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Review Article

Applications Of Unconventional Manufacturing Methods in Shape Memory Alloys

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Abstract

In this review study, it is aimed to determine the gains and shortcomings of the unconventional manufacturing methods used in the machining of smart materials by making a detailed analysis. Among these methods, abrasive water jet machining, laser, electro discharge and wire discharge machining are the most used. Abrasive water jet machining is frequently preferred because it has some superior properties compared to other methods. Compared to other unconventional manufacturing methods, abrasive water jet machining does not create a white layer and thermal damage on the workpiece, has no or low heat affected zone, has a higher material removal rate than wire erosion machining, and has a higher material removal rate than laser machining. It stands out with its positive results such as providing good surface integrity. The advantages of electro-erosion and wire erosion machining processes can be listed as being able to process electrically conductive materials with very complex geometry that are difficult to manufacture, less physical deformation due to no contact between the tool and the workpiece, and fewer areas affected by heat treatment. Shape memory alloys (SMAs) have been the subject of many researchers from the past to present. Many studies have been done in this field. The studies that are carried out and will be carried out in the future will help us to have more information about SMAs and will enable the discovery of new technological products that will benefit humanity. In this study, the applications of unconventional manufacturing methods on innovative and high-performance smart materials are explained and the results of previous research on this subject are summarized. It is thought that this study will be a guide for future studies.

Şekil Hafızalı Alaşımlarda Geleneksel Olmayan İmalat Yöntemlerinin Uygulamaları

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Anahtar Sözcükler

Akıllı Malzemeler
Şekil Hafızalı Alaşımlar
Aşındırıcı Su Jeti ile İşleme
Elektro Erezyon İşleme
Lazer İşleme
Tel Elektro Erezyon İşleme (WEDM)

Özet

Bu derleme çalışmasında, akıllı malzemelerin işlenmesinde kullanılan geleneksel olmayan imalat yöntemlerinin kazanımları ve eksikliklerinin detaylı bir analiz yapılarak belirlenmesi amaçlanmıştır. Bu yöntemler arasında aşındırıcı su jeti ile işleme, lazer, elektro erezyon ve tel erezyon işleme en çok kullanılanlar arasındadır. Aşındırıcı su jeti ile işleme, diğer yöntemlere göre bazı üstün özelliklere sahip olması nedeniyle sıklıkla tercih edilmektedir. Diğer geleneksel olmayan imalat yöntemlerine kıyasla aşındırıcı su jeti ile işleme, iş parçası üzerinde beyaz tabaka ve termal hasar oluşturmaması, ısıdan etkilenen bölgesinin olmaması veya düşük olması, tel erezyon işlemeye göre daha yüksek malzeme kaldırma oranına sahip olması ve lazer işlemeye göre iyi yüzey bütünlüğü sağlaması gibi olumlu sonuçlarıyla öne çıkmaktadır. Elektro erezyon ve tel erezyon işleme proseslerinin avantajları, imalatı zor olan çok karmaşık geometriye sahip elektriksel iletken malzemeleri işleyebilmesi, takım ile iş parçası arasında temas olmaması nedeniyle daha az fiziksel deformasyon oluşması ve ısıl işlemden etkilenen bölgelerin daha az olması olarak sıralanabilir. Şekil hafızalı alaşımlar (SMA'lar) geçmişten günümüze birçok araştırmacının konusu olmuştur. Bu alanda birçok çalışma yapılmıştır. Gerçekleştirilen ve gelecekte gerçekleştirilecek olan çalışmalar, SMA'lar hakkında daha fazla bilgiye sahip olmamıza yardımcı olacak ve insanlığa fayda sağlayacak yeni teknolojik ürünlerin keşfedilmesini sağlayacaktır. Bu çalışmada, geleneksel olmayan imalat yöntemlerinin yenilikçi ve yüksek performanslı akıllı malzemeler üzerindeki uygulamaları açıklanmakta ve bu konudaki önceki araştırmaların sonuçları özetlenmeye çalışılmaktadır. Bu çalışmanın gelecekteki çalışmalara rehberlik edeceği düşünülmektedir.

Introduction

With developing technology, the demand for metal alloys (advanced materials) with functional properties is increasing in sectors such as automotive, electronics, aviation, construction and biomedical. Smart materials, which are one of the most important representatives of advanced materials, have many usage areas. Smart materials, whose structures change due to external influence (light, force, heat, moisture), provide scientists with new ideas due to high technological developments. In recent years, a lot of research has been done on smart materials that twist, shrink, expand or contract under external influence (Bahl, Nagar, Singh, & Sehgal, 2020; Dezfuli & Alam, 2013; Seelecke & Muller, 2004).

With the developments in today's technology, new material groups come into play at points where metals and metal alloys cannot provide the desired properties. The most important of these material groups are alloys with a shape memory effect (Altas, Altin Karatas, Gokkaya, & Akinay, 2021). SMAs, with their superior properties such as superelasticity and shape memory effect, are widely used in various application areas in the industry that require low density, high ductility, strength and impact resistance, superior corrosion and wear resistance and fatigue life. These alloys are used to obtain economically suitable and technically suitable special products. Additionally, they are preferred over all other metallurgical materials in high-temperature applications. This is due to their excellent performance at high temperatures, superior creep and fatigue resistance under heavy loading, and fewer microstructural defects that occur during the production phase (Acar, Saedi, & Karaca, 2023; Altas, Erkan, Ozkan, & Gokkaya, 2022).

SMAs are smart materials that have the ability to return their structure, which is damaged when exposed to external factors, to their original shape, thanks to the application of appropriate heat. These special materials have the ability to change shape thanks to martensite and austenite phase transformations in their crystal structures. SMAs, which are very difficult to machine due to their superior mechanical and physical properties, are very difficult to machine using traditional (usual) methods due to high electrode wear rate and low surface quality. For this reason, non-traditional (unusual) manufacturing methods are used in the processing (machining processes) of SMAs (Altas, Gokkaya, Karatas, & Ozkan, 2020; Guo, Klink, Fu, & Snyder, 2013; Velmurugan, Senthilkumar, Dinesh, & Arulkirubakaran, 2018).

Another issue in the processing of SMAs is determining the most suitable method in terms of processing efficiency and sustainability. Research is being carried out on mathematical modeling to determine the most suitable processing method, parameters affecting yield and their impact ratios, and estimation of processability indicators (Cismasiu, 2010). In these studies, unconventional manufacturing methods applied in the processing of SMAs are generally used, as well as experimental design and analysis methods such as the Taguchi method and surface response method. These methods also enable obtaining results that are very close to the truth with fewer experiments. Thus, savings in terms of both processing time and economy increase. On the other hand, since a small change in individual parameters affects the machining performance in a complex way due to the complex mechanism of material removal in unconventional manufacturing methods, it is of great importance to improve these methods with multivariate optimization processes (Alagha, Hussain, & Zaki, 2021). In this context, it is seen that some studies have been carried out on the simultaneous optimization of processability indicators using techniques such as Taguchi-Gray relational analysis (GRA), response surface methodology (RSM), and particle swarm optimization (Chaudhari et al., 2019; Demers, Brailovski, Prokoshkin, & Inaekyan, 2009; Rathi et al., 2020).

Commonly used SMAs are nickel-titanium (NiTi), titanium nickel zirconium (TiNiZr), nickel aluminum iron (NiAlFe), iron manganese silicon (FeMnSi), iron manganese silicon chromium (FeMnSiCr) and nickel manganese gallium (NiMnGa) (Costanza & Tata, 2020; Wang & Jiang, 2008). The most commonly used SMA material group in the aerospace and defense industry and in the biomedical field is NiTi SMAs. NiTi SMAs show superior mechanical properties such as high elastic deformation of 20-25%, of which approximately 8% is recoverable, high strength and ductility of 200-250 MPa and hardness of 220-275 HV (Altas, Khosravi, et al., 2022). These properties make NiTi SMA a difficult material to machine. Unconventional manufacturing methods such as laser machining method (Al-Ahmari, Rasheed, Mohammed, & Saleh, 2016; Mohammed & Al-Ahmari, 2020), electro-discharge machining (EDM) method (Vinayak N Kulkarni, Gaitonde, Karnik, Manjaiah, & Davim, 2020; Rasheed, Al-Ahmari, El-Tamimi, & Abidi, 2012), electrochemical polishing and abrasive water jet machining method (M. Kong, Axinte, & Voice, 2011; Zadafiya, Kumari, Chatterjee, & Abhishek, 2021) are used for shaping NiTi alloy. In laser and EDM machining, thermal damage caused by high temperatures occurs on the machined surface, and these damages significantly reduce the fatigue life of the machined part. Additional finishing is often required to meet part requirements and remove the heat-affected zone. For this reason, NiTi SMAs, which are widely used especially in the healthcare sector, must be processed at appropriate parameter values. The subject of SMAs has been the subject of many researchers from the past to present. Many studies have been done in this field. This study and future studies will help us gain more information about SMAs and will enable new discoveries to be made to the advantage of technology and humanity (Al-Ahmari et al., 2016; Obeidi et al., 2021).

In this study, previous studies on the processing of SMAs with unconventional manufacturing methods are explained in detail, and their aims and obtained results are stated. Then, by evaluating the results obtained, the differences between the studies are explained and the shortcomings and strengths of the unconventional manufacturing method applications are stated. The main purpose of the study is to express all aspects of the unusual manufacturing method and properties of smart materials, thus helping future studies. At the end of the study, suggestions were explained and new research topics and areas were stated.

Processing Of Innovative and High-Performance Materials With Unconventional Methods

Smart materials are engineering materials that are constantly being developed. Interest in smart materials and manufacturing methods is increasing day by day, especially in industrially developed or developing countries. Difficulties in shaping smart materials with traditional machining methods have led to the development of unconventional manufacturing methods and the emergence of new processing approaches. In this section, studies on unconventional manufacturing methods that are widely used industrially are evaluated.

Studies on the Processing of Smart Materials Using the Abrasive Water Jet Method (AWJ)

Conventional machining of NiTi alloys is quite difficult due to their inherent high cutting forces and wear resistance. The low thermal conductivity, high elasticity, and severe strain hardening of NiTi alloys result in rapid tool wear, heat accumulation in the cutting zone, and poor surface quality, making conventional methods such as turning and milling inadequate for precision machining of these alloys (Altas et al., 2020). Therefore, in recent years, non-traditional machining methods have been used in the machining of these alloys (Zadafiya et al., 2021). Abrasive water jet (AWJ) is widely used in manufacturing industries for machining many metal and non-metal materials. Reasons for choosing the AWJ processing method include: producing a very small amount of heat in the cutting zone, being able to cut and process all kinds of metal or non-metal materials, providing a higher material removal rate than the wire erosion machining (WEDM) method and better surface integrity than the laser processing method, being able to cut materials up to 250 mm thick, and the absence of thermal deterioration in work materials. In addition, the ability to shape complex geometries by cutting, creating minimum cutting force on the workpiece and providing better dimensional accuracy due to very low deformation are the reasons for preference (M. C. Kong et al., 2013; Vora et al., 2022).

By transferring the kinetic energy of the high-speed water jet to the abrasive particles, the abrasive water jet method enables the needed amount of material to be removed or a certain form or geometry to be created on the workpiece. The abrasive water jet method offers many advantages such as minimized material waste, a heat-affected zone, low environmental pollution and no cutting fluid requirement (Mehta, Gupta, Mehta, & Gupta, 2019). It has been reported that in abrasive water jet machining of the surface of NiTi alloys, there are no thermal effects during the process, such as phase changes and microstructures, that can negatively affect the surface integrity. Compared to other unconventional manufacturing methods, abrasive waterjet machining provides positive results such as no thermal degradation on the workpiece, high machining versatility for cutting almost any material, high flexibility for cutting in any direction and low cutting forces (Frotscher, Kahleyss, Simon, Biermann, & Eggeler, 2011; Velmurugan et al., 2018).

Kong et al.(M. C. Kong et al., 2013), investigated the impact of processing parameters, accounting for secondary temperature and mechanical effect-induced transformations, on the surface integrity and geometric precision during multi-stage AWJ (cutting, countersinking, and milling) machining of the NiTi SMA (Figure 1). The researchers concluded from their experiments that cutting NiTi SMAs in straight notch geometry with AWJ is challenging because of their unique characteristics, which include high ductility and deformed twinned martensite transformation. However, they were able to accomplish this by lowering the AWJ's abrasive flow rate until surface integrity was acceptable. According to the researchers, these alloys could be used in the production of parts for the aviation industry if the AWJ machining method is managed optimally. Surfaces that can meet the quality requirements (cut surface: roughness <4 µm; countersink: circularity <0.04 mm, concentricity <0.15; milled surface: roughness <5 µm) can be created.

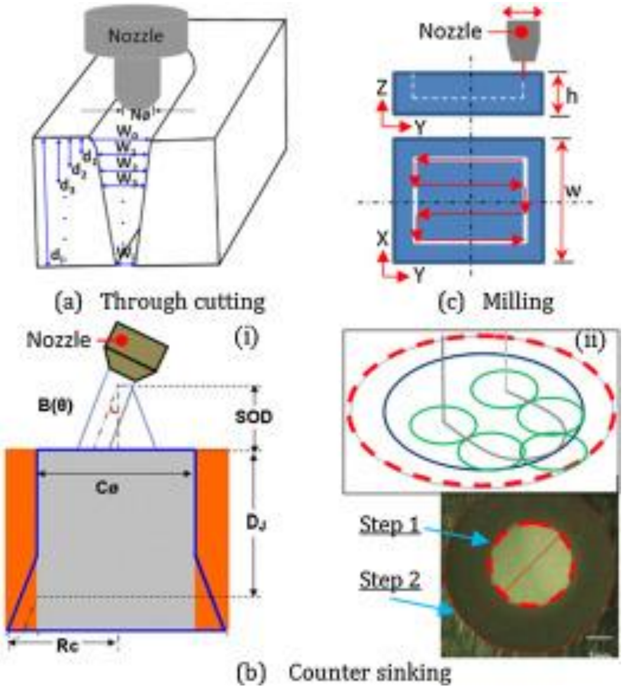

Figure 1. *Schematic representation of cutting operations with multi-option AWJ; (a) Cutting (b) Countersinking (c) Milling (M. C. Kong et al., 2013)*

Kong et al. (M. Kong et al., 2011) studied the mechanical and metallurgical properties of three different alloys (100% martensite, austenite and martensite mixture, 100% austenite) using AWJ and abrasive-free (plain) water jet (WJ) cutting processes. Some images of the surfaces milled with AWJ in their work are given in Figure 2. Researchers stated that in AWJ machining, high-speed abrasive particles create melts and sparks at some points, where the phase change of the NiTi crystal structure from martensite to austenite occurs. They stated that although the AWJ milling approach can provide a more controllable penetration depth, the sample surface integrity may decrease due to abrasive embedment, and this may negatively affect the fatigue life of the part. Researchers stated that although the problem of abrasive embedding occurs in the AWJ milling process, WJ milling can be considered to remove the embedded particles and this method can be an effective method for milling NiTi alloy.

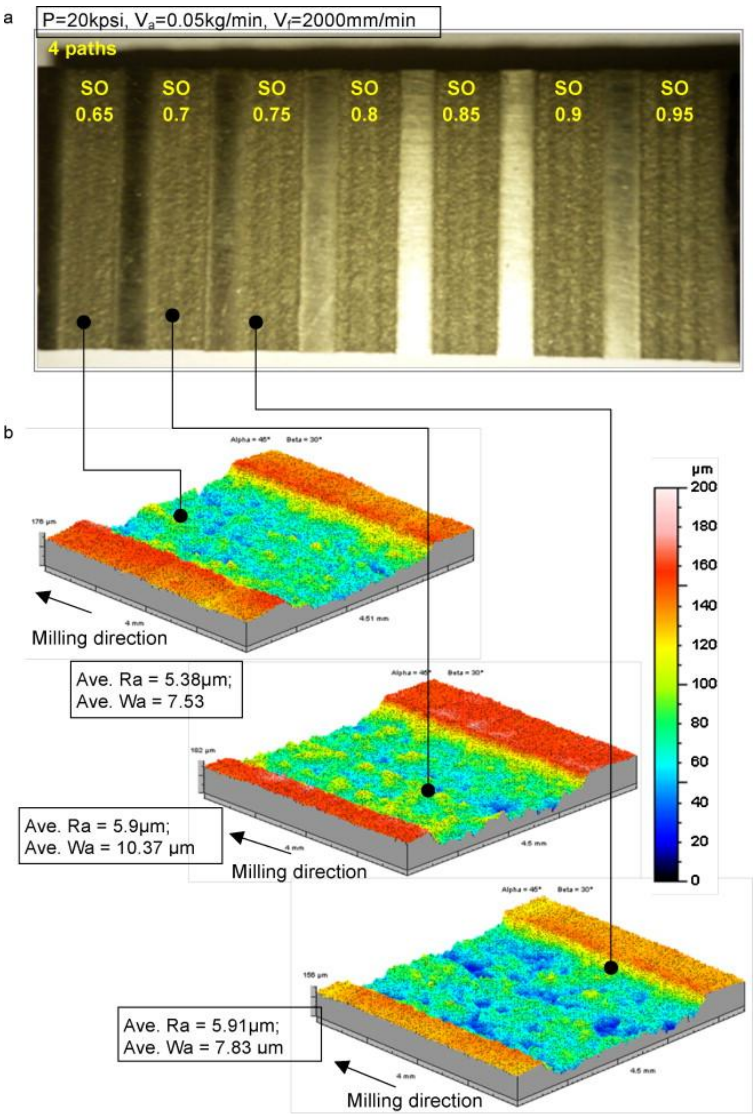

Figure 2. (a) *Image of AWJ milled surfaces created with different steps at a feed rate of 2000 mm/min; (b) Images of the quality of AWJ milled surfaces in steps of 0.65 mm, 0.7 mm, and 0.75 mm (M. Kong et al., 2011).*

Machining of NiTi SMA with abrasive water jet method provides minimized material waste, low cutting forces, very low heat affected zone compared to other machining zones, no thermal distortion, low environmental pollution and no cutting fluid requirements, flexibility and versatility. It offers many advantages such as being a processing process (Frotscher et al., 2011; Zadafiya et al., 2021).

Machining with the abrasive water jet method, compared to other unconventional manufacturing methods, does not create a white layer and thermal damage on the workpiece, has no or low level of heat-affected zone, high machining versatility for shaping difficult-to-machine materials, high flexibility in cutting operations and low shear (M. Kong & Axinte, 2012). It stands out with its positive results such as strength. In this respect, researchers use the abrasive water jet machining method in the machining of materials that are difficult to machine, such as NiTi alloys; they stated that it can be preferred in applications where good surface quality, low kerf angle, and low surface and subsurface defects are desired (Elahinia, Hashemi, Tabesh, & Bhaduri, 2012).

Studies on Processing of Smart Materials with Electro Erosion Method (EDM)

Electro discharge machining (EDM) method is one of the unconventional manufacturing methods widely used in the processing of NiTi SMAs. In this method, which is used to shape hard, brittle, and complex geometry materials, if the machining parameters are not determined correctly, high electrode wear rate, poor surface quality, as well as heat-affected zones under the machined surfaces may occur. This situation negatively affects the shape memory effect and superelastic behavior of NiTi SMAs and also brings about defects that reduce corrosion resistance and fatigue life (Manjaiah, Narendranath, Basavarajappa, & Gaitonde, 2014; W Theisen & A Schuermann, 2004).

Although electro discharge machining processes provide high machining accuracy in the machining of NiTi SMAs, oxides and contaminants dissolved in the dielectric liquid medium during machining can form a layer on the material surface. For this reason, NiTi SMAs, which are widely used especially in the healthcare sector, must be processed at appropriate parameter values (Manjaiah et al., 2014).

Daneshmand et al.(Daneshmand, Monfared, & Lotfi Neyestanak, 2017), investigated the effects of current, voltage, pulse on time, pulse off time, Al_2O_3 powder and electrode rotation speed on the metal removal rate, electrode wear rate and ambient surface roughness in the EDM cutting process of $NiTi_{60}$ SMA using the Taguchi technique. In cutting experiments, they employed copper electrodes as instruments. To lower the electrode wear rate and raise the rate of metal removal, they mixed 3 g/lt of Al_2O_3 powder with ionized water. The rotation of the tool produced a centrifugal force, and Al_2O_3 powder increased the size of the gap and the metal removal rate. The researchers' experiments revealed that these factors increased the metal removal rate with increases in current density, pulse on time, and voltage (Figure 3). They saw that the Al_2O_3 powder filled the space between the tool and the sample and that the tool's rotation around its axis stopped the plasma channel from spreading. It has been observed by researchers that decreasing current density, voltage, and pulse on time while increasing pulse off time can lower average surface roughness (Figure 4).

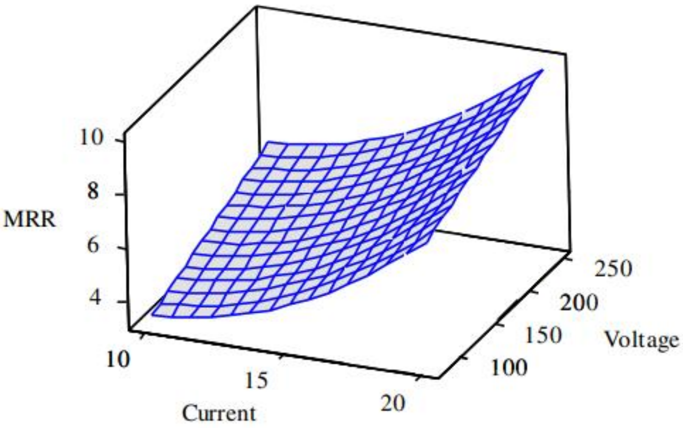

Figure 3. *Graph showing the effect of current and voltage on the metal removal rate (Daneshmand et al., 2017).*

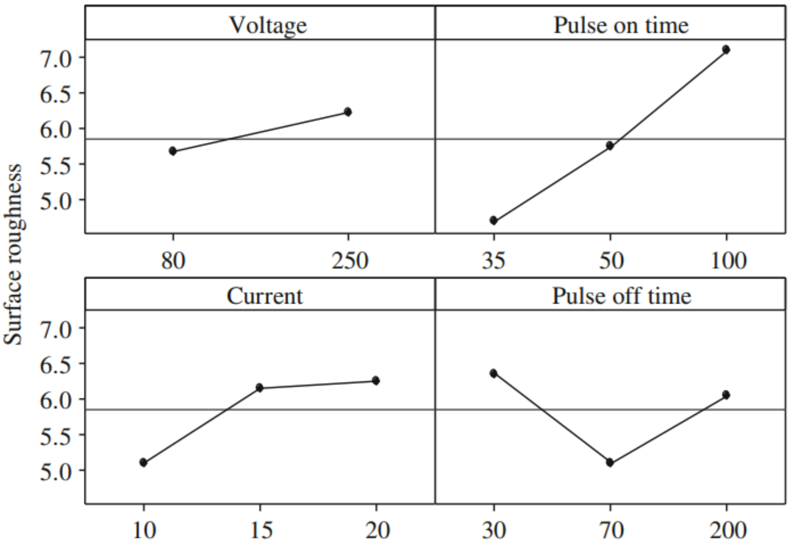

Figure 4. *Graph showing the effect of current and voltage on the metal removal rate (Daneshmand et al., 2017).*

Theisen and Schuermann (W. Theisen & A. Schuermann, 2004), examined the average surface roughness, molten zone thickness and metal removal rate in EDM machining of NiTi SMA. Researchers stated that there are cavities, cracks and precipitations in the microstructure of the melting zone during EDM processing (Figure 5), cracks form on the surface as a result of random and locally overlapping thermal shocks, and the cracks start from the surface and grow vertically into the sample. They found that the metal removal rate increased approximately linearly with the discharge energy, while the molten zone thickness increased with the operating current and decreased with the frequency. They reported that the average surface roughness tended to increase with the operating current.

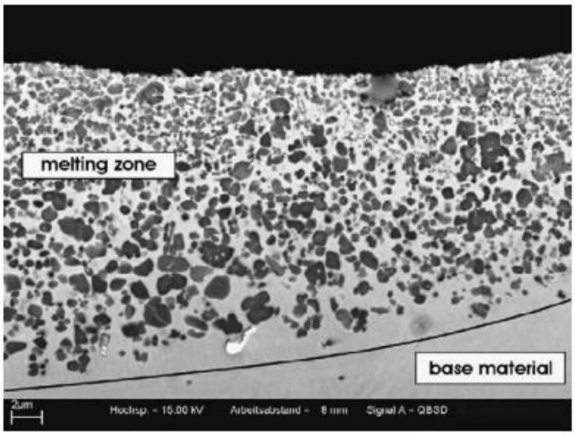

Figure 5. *Image of TiC precipitates in the melting zone of the processed NiTi alloy (W. Theisen & A. Schuermann, 2004).*

Gaikwad and Jatti (Gaikwad & Jatti, 2016), investigated the process parameter optimization of the electro discharge machining method to enhance the metal removal rate during the NiTi SMA machining process. They conducted the trials using the L36 orthogonal array proposed by Taguchi. They concluded from their investigation that the metal removal rate is significantly influenced by the workpiece's electrical conductivity, gap current, and pulse open time. The best metal removal rate was found to be 7.08 mm3/min at workpiece electrical conductivity of 4219 S/m, gap current of 16 A, and pulse open time of 38 µs.

Chen et al.(Chen, Hsieh, Lin, Lin, & Huang, 2007), studied the effect of processing parameters on TiNiCr and TiNiZr ternary SMAs using the electro discharge machining method. In the experiments, $Ti_{50}Ni_{49.5}Cr_{0.5}$ and $Ti_{35.5}Ni_{49.5}Zr_{15}$ alloys produced by the conventional tungsten arc melting technique were used as workpieces. Researchers have stated that TiNiCr and TiNiZr alloys in the EDM process show an inverse relationship to the melting temperature and thermal conductivity of the alloy. The average surface roughness of EDM processed TiNiX alloys obeys the empirical equation Ra=β(IP×τP)α; the TiNiCr alloy with a low TΘ×KT value obtains larger average surface roughness values than the TiNiZr alloy after EDM, TiNiX SMAs are produced by EDM. They stated that in order to be able to process precisely, low discharge current IP and short pulse duration τP should be selected. For EDM processed TiNiX alloys, the hardening effect near the outer surface is due to the melting and re-solidifying layer, the impact duration varies depending on the layer thickness, and minimum values are selected for the maximum metal removal rate.

Soni et al. (Soni, Sannayellappa, & Rangarasaiah, 2017), examined the effects of machining parameters on the average surface roughness, metal removal rate, microstructure, melting and solidifying layer thickness and microhardness of $Ti_{50}Ni_{40}Co_{10}$ SMA during EDM machining. As a result of their experiments, the researchers found that pulse on time, pulse off time and servo voltage were the most effective process parameters on average surface roughness and metal removal rate; they found that the average surface roughness and metal removal rate increased with increasing pulse on time, but decreased with increasing pulse off time and servo voltage. They stated that at a high pulse on time of 125 µs and low servo voltage of 20 V, the formation of microcracks, microdroplets and microvoids was greater, and therefore the quality of the machined surface deteriorated. They observed that the melted and solidified layer thickness was higher at 125 µs pulse on time and 20 V low servo voltage. Abidi et al. (Abidi et al., 2017), reported that circularity errors could be reduced and good surface quality could be achieved in machining NiTi SMAs with optimized EDM parameters. Jatti and Singh (Jatti & Singh, 2014), touched upon the points where electrical conductivity is important in the processing of NiTi SMAs using the EDM process. In their study, they increased the electrical conductivity of the workpiece by around 29% through cryogenic processes, ensuring that the thermal vibration of the atoms in the metal was weaker. They aimed to facilitate the movement of electrons on their path with these vibrations. As a result, they reported significant increases in the metal removal rate.

In addition to achieving good surface quality and low circularity error, the electro discharge machining process can result in the formation of a thick white layer on the surface of NiTi SMAs (W Theisen & A Schuermann, 2004).

Studies on Processing Smart Materials with Laser Method

Laser machining is an unconventional manufacturing method that uses thermal energy based on a high-energy beam, removing material from the workpiece's surface by melting and evaporation (Krishna, Bose, & Bandyopadhyay, 2007). As a result of processing, a thermally affected zone under the surface and, accordingly, a residual tensile stress occurs. Due to the progression of the laser beam on the workpiece, machining lines, high surface roughness and burr formation are observed on the machined surfaces. The main disadvantage of laser processing is the reshaping of the surface layer resulting from the thermal nature of the process, microstructural changes such as the heat-affected zone, localized cracks and contamination. All these defects can generally lead to loss of material properties and reduction of geometric quality near the kerf. For this reason, studies investigating the effects of processing conditions on the surface integrity of NiTi alloys using laser processing methods are of great importance (Mehrpouya, Gisario, & Elahinia, 2018; Saedi et al., 2018).

Fu et al. (C. H. Fu, Guo, & Sealy, 2014), they developed a three-dimensional finite element model of the temperature distribution, stress formation and heat-affected zone formation in the laser pulse cutting process of NiTi SMA. They used ABAQUS/Standard software for modeling studies. In addition, they included a material subprogram they created with DFLUX software in the model to model the superelasticity and shape memory feature of the SMA. They stated that after the modeling studies, the characteristics of the notch width and taper were predicted and that they were in acceptable agreement with the experimental data. They stated that the kerf width can be narrowed by increasing the cutting speed and decreasing the maximum power, and on the other hand, the taper can be reduced by increasing the cutting speed and maximum power. They stated that high cutting speed and low maximum power not only cause an excessive temperature change near the material subsurface, but also shift the maximum effective stress from the top surface to the subsurface. Pulse width only affects stress distribution near the subsurface. They concluded that laser cutting speed is a more effective factor on the heat-affected zone thickness than pulse power and pulse width (Figure 6).

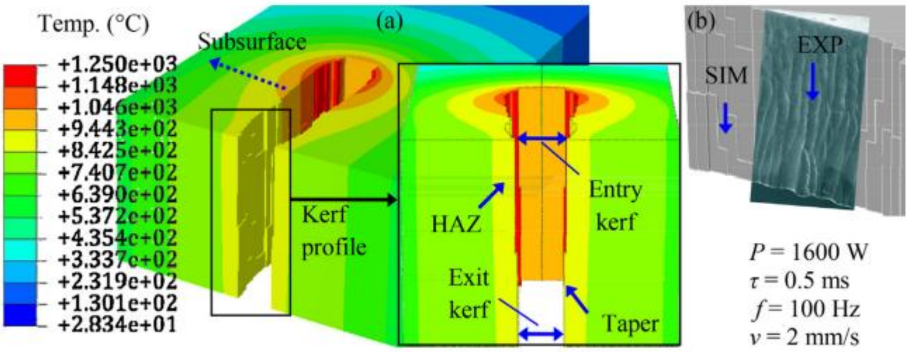

Figure 6. *(a) An image of the model of the notch formed during laser cutting, (b) Images of the laser-cut surfaces predicted by modeling and measured after the experiment (C. H. Fu et al., 2014).*

Pfeifer et al. (Pfeifer, Herzog, Hustedt, & Barcikowski, 2010), investigated the cutting of 1 mm thick NiTi SMA used for medical applications with a pulsed Nd:YAG laser and the effects of pulse energy, pulse width, cutting speed and overlapping of the laser spot during cutting on the cutting geometry, roughness and heat-affected zone (Figure 7). They achieved sufficient cutting quality (Rz = 10-30 μm) for short and ultra-short laser processing of SMA using high cutting speeds (υ=2-12 mm/s). They stated that the heat-affected zone was small due to regional energy input and shape memory properties continued.

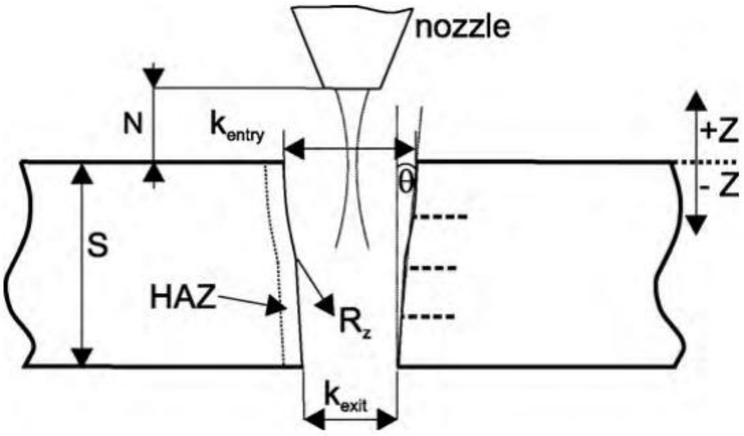

Figure 7. *Schematic illustration showing various laser cutting quality features: k_{input}: kerf entry (top) width, k_{output}: kerf exit (bottom) width, Z: focus position, N: nozzle distance, Θ: taper angle, HAZ: heat affected zone, Rz: surface roughness, S: material thickness (Pfeifer et al., 2010).*

Fu et al. (C. H. Fu, Liu, Guo, & Zhao, 2016), compared the average surface roughness and hardness properties of the white layer (resolidified layer) formed during laser cutting and EDM cutting processes of $Ni_{50.8}Ti_{49.2}$ SMA. In laser cutting tests, two different laser powers, low energy (600 W) and high energy (1200 W), constant cutting speed (200 mm/tooth), pulse width (0.75 ms) and frequency (100 Hz) were used as processing parameters. In EDM cutting tests, two different discharge voltages (42 and 57 V), pulse interval time (1 and 8 µs), electrode advance rate (3.3 and 6.6 mm/tooth), pulse frequency (8 and 12 kHz) were used as processing parameters. They used constant power density (6) and wire movement speed (12 mm/tooth). Researchers stated that the white layer formed during laser cutting is distributed more uniformly on the surface than that obtained with EDM. They observed that while laser cutting resulted in an average surface roughness of approximately 7 µm on the white layer, this value decreased to approximately 1 µm with EDM. They stated that while the hardness of the white layer obtained during laser cutting was lower than that of the unprocessed sample, this hardness was higher in EDM processing. Fu et al. (C. Fu, Liu, & Guo, 2015), in their study titled “Surface Integrity Characteristics of Nitinol Vascular Stents with Fiber Laser Cutting,” used a high beam quality fiber laser cutting process to process $Ni_{50.8}Ti_{49.2}$ SMA and determined the notch geometry, surface roughness, microstructure and hardness. As a result of their experiments, the researchers stated that a narrow (notch width ~100 µm) and uniform notch (taper angle ~0.1°) were obtained due to the special beam quality of the fiber laser. They found that a non-uniform resolidification layer formed on the laser cutting surface and the hardness of this layer was lower than that of the untreated alloy. Researchers observed that cutting speed increases the average surface roughness. They reported that the smallest average surface roughness (4 µm) was obtained at medium cutting speed and the highest laser power. When the effect of cutting speed on the microstructure of NiTi SMA was examined, they stated that increasing cutting speed caused the formation of a re-solidified layer.

Studies On Processing Of Smart Materials Using Wire Electrical Discharge Machining (WEDM) Method

The wire erosion method has a wide range of applications in industrial applications because it has many advantages over traditional cutting methods. Cutting conductive materials to precise dimensions by means of a wire charged with high-intensity electric current is called wire erosion cutting. The cutting process is based on the principle of removing particles as a result of the partial melting of the metal caused by the heat generated by the electrical discharge that occurs when the electrode attached to different electrical poles is brought closer to the part to be cut. The removal of particles depends on the amount of energy in each spark and the elapsed time of each spark. Processing of

SMAs by wire erosion causes some surface defects such as reshaping of the surface layer, air bubbles, molten droplets, debris and microcracks, resulting in a decrease in surface quality and therefore an increase in the resulting surface roughness.

For this reason, studies investigating the effects of machining conditions on the surface integrity of NiTi alloys using wire erosion machining methods are of great importance (Bisaria & Shandilya, 2019; Majumder & Maity, 2018). Bisaria and Shandilya (Himanshu & Pragya, 2018), examined the effects of processing parameters on wire wear and dimensional deviation rates in wire erosion processing of NiTi SMA. Researchers' experimental studies were carried out at five different pulse duration (18, 20, 22, 24, 26 µs), pulse interval times (48, 49, 50, 51, 52 µs) and current (160, 170, 180, 190, 200 A) values. Machining operations were carried out on a four-axis computer numerically controlled (CNC) wire erosion bench using a Ni55.7Ti SHA sample, rich in Ni and measuring 10x10x6 mm. The dimensional deviation value was measured with the "Mitutoyo" digital micrometer device. As a result of experimental studies, it was stated that by increasing the pulse duration (18 → 26 µs) and current (160 → 200 A) values, electrode wear rate values increased by 52% and 100%, and dimensional deviation values increased by 14% and 14.3% (Figure 8). It was also stated that by increasing the pulse interval time to (48 → 52 µs), electrode wear rate and dimensional deviation values decreased by 58% and 12.5% [53].

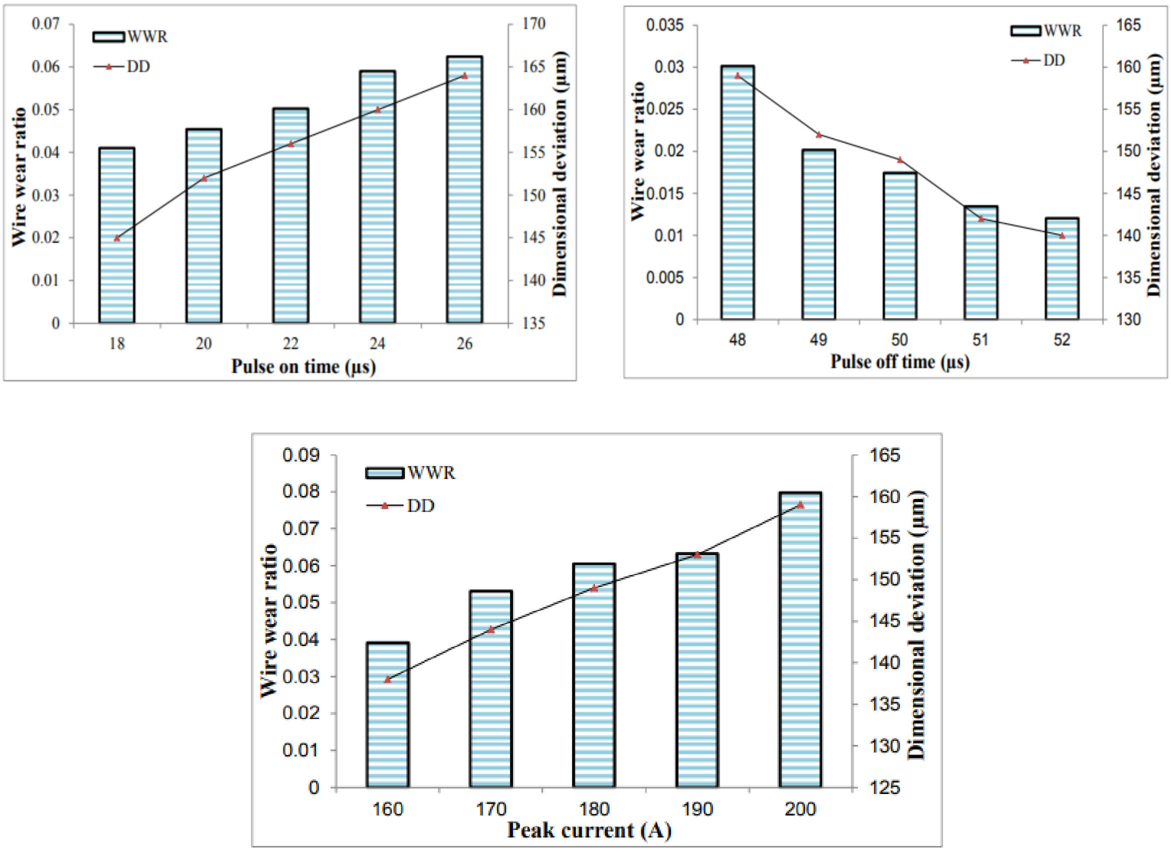

Figure 8. *Electrode wear rate and dimensional deviation rate values obtained at different machining parameter values (Himanshu & Pragya, 2018).*

Abhinaba and Roy (Roy & Narendranath, 2018), examined the effect of wire erosion cutting parameters of TiNiCu alloys on kerf width, the thickness of the rejoined layer and microhardness values of the cut surfaces. They stated that the optimum value for obtaining low kerf width, where the kerf width decreases with the increase in servo voltage, is 60 volts. In the study, they stated that the thickness of the resolidified layer increased with the increase of pulse interval time. They also stated that the hardness values of the cut surfaces increased due to the presence of oxides formed on the surface due to higher energy discharge processing, and the surface hardness of the cut samples was considerably higher (560 HV) than the untreated samples due to the nickel-rich phases γ-CuTi precipitate phases formed as a result of phase transformations. It has been reported that the most effective parameter on the hardness values is the pulse interval time, and the servo voltage duration is a minor factor, but the effect of other parameters is negligible. Soni, Narendranath and Ramesh (Soni & MR, 2018), in their study on the wire erosion cutting parameters of TiNiCo SMAs, stated that in the case of processing these alloys with traditional methods, losses in their properties may occur, in addition to low surface quality being obtained and that wire erosion or water jet shaping in these alloys may cause losses in their properties. They stated that it was more suitable. In their study, they examined the effects of Ti50Ni45Co5 alloy on microstructure, surface topography, microhardness, XRD analysis and residual stresses depending on wire erosion parameters and used the Taguchi method. They determined that the process parameters for optimum surface roughness were pulse duration 125 µs, pulse interval time 35 µs and servo voltage 40 V. They stated that higher hardness values occurred under the resolidified region and the presence of TiNiO3 and TiO2 oxide formations in this region. They also stated that there were residual stresses on the cut surfaces.

During wire erosion machining of NiTi SMAs, Kulkarni et al.(Vinayak N. Kulkarni, Gaitonde, Hadimani, & Aiholi, 2018), he studied how machining settings affected the average surface roughness and metal removal rate. The researchers concluded from their trials that the two main determinants lowering average surface roughness were pulse on time and voltage, which also enhanced the rate of metal removal. According to their findings, the average surface roughness rose as the pulse on time grew and dropped as the voltage and pulse off time increased. According to their findings, the metal removal rate rose as the pulse open time grew and fell as the pulse closed time increased. They came to the conclusion that although the metal removal rate rose when the voltage was raised to 40 V, it decreased as the voltage was raised further. Kulkarni et al.(Vinayak N. Kulkarni, Gaitonde, Aiholi, & Hadimani, 2018) optimized the machining parameters to increase the metal removal rate and reduce the average surface roughness during wire erosion machining of $Ni_{55.74}Ti_{44.26}$ SMA. They performed multiple performance characteristic optimizations using the Taguchi technique and quality loss function. In the cutting tests, a brass wire electrode was used as a tool, three different wire feed rates (4, 6 and 8 mm/tooth), pulse on time (105, 115, 125 µs), pulse off time (25, 40 and 40 mm) were used as processing parameters. 55 µs) and voltage (20, 40 and 60 V). Researchers determined that the optimum parameters to obtain the highest metal removal rate and the smallest average surface roughness are 115 μs pulse on time, 25 μs pulse off time, 6 mm/wire feed rate and 40 V voltage. They stated that the wire feed rate is the most important parameter affecting the average surface roughness and metal removal rate. Manjaiah et al. (Manjaiah, Narendranath, Basavarajappa, & Gaitonde, 2015), evaluated the surface roughness results obtained when the SMA $Ti_{50}Ni_{50-x}Cu_x$ workpiece material was processed with different types of electrodes. They found that the surface roughness values obtained when processing with zinc-coated wire were lower than the surface roughness values obtained with brass wire. They also investigated the effect of machining parameters on surface roughness. Based on the results obtained, they found that the surface roughness worsened as the pulse duration increased. Liu et al. (Liu, Li, & Guo, 2014), conducted a study on the surface roughness resulting from the processing of SMAs by wire electro-erosion.

Studies on the Processing of Smart Materials with Other Unconventional Manufacturing Methods

Apart from the methods described, there are many different unconventional manufacturing methods depending on the materials used and the desired properties. Each method has advantages and disadvantages over the other. Determining the correct method depends on machining outputs such as material type and properties, desired dimensions and tolerances. Related research using other unconventional manufacturing methods of smart materials is given below.

Ma et al. (Liu et al., 2014), used the ultrasonic nano-crystal surface modification method to reduce the Ni ion release in NiTi samples produced by the selective laser melting method. The researchers found that the ultrasonic nano-crystal surface modification method significantly improved the surface quality thanks to simultaneous ultrasonic pulses and polishing. They stated that it can heal and reduce surface porosity. The average surface roughness was reduced from 12.1 μm to 9.0 μm, and the subsurface porosity ratio was obtained as 11:1 for before and after ultrasonic treatment. They also stated that the ultrasonic nano-crystal surface modification method causes plastic strain and thus hardening of the surface layer. A surface layer with a thickness of 125 μm and a hardness increase of 34.2% was obtained. They stated that these changes provided high wear and corrosion resistance. The corrosion current decreased from 157 nA to 53 nA. The wear volume decreased from 92137 μm3 to 64011 μm3 in 6000 cycles. Shiva et al. (Shiva, Palani, Mishra, Paul, & Kukreja, 2015), produced ring-shaped NiTi SMA in three different compositions (45%Ni-55%Ti; 50%Ni-50%Ti; 55%Ni-45%Ti) by laser-based additive manufacturing method using Ni and Ti powders. Researchers stated that SMA can be produced by laser-based additive manufacturing process, and the properties of $Ni_{5}0Ti_{50}$ alloy produced by laser-based additive manufacturing method are close to the properties of conventionally produced NiTi alloy.

