allows greater discharge energy to melt and penetrate deeper into the material, which produces deeper and larger craters, causing an increased surface roughness on the work-piece[20].

![Fig.3.2 The surface roughness vs. the pulse duration $\tau_p$ at various discharge currents $I_p$ for the Ti$_{50}$Ni$_{49.5}$Cr$_{0.5}$ alloy.[5]](image)

**3.2.2) Microhardness**

The hardness of the material after being machined has been found to be greater on the surface of the material than through the depth of the material. Where the heat and strain effects are neutralized for bulk of material. These types of microhardness changes are also related to surface integrity issues [7,21]. The machined surface hardness is changing in EDM/ WEDM with using any fluid as a dielectric fluid. The machined surface hardness increases up to a certain depth it’s off around 100μm later it remains constant. Concluded that the machined surface hardness of EDMed TiNi and TiNiCu alloy were increased from 260Hv to 550Hv [221]. The hardness varies from the machined outer surface to inner depth surface. It has been shown there is an increase in near the outer machined surface hardness with the higher pulse duration and peak current [5,23].

The outer machined surface hardness slightly varied with electrode material. This is owing to recast of melted electrode material on the machined surface. This is due to effect of tool material on EDMed surface hardness [24]. The hardening effect is because of the formation of oxides Cr$_2$O$_3$, ZrO$_2$, TiO$_2$, TiNiO$_3$, carbides like TiC in the recast layer. It is mainly during use of copper electrode and kerosene as dielectric fluid during the EDM of TiNi based ternary alloy [25].

![Fig.3.3 shows the cross-sectional hardness versus distance form the EDMed surfaces of Ti$_{50}$Ni$_{49.5}$Cr$_{0.5}$ and Ti$_{35.5}$Ni$_{49.5}$Zr$_{15}$ alloys under the conditions of $I_p = 10A$ and $\tau_p = 100\mu s$. It indicates that the specimen’s hardness near the outer surface can reach 913 Hv for Ti$_{50}$Ni$_{49.5}$Cr$_{0.5}$ alloy, but 1087 Hv for Ti$_{35.5}$Ni$_{49.5}$Zr$_{15}$ alloy. This hardening effect is due to the formation of the oxides Cr$_2$O$_3$, ZrO$_2$, TiO$_2$, TiNiO$_3$, carbides TiC and the deposition particles in the recast layer. Besides, the hardness of the matrix in TiNiX alloys is not affected by the EDM process[26].](image)
3.2.3) Residual stresses

Residual stresses are generated on the machined surface, due to inhomogeneous temperature distribution and quenching by the dielectric fluid. The cracks are originated in blow hole and white layer on the surface in the WEDM. This is arising at higher pulse durations rather than at lower pulse duration because thermally induced stresses are more at higher pulse durations [14,27]. The residual stresses present potential risk in terms of crack initiation and fatigue failure of end products.

The stresses increase due to the rapid heating and cooling of material by the dielectric fluid [15,28]. The EDM processed specimens with residual tensile stresses have poor fatigue strength. The presence of carbon, carbides oxides in the surface layer is also observed, it may be due to the fact that, the tool electrode and the dielectric fluid cause inhomogeneity and more residual stresses in the material. The machined surface contains craters, blow holes, pock marks, melted droplets, debris and substantial layers, these may deviate the residual stress distribution to some extent [28].

3.2.4) Microstructure

During the Electro discharge machining the surface of the work-piece is exposed to thermal, mechanical and chemical energy, thus leads to the changes in the surface and subsurface properties because of high temperature around 10000°C-12000°C and quenching effect. The machined surface layer of the work piece always undergoes various kinds of metallurgical alterations. The surface integrity is affected by the plastic deformation during the machining. These changes occur in the material surface are influenced by the machining conditions such as electrical and non-electrical parameters [29].
Studies on Ti base alloys showed that a very thin layer of plastic deformation was formed in the immediate sub-surface of the workpiece, and as the tool wears out, plastic deformation and subsequently the thickness of the deformed layer increased, due to microstructural alterations. The depth of these micro-structural alterations beneath the surface has been observed to increase when the cutting speed and feed rate are increased [30].

Fig.3.4 shows the melted recast layer of WEDMed surface on Ti$_{35.5}$Ni$_{49.5}$Zr$_{15}$ SMA. It is observed that craters, melted drops, cracks and the surface texture cause the roughness. This recast layer consists of some oxides as discussed in EDM surfaces of SMA. The recast layer also consists of Ni rich phases, TiO$_2$, TiC and so on. The Cu$_2$O is formed on the machined surface due to the copper electrode [31]. The craters are formed on the machined surface, as shown in Fig.3.4, which influences the surface roughness on the machining surface. The higher surface roughness appears probably because of higher discharge current and longer pulse on time which are influenced to form deeper and wider craters on the machined surface.

![Micrograph of surface machined using WEDM for Ti$_{35.5}$Ni$_{49.5}$Zr$_{15}$ alloy.](image)

**3.2.5) Recast Layer**

The characteristic surface layer is formed due to resolidification of melted material, high temperature and due to cooling effect. The surface layer is a white layer under that recast layer. It is essential to understand the layer formation and to minimize its thickness during the machining process. The layer formation occurs under the circumstances of higher discharge current and pulse duration with insufficient flushing conditions. The evaluation of layer formation is based on the discharge current, pulse duration, type of dielectric fluid and flushing pressure [32].

Fig.3.5 shows the thickness of recast layer formed on the machined surface. The recast layer can be reduced by higher pulse on time, because higher discharge energy impacts the dielectric fluid effectively which flushes away the molten material from the machined surface. The recast layer also influences the SME of the machined surface [33,34]. The thickness of recast layer affects the surface hardness because it contains different oxides, phases, compounds and matrix element. The recast layer thickness of SMA using WEDM can be controlled by choosing the optimum pulse on time, peak current and other process parameters[35].
4. Conclusion

The references presented above reveal that the EDM and WEDM of SMAs have been reported on the effect of pulse durations, discharge current and discharge voltage on the responses. The researchers represented the topography characteristics such as surface roughness, mechanical properties affected such as microhardness and residual stresses and metallurgical state such as microstructure and recast layer in EDM and WEDM. Very little work has been reported on the TiNi SMAs using EDM and WEDM and optimization of process parameters. As such there is a need to study the effect of parameters in EDM and WEDM of NiTi shape memory alloy on surface roughness, microhardness, residual stresses, microstructure and recast layer on the machined surface, and optimize EDM and WEDM process parameters.

5. References:


