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A Review on Machinability of Shape Memory Alloys Through Traditional and Non-Traditional Machining Processes

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ABSTRACT

This review article offers consolidated knowledge on the subject of several traditional and non-traditional procedures that are taking place throughout the years to form shape memory alloys (SMAs). At the primary part of the review, the usage of several shape memory alloys was shown. The dialogue then continued towards numerous traditional techniques of operating followed by the obstacles in the running of SMAs utilizing traditional techniques of operating. Moreover, numerous non-traditional processes of operations such WJM (Water jet Machining), cryogenic, WEDM (Wire Electro Discharge Machining), EDM (Electro Discharge Machining), and electrochemical machining explored. As well, Numerous of outcomes reactions that may occur during the operation procedures have been emphasized such as material removal rate (MRR), rate of tool wear, surface roughness (SR), the surface integrity. A consolidated records of various academics and their findings on this issue has been evaluated. After all, the article has been concluded by suggesting a variety of key points seen throughout the review process.

Şekil Hafızalı Alaşımların Geleneksel ve Geleneksel Olmayan İşleme Yöntemleriyle İşlenebilirliği Üzerine Derleme

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ÖZET

Bu derleme makalesi, şekil hafızalı alaşımları (ŞHA'lar) üretmek için yıllar boyunca yer alan çeşitli geleneksel ve geleneksel olmayan prosedürler konusunda bilgi sunmaktadır. İncelemenin ilk kısmında, çeşitli şekil hafızalı alaşımların kullanımı gösterilmiştir. Araştırma daha sonra çok sayıda geleneksel üretim tekniğine ve ardından geleneksel üretim tekniklerini kullanan ŞHA'ların çalıştırılmasındaki engellere doğru devam etmiştir. Ayrıca, SJİ (Su jeti İşleme), kriyojenik, TEBİ (Tel Elektro Boşaltma İşleme), EBİ (Elektro Boşaltma İşleme) ve elektrokimyasal işleme gibi çok sayıda geleneksel olmayan işlem süreçleri araştırılmıştır. Ayrıca, talaş kaldırma hızı (TKH), takım aşınma hızı, yüzey pürüzlülüğü (YP), yüzey bütünlüğü gibi operasyon prosedürleri sırasında meydana gelebilecek birçok sonuç reaksiyonu üzerinde durulmuştur. Çeşitli araştırmacıların çalışmaları ve bu konudaki bulguları değerlendirilmiştir. Sonuç olarak makale, inceleme süreci boyunca görülen çeşitli kilit noktalar önerilerek sonlandırılmıştır.

1. INTRODUCTION (GİRİŞ)

By the 1960s, Blair and Willie developed a nickel-titanium alloy containing 53% to 57% nickel, which led to the emergence of a strange case where distorted samples were formed with different strains ranging from 8% to 15%, and these alloys are preparing their original shape after going through a thermal cycle. Hence the name of a shape-memory alloy has appeared. These alloys are characterized by their ability to restore their original condition when heated (to a heat elevated than their transformation temperature). Also, these alloys are distinguished by a low yield strength, which facilitates their formation and transformation into any new form [1]. In other words, (SMAs) are a unique category of compounds which own a capacity to retain their previous appearance after

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deformation even after being bent. SMAs could be plastically deformed at a low temperature, but this 'plastic' strain could be gained by raising the heat, known as shape memory effect (SME). By high temperatures, a substantial deformation could gained only by releasing the affected force [2].

The nickel-titanium alloy, known as a Nitinol alloy, is the greatest utilized shape-memory alloy and the highest in price because of its mechanical and unique electrical features, extended fatigue life, and great corrosion resistance. Among the alloys further traded in this field is the copper-aluminum-nickel alloy. Moreover, SMAs may additionally be obtained via using iron zinc, and copper as alloying elements [1-3].

Shape-remembering alloys provide many advantages such as safety, susceptibility to pressure, and provide excellent working conditions such as cleanliness, quietness, and spark-free, and they can work in zero-gravity conditions. Therefore, they are recently used in several applications in various fields such as reciprocating applications (i.e., they are in a permanent state of stopping and working) such as refrigerant circuit valves, fire detection systems, and clamping devices. For example, these reciprocating applications exist in small sizes, such as tiny motors, which are electrically driven machines. It is also used for many purposes in the medical field, like braces, orthodontics, and medical guidewire. Moreover, these alloys were employed in the aerospace industry and in fixed-wing aircraft, where SMAs utilized in the wires (strings) that power the hingeless ailerons. Also, SMAs torque tube utilized to begin spanwise wing twisting of a scaled-down F-18. In all of those implementations, SME is utilized to give actuation through recovering the form that happens when stresses occur [2,4].

These attributes of shape memory compounds are issued by the reversible transformation of the martensite phase, transforming from a solid to a solid-state without diffusion. It is a transition between a crystal structured form represented by austenite and another less organized form martensite. The SMAs are in the austenite phase near relatively high temperatures and shift to a martensite phase when cooled. At the same time, austenite is characterized by a cubic crystal structure, while martensite is designated by a monoclinic crystalline formation, as shown in (Fig. 1)

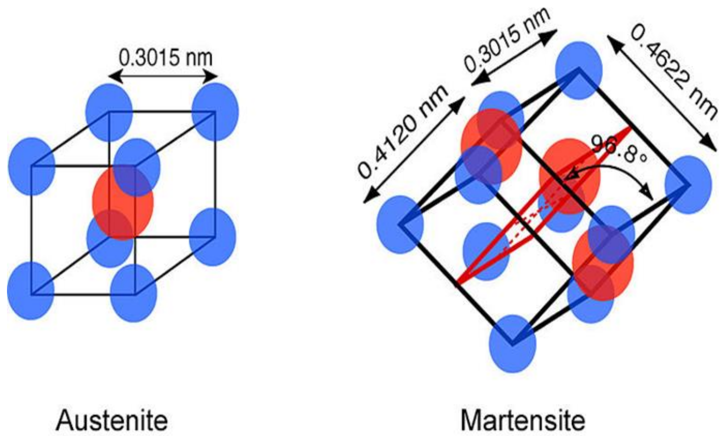

Figure 1. Nitinol austenite and martensite (Nitinol östenit ve martensit) [5].

The transformation from austenite to martensite is carried out through a process of distortion or alteration in the shape of the crystal structure by displacement, where these changes occur in the internal system of the material.

Furthermore, the austenite is stable in the case of low pressures and high temperatures, while martensite is more stable at higher pressures and lower temperatures. The meaning of high or low temperature could be explained more in (Fig. 2). In addition, there is a passage between stage transitions. The austenite and martensite have various start and final temperatures. Thus, temperature variations of 50% martensite to 50% of austenite state are identified as temperature hysteresis [6] (Fig. 2).

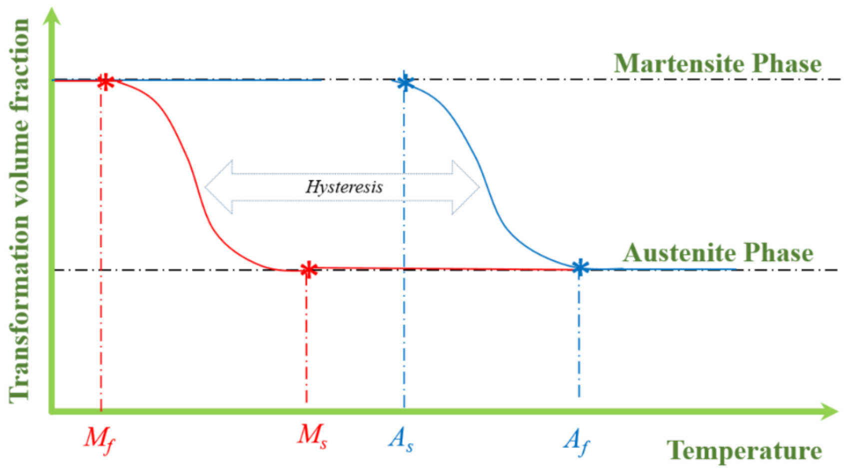

Figure 2. Phase transformation of SMAs (ŞHA'ların faz dönüşümü) [6].

Four transition temperatures describe SMAs: Mf, Ms, As, and Af. Temperatures As and Af are the heats during the transformation of (martensite to austenite) begins and ends, and the temperatures Ms and Mf are the temperatures at which the reverse conversion from austenite to austenite to martensite take place. In contrast, the state of martensite is called the inverse state. When the primary and reverse transformation process is repeated depending on the shape memory alloy property, this may lead to a transition in the temperatures through transformation process starts and ends. This phenomenon is called functional stress, as it is related to varying the fine structure of the material and altering its operating properties as well [7].

The austenite phase crystal structure is shifted with a decrease in the temperature to twinned martensite. This process is beginning from Ms and will finish below Mf. Meanwhile, mechanical stress distorts the twinned martensite to a detwinned structure, and the primary shape is retained inside the SMAs. To regain its original condition, it must go within extra two steps. Firstly, the outside load has to be lifted then heated to an austenite form transformation occurs. This high-temperature period begins from As and takes progression until Af. All these actions create a cycle; thus, the strain recovery depends on the region of the process. The elements that establish these steps are named one-way SMAs. While the final approach, which has a unique property, is termed two ways SME. One-way SMAs have only one initial shape at a higher temperature. However, two recoverable conditions could be produced for two-way SMAs: one of them in the austenite state and the other with a martensite state [6] (Fig. 3). Describe various SMAs for strain, stress, and temperature.

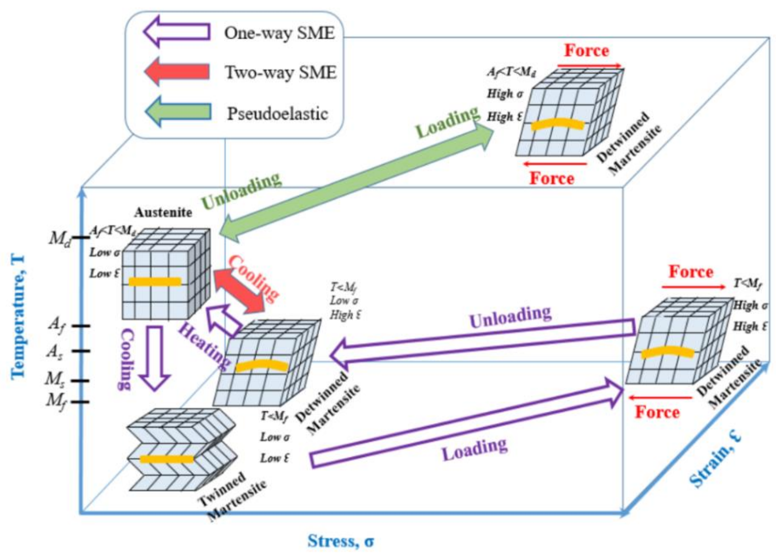

Figure 3. Description of various SMAs for strain, stress, and temperature (Gerinim, stres ve sıcaklık için çeşitli ŞHA'ları tanımlanması) [6].

This article summarizes various operation approaches that could be utilized to form the SMAs and their surface attributes like surface integrity, hardness, generated layer, and residual stress. Also its behavior with various kinds of cutting fluids and dissimilar sorts of cutting tools. However, the behavior and the machinability of shape memory alloys are concerned underneath the variety of conventional, non-traditional, and micro-operating including the consequence of different input factors such as cutting velocity, rate of feed, depth of cutting, style of used coolants, and the variety in the coating types that submitted for cutting instruments.

2. MACHINING OF SHAPE MEMORY ALLOYS (ŞEKİL HAFIZALI ALAŞIMLARIN İŞLENMESİ)

The phrase machining indicates removing undesired substances from the specimen to provide it the wanted appearance with assistance of cutting instruments. Undesired metallic element is discharged from the specimen in a style of chips that are created because of strain hardening of the compound when there is a connection between the cutting tool-specimen, as long as there is a relative movement among the tool and the specimen. Like these manners are regularly known as traditional machining methods, that involve milling, turning, and drilling. The extra, quite-popular manner described by grinding, where cutting operations could be done by abrasive performance, displays much weightage in traditional machining production. Different non-traditional machining processes such as Electro-Discharge (EDM), laser, Water Jet (WJM), and Electrochemical Machining have not owned a connection between the specimen and the shaping tool. There are no cutting tools as in the traditional methods; these methods employ chemical or thermic power for processing. As a result, work hardening or strain hardening, performing quality and cost aims is quite a complicated task. One of the essential matters that require to be dealt with while machining processes is the amount of material that sound be removed besides cutting tool wear. Hence, by studying the influence of engineering machining of SMAs, the subsequent sections illustrate the traditional and non-traditional machining methods to which shape-memory materials might be administered. Viewpoints linked with the operation manner similar feed rate, forming tools, and operation circumstances are analyzed, reviewed, and the results are displayed.

2.1. Traditional Machining of SMAs (Şekil Hafızalı Alaşımların Geleneksel Yöntemle İşlenmesi)

Much of the operation carried out on traditional machining of SMAs concerns Nitinol and Titanium or ternary compounds of NiTi; therefore, the knowledge given turns about those elements. An initial review of the machinability characteristics of NiTi mixtures could penetrate the phenomes that appear when Titanium and Nickel shape memory elements are examined. Titanium's reactivity with the low heat conductivity, shaping tools, significant strength at raised heats, and soft elastic modulus effect in extended temperatures at the tool and chip interface which lead to high dynamic loads, specimen distortions, and decreased tool life [8]. Nickel-based metals and superalloys, similarly to Titanium compounds, exhibit large strength and are supposed hard-to-machine ores. Furthermore, because of their austenitic pattern, nickel superalloys performance hardens immediately while machining and conduce to create connected chips that are unmanageable during operations [9]. The consequences of the earlier characteristics guide to fast flank wear, and notching, and cratering, so they depend on the tool element and the operation circumstances involved.

All the challenges summarized for NiTi alloys individually apply for NiTi alloys. Besides, critical hallmarks of shape memory alloys as pseudoelasticity, pseudo-plasticity, and high ductility of Titanium and Nickel alloys force more challenges during machining these compounds, driving not simply to fast shaping tool defeat but further to lower specimens' quality as a result of extreme burr generation, adhesions on the surface of the shaped part and changes in the microstructure of the sample substance. Operation of SMAs in Circumstances of high stress, strain rates, and temperatures causes surface and sub-surface defects like the creation of a white layer and the rise of microcracks [10].

2.1.1. Turning process (Tornalama işlemi)

Weinert et al. [11] used several tools, including indexable coated, uncoated cemented carbide, CBN, PCD, and ceramic inserts, to operate a shape memory alloy Ni-Ti by turning machine. However, they realized that coated cemented carbide instruments exhibited decreased wear. Further, instruments with eight various bands of TiAlN, TiCN achieved better than yet instruments with more complex coatings such as TiB2. However, uncoated cemented carbide instruments offer massive wear, and ceramic cutting devices cannot machine Nitinol-Titanium mixture irrespective of parameters of cutting. Furthermore, Notch wear was visible on PCD instruments, resulting in unanticipated tool damage, and the wear of CBN instruments was higher than cemented carbide instruments, moreover, in combination with their unusual cost, they were considered as unfavored. Concerning the cutting variables, it was determined that coated cemented carbide instruments with more powerful cutting speeds could be used to machine NiTi as recommended by the related literature and the instrument providers. As a result, the wear of the tool was lessened, and the surface condition is improved at a cutting velocity of (100 m/min).

The turning operating of (β-Ni-Ti) mixture was achieved by wet-dry situations with different machining speeds by Weinert et al.[12]. According to their laboratory issues, the investigators suggested distinguishing three planes for explaining the machinability of the mixture. Through quiet operating velocities equal to or less than (60m/min), as a result, the operating forces were very high, which causes in a case in tool wear including elevated notch wear. Utilizing emulsion as lubricant reduced operating forces and the wear of the tool just for the low cutting velocity rate of (20m/min). During the next step, when operating speeds were ($60 \leq VC \leq 130$m/min), the wear of tool and the operation forces seemed to be unchanged by altering the quickness rate and changing cooling liquid. In the third stage, when the forming speed is higher than (130m/min), the wear and the resulted forces grew significantly for dry states. As a result of its special ductility, a usual burr generation happened when operating NiTi alloys. With the starting of the cutting, the breadth of the burr was lower than the rate of feed, then suddenly it developed quickly until it achieved greater amounts. Nevertheless, the top of burr could create up over numerous millimeters. They noticed that the depth of cutting shall be defined to the tool's cutting-edge radius. Meanwhile, high notch wear occurs when the depth of cutting passes the radius of the cutting-edge. Also, during the turning of TiNi alloy, the poor chip breaking was an extra obstacle.

Ezugwu et al. [13] studied the impact of powerful-pressure coolant applied during machining of (Inconel 90) among carbide inserts (K10 grade) of ISO designation (CNMA & CNMP 20408). The running speeds of (55m/min) with feeds of (0.127 mm/rev) were utilized below both regular and powerful-pressure coolant supplies. Overall examination results explained that more extended tool lives could be obtained among the regular coolant supply than the huge-pressure coolant equipment. Besides, the raised-pressure supply overcame the early breakage of the carbide tools with more powerful velocity and depth of cut; as a result, compared to standard coolant rationing, the tool life is increased. Furthermore, extreme-pressure coolant rationing produced tiny-segmented chips that might be effortlessly removed. In most states, the predominant mode of tool failure was Notching. Tool rejection under powerful-pressure coolant equipment was caused by flank wear in the issue of sharp-nosed tools (CNMA & CNMP 20408). Broad-nosed tools (CNMA & CNMP 1204 12) may have an extended tool life than sharp-nosed tools, which might be caused by the heightened strength of the big nose radius.

A machining test related to the surface integrity characteristics of an Inconel 718 was conducted on a CNC lathe machine by Pusavec et al.[14]. However, the machining operation was handled by utilizing four various coolants, namely: dry, minimum quantity lubrication machining (MQL), cryogenic machining, and the last is an amalgam of cryogenic. After the experiment, it was determined that the cryogenic machining manner achieved the surface with the lowest roughness condition. Additionally seen that cryogenic machining fairly changes the final product microstructure and produces the most downward plastic deformation compared to the other operations on the specimen's machined surface.

Zlatin et al. [15] investigated the operating properties of nickel-based heat-resistant alloys. The high work hardening and the abrasive carbides in the nickel-based microstructure were the primary causes for difficulty operating. Moreover, the determination of a suitable rate of feed is an essential factor, however, was seen that the most extended tool life could be gained from rates of feed ranging in (0.18-0.25 mm/rev). It is a middle ground among the negative impacts of small and elevated feeds.

In other research, Rahman et al. [16] investigated how instrument geometry affects tool life (coated cemented carbides). Equally (PVD, CVD) coated insertions were examined through various feeds of cutting and speeds. Outcomes displayed that with a raise in the side cutting edge angle (SCEA) from (-5° to 15°), and further up to 45°, there was a notable improvement in the life of the tool, though the surface finish SR is negotiated. PVD acts more favorably than multi-CVD-coated carbides. The suitable cutting situation is 45° of (SCEA) with a 30m/min operating speed and feed rate of 0.2 mm/rev.

Arunachalam et al. [17] reviewed the influence of various chip breaker range on the life of the tool by using coated cemented carbides. However, outcomes exhibited that those chip breakers did not cause many effects on the instrument life. Furthermore, events pointed out that coated carbides' acting is more valuable at (SCEA) of 15° than at 45°, promoting Rahman et al.'s findings [16].

2.1.2. Milling process (Frezeleme işlemi)

On the other side, Guo et al. [18] analyzed the milling of a NiTi alloy that employed for biomedical purposes. The authors carried out quasi-static and split-Hopkinson pressure bar compression experiments to estimate the mechanical characteristics of the element. The results illustrated the high strength of the substance beneath static and dynamic statuses registered that NiTi is more difficult to be machine than Ti or Ni-based superalloys. However, they utilized coated carbide inserts, and once again, shorter tool life was recognized compared to milling conventional elements. Furthermore, a rise in feed rate guides to an increment in surface roughness; nevertheless, a high surface roughness resulted from a minimal rate of feeds, and by association, a growing in the flank wear of the instrument also raises the surface roughness. Besides, the high ductility of Ni-Ti is bound for large outlet burrs. Eventually, from the subsurface microstructure and microhardness research, possible to say that tinier rates of feed cause a thicker white layer, suggestive of the phase transformation resulting from extreme loading and temperatures.

Ezugwu et al. [19] tested titanium (Ti6A14V) and nickel-based alloys (Nimonic75 & Inconel 718) at various cutting conditions by applying K20, K40, and P25 of carbide inserts to compare their performances. Outcomes determined that the K20 grade was more reliable than the K40, and P25 because of the compressive strength and comparatively high hot hardness of the K20. Furthermore, K20 has high abrasion resistance due to the low cobalt content. Also, variables such as the low coefficient of thermal expansion and high thermal conductivity of the K20 helps in a more excellent performance by diminishing the thermal shock. In most cases, the dominant forms of the failure of tool are the fracture and chipping. Speeds of 23 m/min, feeds of 0.08 mm/tooth were the optimum cutting situation for (Inconel 718), and the best operating condition for (Nimonic75) achieved by a speed of 27 m/min, feeds of 0.08 mm/tooth. Additionally, sequences recorded that titanium alloys were more manageable than the Inconel 718 & Nimonic75 to be machined, while the most difficult was the (Inconel 718). Ezugwu et al. [20] investigated milling cutting experiments for (Nimonic75) combination utilizing two kinds of cutters: a 70° bevel cutter carbide inserts (P40) also a 45° path angle cutter carbide inserts (K20 & K40). As in the previous study, the K20 offered more remarkably due to their enhanced characteristics than the others. The 70° bevel cutter usage P40 grade was achieved excellently with an unusual tool life of 86 min.

Widespread analysis about the end milling of (Inconel 718) has been held, offered through Alauddin et al.[21], [22] studied the milling operations were by utilizing K20 carbide to investigate cutting requirements, surfaces roughness, and tool life. Of the cutting inspections was seen that the life of tool ranges from 5 to 9.5 min could be reached at speeds of 19.32 to 29 m/min and feeds of 0.091 mm/ tooth with an axial depth of cut 1.0 mm. Furthermore, cutting forces decline by growing cutting speed while forces rise by either a rising feed or an axial depth of penetration. Alauddin et al. [23] performed tool life experiment throughout end milling operating of Inconel 718. Conclusions recorded a notable variation in the life of tools throughout up and down cut end milling, whereas the life of tools in down-cutting was more useful than in up-cutting.

Some thoughts concern the generation of micro-components using milling [24, 25]. The micro-milling operation has been chosen as complicated geometries needed for micro components in micro-devices and medical treatments. The researchers reviewed the appropriate cutting circumstances and the properties of shape memory alloy machining, such as burr creation during micro-scale; a direct downscaling was unlikely because aspects might vary compared to the methods reviewed in the earlier statements. It showed that micro-operating is as challenging as traditional operating methods, if not even more, where the ranges of appropriate operating circumstances were relatively poor.

2.1.3. Drilling process (Delme işlemi)

Machining shape memory alloys by employing a drilling process impact the tool wear and surface integrity. Weinert et al. [26] drilled NiTi alloy by utilizing cutting tools coated by (TiCN/ TiN) also they submitted a lubricant and inner coolant during machining to reduce the wear of tool. However, it was observed that the high cutting speeds lead to excessive tool wear while the suitable speed for the drilling process was remarked at 30m/min. with improved surface roughness up to 5.9μm. Drilling of tubes made off Ni-Ti alloy that utilized in production parts for medical applications was studied by Petzoldt et al. [27]. They claim that the hardening of work in a subsurface region has an effect during this machining procedure is held. As a consequence, the hardness of the element was built during low cutting rates or high feeds rate. Moreover, no advantages have been seen using coated rather than uncoated cemented carbide. The picking of suitable spindle speed and cutting speed is demanded during drilling operation basically for getting better surface attributes. Mousavi et al. [28] informed the functions governing the drilling of SMAs via fuzzy logic methods. For the drilling of NiTi, a tool diameter of 1-30 mm and a depth of 0.25-3.0 mm were chosen. The range of 20-50 m/min for cutting speed, and 20-6000 rpm for spindle speed were the best machining factors during the drilling process for better surface integrity. Drilling outcomes can be improved by employing tools with tiny diameters. The composition and the sort of drilling tools also influence the drilling operations of SMAs. However, these factors have been researched by Lin et al. [29]. Two compositions of shape memory alloys (Ti_{50} Ni_{50} and $Ti_{49}Ni_{51}$) were drilled with three sorts of twist tools namely HSS, HSS + TiN, and TC under nine surroundings of rotational velocities, and feed rate. The HSS + TiN coated drills displayed more acceptable performance for drilling NiTi when it is compared to other instruments because of their elevated hardness and high wear resistance.Moreover, the composition (Ti_{50} Ni_{50}) exhibited better surface integrity of hardness near the drilled hole compared with other elements because of increased plastic deformation of NiTi as illustrated in (Fig. 4).

The necessity of SMAs micro-sized applications is appearing in medical areas such as grooves, micro-slots, and forms with dimensions smaller than 0.5 mm. Because of the superior mechanical features of SMA, it makes a (NiTi) micro-devices a big challenge for designers. As a result, micromachining techniques like micro-drilling are employed to organize these micro-devices. Biermann et al. [30] utilized single-lip and twist drills during their micro-drilling process. They claimed that tool wear increased during single-lip drilling due to adhesion caused by friction between the hole wall and guide pad of tool. The adhesive could be reduced by using a smaller tip angle or by submitting a layers coating of TiN or TiAlN, which assists in declining the friction. On the other hand, the twist drills show no sign of adhesion wears. This is owing to their symmetric construction, that lacks a radial force feature, as well as TiAlN coating. The proper selection of cutting speed is also required for the most optimum utilization of drilling instruments. The velocity shall not be more than Vc= 30 m/min. Moreover, twist tools at a diameter of 1.0 mm attained to a depth of 1200 mm, while single-lip instruments only had a deep of 420 mm.

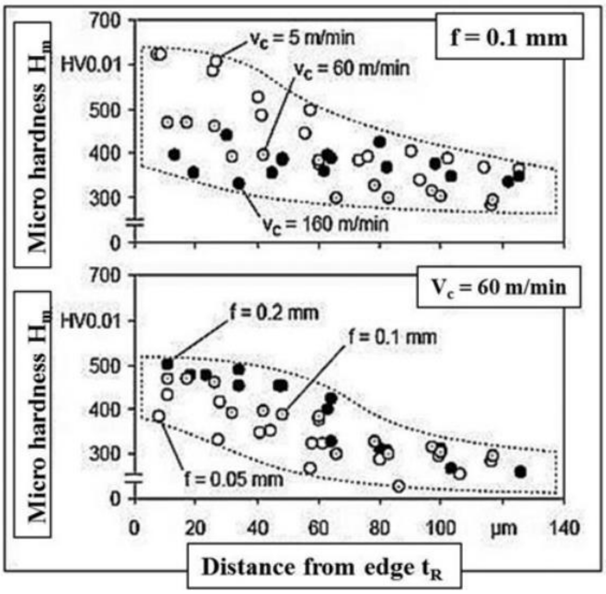

Figure 4. Microhardness in subsurface area while drilling-NiTi under separated cutting parameters (Farklı kesme parametreleriyle delme sırasında yüzey altı bölgesinde mikro sertlik-NiTi) [29].

2.1.4. Grinding process (Taşlama işlemi)

Grinding is typically one of the last finishing techniques on a manufacturing plan; therefore, measurement accuracy and surface quality must constantly be maintained. Roughness of surface and microstructure are being employed to assess the tool efficiency as well as the grinding features of particular elements. Tao et al. [31] employed three types of Ni-Ti+TiH_2 compositions with various wt.% as shown in Table 1. In order to measure the surface roughness and the specific energy during grinding machining.

Table 1. NiTi alloy chemical composition and its properties (NiTi alaşımının kimyasal bileşimi ve özellikleri)

Specimen No.	Ni	Ti	TiH2	Pore rate	Density $(g \cdot cm^{-3})$
1#	55.1	44.9	0.0	37.56 %	4.09
2#	54.9	35.8	9.3	39.39 %	3.97
3#	54.4	17.8	27.8	39.54 %	3.96

The subsequent three grinding settings were used for the process, namely wheel acceleration of 17.5, 20.0 22.5, 25.0 m/s, depth of 0.01~0.09 µm, and specimen infeed rate of 0.3, 0.6, 0.9, 1.2 m/min. However, they claimed that during a very shallow cutting depth of single active grain, the first specimen showed the highest specific energy while the lowest was exhibited by the second sample. When the grit depth of the cut has been elevated to around 0.06 µm, there has been little variation between the different forms of alloys. In addition, as the grit depth of cutting increases, a quite identical tendency can be seen in alloys. Because of the weak grain wear, roughness values climb dramatically with increasing cutting depth, as shown in (Fig. 5).

Smala cutting depth | Middle cuting depth | Large cutting depth

Figure 5. The ground surface's microstructure (Zemin yüzeyinin mikro yapısı) [31].

When the depth of cut was over 0.08 µm, a higher surface roughness has been notalised with significant wear of the abrasive grits' cutting edges, which further limits the capacity to keep its cutting ability.

Production of Ni-Ti alloy in a form of powder by utilizing a high-energy ball grinding approach (Pulverisette 7 premium line) was analyzed by Goryczka et al. [32]. The research was split into two groups. The foremost one was 10 g ground for 100 h, then ground 20 g for 100, 120, and 140 hours**.** The amount of the phase increased, and the intermediate size of the agglomerates was grown to 700 µm by expanding the sample mass to 20 g and expanding the grinding duration up to 140 h, while the average crystallite size was lowered to just a few nanometers range. Micro-strains have also been minimized as grinding duration was extended. In addition, Mizutani et al. [33] studied the surface quality of Ni-Ti SMA operated by the electrical grinding method (EG-X) based on Electrolytic In-process Dressing grinding in comparison to Thermal Oxidation (TO) surface treatment. In comparison to the standard TO treated surface, the outcomes demonstrated that the electrical grinding process (EG-X) could provide an elevated surface quality.

2.2. Non-Traditional Machining of SMAs (Şekil Hafızalı Alaşımın Geleneksel Olmayan Yöntemle İşlenmesi)

This section of operation regards techniques of elements forming that involve no connection between tools and specimens. As a result, the wear of tools is lessened or wholly diminished, whereas surface integrity could be frequently concerned because of thermal loading. These techniques, such as electric discharge (EDM), laser operating, wire-electric discharge machining (WEDM), (WJM), and electrochemical machining, are extensively applied to SMAs machining particularly for parts with minimal dimensions.

2.2.1. Electrical discharge machining (Elektro erozyonla işleme)

The highly complicated forms could be shaped using high accuracy by electric discharge machining (EDM). In this technique, discharge sparks are employed to meltdown and evaporate the element; a dielectric liquid is also utilized as a medium among the workpiece and electrode [34]. Daneshmand et al. [35] researched the actions of Ni-Ti beneath different electric discharge machining (EDM) parameters. The parameters of (EDM) were arranged such that the pulse on/off time, the discharge current, and voltage. However, the outputs that were examined, namely material removal rate (MRR), rate of tool wear, surface roughness (SR), and relative electrode wear. During this mode, was seen that the most meaningful parameters that alter the (MRR) are the pulse current and the pulse on time. At same time, growth in those two variables grows the element removal rate. Additionally, the growth of pulse current causes an increase in surface roughness. Also, they found that the rate of tool wear raises along with a rise in pulse on time just up to a particular threshold, after which the rate of tool wear begins declining. Besides, they also remarked that by growing the pulse off time, MRR and SR are reduced. Extra investigations on the impact of the machining circumstances during EDM tests on the surface roughness (SR) have been done [36, 37]. These analyses showed that the rise of the working energy leads to worsening surface roughness.

Additionally, a thicker and more irregular melting area was caused by the growth of current, voltage, and pulse on time. Surface roughness SR also depends on the tested material's thermal features, such as melting point and thermal conductivity.

Gangele et al. [38] employed Taguchi’s technique to optimize the impact of machining parameters on the surface roughness of Ni-Ti alloy through operating by the EDM method. They noted that the most critical influence on surface roughness was shown to be the pulse-off time. In addition, Jatti [39] applied Taguchi's analysis during EDM machining for three shape memory alloys (NiTi, NiCu, BeCu) to learning the influence of operational factors such pulse on/off duration, gap current/voltage, and electrical conductivity on the output responses like tool wear rate (TWR), material removal rate (MRR). The outcomes revealed that by increasing the gap current, and workpiece electrical conductivity, the MRR increases, although the increase in the gap voltage causes a decrease in MRR. Additionally, the low electrical conductivity of the workpiece yields to lower TWR because of increased heat transmission from tool to workpiece. But, with an increase in gap current, TWR rises. Other ways, the tool wear rate is unaffected by pulses off time or gap voltage, according to the findings. Additionally, Abidi et al. [40] operated a multi-objective genetic algorithm (MOGA-II) to enhance the weights of micro-electrical discharge machining (MEDM) of Ni-Ti alloy to produce superior MRR with great surface condition. Capacitance and electrode material are two critical considerations that influence the (MEDM) process. It was noted that the brass electrode had a higher material removal rate than the tungsten electrode, as well as more tool wear and worse surface quality. On the other hand, the tungsten electrode demonstrated exceptional micro-hole quality as well as a low tool wear rate. Daneshmand et al.[41] explored the impact of tool rotational, AI_2O_3 powder, current, pulse on/off time, and voltage during machining NiTi-60 SMA by the EDM method. And thy pointed out that the AI_2O_3 powder lowers the kinetic energy of ions, and tool rotation can limit the high spread, reducing tool wear. The AI_2O_3 powder loosens plasma channels quicker, and tool rotation reduces pulse off time, grows material removal rate, and reduces processing costs. The material removal rate may increase by raising current intensity and pulse on time while reducing pulse off time and voltage. With high current intensity and voltage, a reduced tool wear rate may be achieved while expanding the pulse on/off time. Surface toughness is also altered by current intensity, voltage, and pulse on/off time. Fu et al. [42] utilized EDM, and laser operations to compare the recast layer of Nitinol shape memory alloy. They revealed that the Electrical discharge machining caused a non-uniform and containing voids recast layer compared to laser cutting. In comparison to EDM, the melt flow formed columnar patterns, which resulted in lower surface integrity of the operated part produced by laser cutting. In addition, EDM created a more rigid recast layer than laser method due to the production of oxides and varied quenching rates.

2.2.2. Wire electrical discharge machining (Tel erozyonla işleme)

There is another type of EDM pronounced as the wire electro-discharge machining WEDM. However, in this method, the substance is consumed from the specimen by employing several sparks caused by a wire. Hsieh et al. [43] examined the operating properties and shape recovery capability of (Ti-Ni-Zr/Cr) SMAs developed with traditional tungsten arc-melting by employing WEDM. They noticed that raising the peak current and pulse on-time improved the SR, also, resulting in higher MRR. The surface quality is determined by the volume of shifted materials on the operated surface, the wire substance, flushing pressure, and dielectric fluid. In another study, R. Chaudhari et al. [44] explored the surface integrity of Nitinol SMA that was machined by the WEDM method. They have chosen the operating factors as pulse-on, off time, and current. Whereas the material removal rate, SR was determined as output parameters. As a result of their examination, they recognized that to achieve a higher material removal rate, elevated discharge energy is needed, which could be gained by increasing the rates of current, and pulse on time. Besides, to obtain a lesser surface roughness (SR), lower discharge energy is demanded that might be performed by decreasing the values of the pulse-off time. Moreover, Praveen et al. [45] examined the influence of current, and pulse on/off time on (MMR) during operating of Cu-Al-Mn

(CAM) SMA by utilizing (WEDM) method. It was discovered that the MRR could be enhanced by raising the current and pulse on time. In contrast, the rise in Pulse off time produces a decline in the MMR measure.

Moreover, the consequence of WEDM factors on the surface integrity of Ti-Ni-Co shape memory alloy was examined by Soni et al. [46]. Pulse on-off duration and servo voltage were the essential factors in Ti-Ni-Co WEDM machining. When the pulse rate was raised over time, the MRR went up, and vice versa. Surface quality was found to be poor in the presence of microvoids, micro-cracks, and micro globules when a specific combination of high pulse on time and low servo voltage was used. The recast layer's minimal thickness was observed by extreme servo voltage and little pulse on time.

WEDM operations were further reviewed by Soni et al. [47] studied the most suitable setting of the WEDM input factors to gain the best outcomes for the material removal rate, and surface integrity of (Ti_{50} Ni_{45} Co_5) SMA created using a vacuum arc melt process by the usage of optimization techniques, i.e., Principal Component Analysis (PCA) and Grey Relational Analysis (GRA). In the present study, the suitable setting to obtain higher MRR, and better SR could be fulfilled by applying 125µs, 35µs, and 40V of pulse on/off time, and servo voltage respectively. Bisaria et al. [48] employed WEDM to investigate Ni-rich NiTi alloy's mechanical properties and surface integrity. Spark gap voltage and on-off pulse duration have a big impact on surface roughness and cutting efficiency. By raising the pulse on time and decreasing the pulse off time, surface roughness and cutting efficiency were improved. Many microcracks, craters, voids may be seen on NiTi's surface. The XRD investigation of the NiTi surface is shown in (Fig. 6).

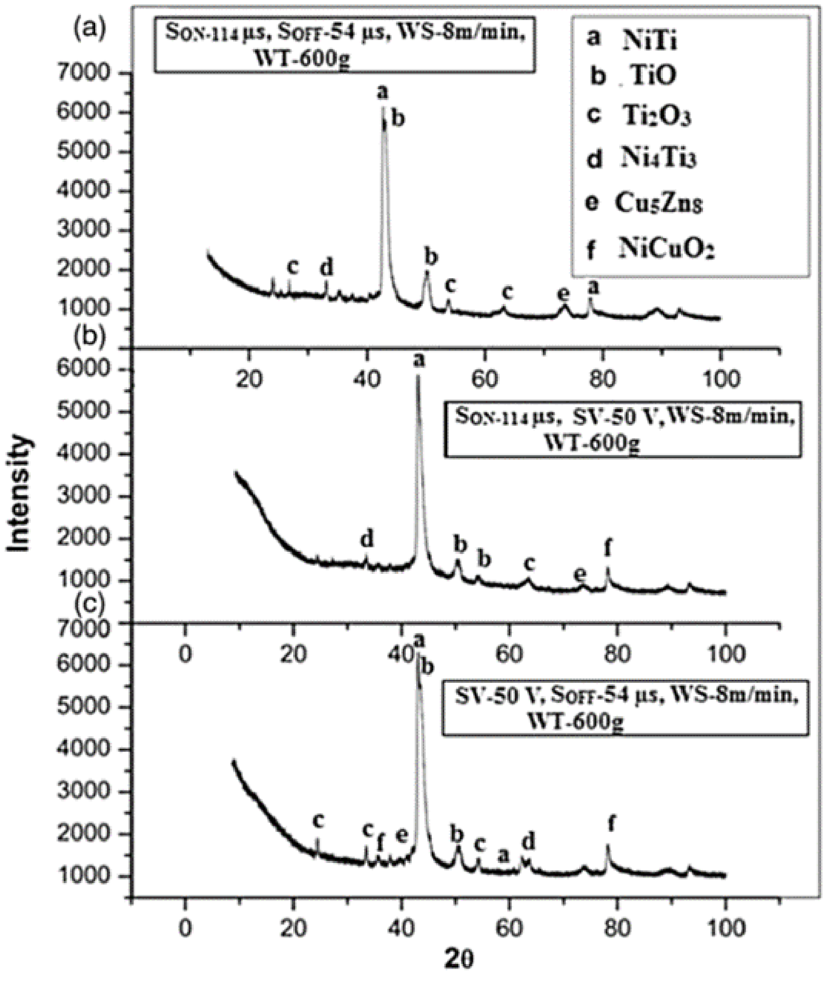

Figure. 6. XRD analysis of NiTi's surface. a) 35 V spark gap voltage; b) 52 µs pulse off time; c) 125 µs pulse on time WT: Wire tension, WS: Wire speed.(NiTi yüzeyinin XRD analizi. a) 35 V kıvılcım aralığı voltajı; b) 52 µs darbe kapatma süresi; c) 125 µs darbe süresi WT: Tel gerilimi, WS: Tel hızı) [48].

Due to atom diffusion from the wire and dielectric, the foreign element was carried to the recast layer. TiO, Ti2O3, Ni4Ti3, Cu5Zn3, and NiCuO2 are some of the chemical components and oxides formed by these elements. The chemicals on the machine surface substantially support the EDS findings. The development of Ni and Ti oxides was primarily caused by the strong reactivity of Ni and Ti atoms. The formation of oxides and quenching processes contribute to the hardness of the surface.

2.2.3. Laser machining (Lazer işleme)

Shape memory alloys may also be operated using lasers. Laser operation creates a heat irritated region on the specimen body, similar to electrical discharge machining. Machining of TiNi SMAs was investigated using a femtosecond laser by Li et al. [49] examined the effect of tool path and technique on the manufacture of precision segments. They found that femtosecond laser machining is a primarily thermal mechanism that creates a high ablation rate and notable recast layer. As a result, Lesser beam produces superior cutting quality at a lower cost. Moreover, by using appropriate sideways motion, high quality, recast-free, and exact parts might be created. Too, Tung et al. [50, 51] presented machining of SMAs utilizing laser operating for medical purposes. However, it was announced that the mechanical features would be enhanced, but the private features of SMAs like large hysteresis is tricky. Laser machining tolerances and electropolishing tolerances change the dimensions and geometry.