Lee and Shin (Lee & Shin, 2011), examined the application of electrochemical polishing in the processing of NiTi SMA. They examined the effect of each parameter on the machined surface quality and determined the most suitable electrochemical processing condition for NiTi alloy. In their comparison of the use of acidic and neutral electrodes, the researchers stated that electrochemical machining with the neutral electrode caused the formation of many ultra-microscopic holes on the NiTi material surface, but the process was fast and therefore the neutral electrode was suitable when the chip removal was of primary importance. They stated that electrochemical machining with an acidic electrode is suitable for slow machining and can be preferred for precision machining. They stated that the surface roughness is generally better when a high current is applied, but the machining process becomes unstable when excessive current is applied. They stated that the surface roughness is generally better if the inter-electrode gap is small, but using an excessively close inter-electrode gap causes uneven machining, which results in the formation of bubble marks on the NiTi alloy. They stated that they reduced the surface roughness of a NiTi alloy with 1 µm roughness to 0.31 µm with an acid electrode, 18 A current, 800 µs/200 µs pulse on/off time, 0.5 mm inter-electrode gap distance and 300 seconds processing time.

Zhu et al. (Zhu et al., 2020), investigated corrosion forms that could result in allergy and poisoning in humans in their investigation of the surface modification features of NiTi SMAs processed with micro EDM utilizing a concentration of titanium carbide (TiC) powder. The objective of the study was to examine how the concentration of TiC powder and the parameters of the EDM processing affect the surface characteristics and processing of NiTi SMA. They found that the rate of metal removal, the roughness of the surface, and the thickness of the layers that formed after processing all increased with hitting time. According to the researchers, the addition of TiC powder increased the frequency of electro-discharges and the rate at which material was removed, as well as decreased surface roughness. The lowest surface roughness and greatest metal removal rate were seen at a mixed powder concentration of 5 g/L. They also discovered that, as a result of metallurgical bonding, the newly created layer on the surface following milling had strong adhesion and high hardness. The machined surface's microhardness increased from 258.5 HV to 438.7 HV after processing, according to XRD analyses, and the surface contained phases of copper dioxide (CuO2), titanium dioxide (TiO2), and TiC. These findings may be helpful for wear resistance in biomedical orthodontic applications. Jamaluddin et al.(Jamaluddin, Tan, Hamidon, Mansor, & Azmi, 2021), in their study titled "Electrical discharge coating of NiTi alloy in the deionized liquid environment," examined the developability of the titanium oxide layer on the NiTi alloy surface by electro-erosion coating. They aimed to improve the biocompatibility of the NiTi alloy and to minimize the harmful effects of the Ni ions in the alloy on the human body. They determined that high-level voltage provides titanium oxide structure on the surface of NiTi alloy. Researchers also found that polarity and voltage show a significant effect on average surface roughness. They stated that the spark energy increased as a result of the interaction between high voltage and polarity, and this caused the formation of deep and wide craters on the machined surfaces.

Rasheed et al.(Rasheed et al., 2012), carried out experimental studies to determine the optimum processing parameters for micro-EDM machining of NiTi SMAs. In their study, they examined the effects of capacitance and voltage parameters on the metal removal rate, electrode wear rate and average surface roughness value. Using $Ni_{55.8}Ti_{44.2}$ superelastic SMAs in their experimental studies, the researchers planned to examine different capacitance (155, 475 pF) and voltage (80, 100 V) values during the machining processes. Researchers carried out machining operations in deionized liquid with a brass electrode in the form of a cylindrical rod at the capacitance and voltage parameters determined according to the Taguchi L24 orthogonal array. As a result of the experimental studies, the maximum metal removal rate in metal removal operations using brass electrodes is (0.000953832 mm^3/min); they found that it performed at high capacitance (475 pF) and voltage (100 V) values.

Conclusions

In this study, the research done to date on the processing of smart materials with unconventional manufacturing methods has been evaluated. The results obtained as a result of the examination and evaluations are summarized below.

- In recent years, NiTi SMAs have been used in fields such as automotive, aerospace, biomedical and medicine due to their important properties such as shape memory effect, superelasticity, high corrosion resistance, fatigue life and biocompatibility. In addition to their superior mechanical properties, their low thermal conductivity causes high stresses and electrode wear rate on the material surface during processing. For this reason, unconventional manufacturing methods are often preferred in the processing of NiTi SMAs. Advanced non-traditional manufacturing methods based on thermal, mechanical energy and electrochemical; it supports corrosion, material deterioration, irregular surfaces and, as a result, the formation of a quality surface form. Scientific studies related to machinability in the literature; it is seen that it is aimed at determining the maximum metal removal rate, minimum electrode wear rate and average surface roughness values.
- The studies carried out were generally aimed at improving the machinability feature. In addition, it is seen that the studies carried out in recent years are on the development of systems used in unconventional manufacturing methods, optimizing the parameters affecting processing efficiency and modeling machinability indicators such as surface roughness and processing speed. In these studies, mostly Taguchi method experimental design and analysis techniques were widely used and the effective parameters in the processing method were determined by analysis of variance. Current studies have revealed that the surface quality and the protective oxide layer formed on the surface have a significant impact potential in terms of improving corrosion resistance and increasing fatigue life. It was concluded that the data obtained revealed important results showing

that the unconventional manufacturing method is preferable in the processing of SMAs.

- The subject of SMA has been the subject of many researchers from the past to the present. Many studies have been done in this field. This study and future studies will help us gain more information about SMAs and will enable new discoveries to be made to the advantage of technology and humanity.

ABBREVİATİONS

SMA : Shape memory alloy

NiTi : Nickel-titanium

TiNiZr : Titanium nickel zirconium

NiAlFe : Nickel aluminum iron

FeMnSi : Iron manganese silicon

FeMnSiCr : Iron manganese silicon chromium

NiMnGa : Nickel manganese gallium

EDM : Electro-discharge machining

AWJ : Abrasive water jet

WJ : Water jet

WEDM : Wire erosion machining

CNC : Computer numerically controlled

CONFLICT OF INTEREST STATEMENT

The author acknowledge that there is no known conflict of interest or common interest with any institution/organization or person.

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