2.2.4. Water jet machining (Su jeti ile işleme)

Water jet machining (WJM) was also investigated as a non-traditional approach for machining SMAs. Kong et al. [52] described the plain and abrasive (WJM) properties of (Ti-Ni) SMAs. Nevertheless, the investigation showed that abrasive (AWJM) operating has more excellent depth performance in the milling process than (PWJM) running. Also, (AWJM) has a higher thermal impact than (PWJM) because of the increased influence speed of abrasive particles. Temperatures exceeding the austenite transition have been achieved as a result of a compact field collision with a high-velocity abrasive particle, causing the material to melt. This might have an effect on the transition from martensite to austenite. The cracks have started to propagate, and they may originate in the Ti2Ni range rather than the Ti-Ni range. They recommended that the (AWJM) might be a valuable and efficient approach for elements having a complicated crystal structure and phase transition. Frotscher et al. [53] reviewed the different techniques for forming fluffy sheets of Nitani-Titanium-based. However, two methods were employed in their analysis, micro milling and (WJM) operating. However, they determined that in terms of operational value, the cutting time (WJM) process was pretty good. But for the medical application where remarkable accuracy and correctness are needed, their electropolishing was required. Hence after their operations, they got surface with sufficient precision, but the burr resides in the machined part, and de-burring is wanted.

2.2.5. Electrochemical machining (Elektrokimyasal işleme)

Lee et al. [54] served on multiple machining situations to gain the steady electrochemical polishing method for Nitinol based SMAs. They applied acid and the neutral electrolyte in the operating, and they discovered that acid electrolyte is fitting for slow down and accurate operating. At the same time, the neutral electrolyte does not provide precision machining; it generates holes on the nitinol surface. With the most prominent shape, the surface of Nitinol was polished up to a roughness of 0.37 μm, and an acid electrolyte was employed. The adjusted current was 18A, and the pulse off/on time were 200μs and 800 μs. Eventually, the surface roughness of 0.31 μm was achieved. The pulse electrochemical machining has been acquired by Frensemeier et al. [55] to examine the two-way shape memory impact on the Ni-Ti alloys. However, it was found that the more fitting way to operate the (Ni-Ti) alloy is the pulse electrochemical machining because it generated a microstructure that was distortion- and thermal-damage-free and did not oxidize or deform. In pulse electrochemical machining, the use of grooves and hole tools allows for the formation of various protrusion structures on the surface of Ni-Ti. Ao et al. [56] utilized water-free electrolyte (ethylene glycol–NaCl electrolyte including ethanol) during electrochemical operating to create the microstructure of shape memory alloy (Ni-Ti). They discovered that an ethanol-immersed electrolyte solution could dissolve $TiCI_4$ and so reduce the formation of the oxide. The electrolyte solution containing 20% vol. ethanol produced the best microgroove surface quality. An excessive quantity of ethanol also harmed surface quality and the machined surface.

3. SUMMARY OF TRADITIONAL AND NON-TRADITIONAL MACHINING
(GELENEKSEL VE GELENEKSEL OLMAYAN İŞLEME ÖZETİ)

The formability of SMAs during traditional operations is controlled by the processing settings, coating, and cutting fluids, all of which are illustrated in Table 2. Unconventional machining procedures should be used to address several challenges in the traditional machining process of shape memory alloys, and their recognized specifics are presented in Table 3.

Table 2. Traditional operations of SMAs (SMA'ların geleneksel işlenmesi)

Authors	Material	Tool type	Process	Coolant	Result
K. Weinert, et al. [11]	Ni-Ti alloy	Coated, uncoated cemented carbide, CBN, PCD, and ceramic inserts	Turning	--	It was determined that the coated cemented carbide instruments with cutting velocity of (100 m/min) improved surface condition and lessened the wear of tool.
E. Ezugwu et al. [13]	Inconel 90	Carbide inserts (K10 grade)	Turning	Regular and high-pressure coolant	Examination consequences explained that more extended tool lives could be obtained among the regular coolant supply than the huge-pressure coolant equipment.
F. Pusavec et al.[14]	Inconel 718	--	CNC turning	Dry, MQL, cryogenic, and Amalgam of cryogenic	The cryogenic machining manner achieved the surface with the lowest roughness condition
M. Rahman et al. [16]	Inconel718	(PVD, CVD) coated	Turning	--	Outcomes displayed that with a raise in the side cutting edge angle (SCEA) from (-5° to 15°), and further up to 45°, there was a notable improvement in the life of the tool, though the surface finish SR is negotiated.
E. Ezugwu et al. [19]	(Ti6A14V) and (Nimonic75 & Inconel 718)	K20, K40, and P25 of carbide inserts	Milling	--	The K20 grade was more reliable than the K40, and P25 because of the compressive strength and comparatively high hot hardness of the K20.
E. Ezugwu et al. [20]	Nimonic 75	70° bevel cutter carbide inserts (P40) also a 45° path angle cutter carbide inserts (K20 & K40)	Milling	--	The K20 offered more remarkably due to their enhanced characteristics than the others

M. Alauddin et al. [23]	Inconel 718	Uncoated tungsten carbide inserts	End milling	Dry conditions	The life of tools in down-cutting was more useful than in up-cutting.
Weinert et al. [26]	Ni-Ti alloy	Tools coated (TiCN / TiN)	Drilling	Lubricant and inner coolant	The high cutting speeds lead to excessive tool wear while the suitable speed for the drilling process was remarked at 30m/min. with improved surface roughness up to 5.9μm.
D. Biermann et al. [30]	Ni-Ti alloy	Single-lip and twist drills	Micro-drilling	--	Tool wear increased during single lip drilling due to adhesion caused by friction between the hole wall and the guide pad of tool. The twist drills show no sign of adhesion wears.
Y. Tao et al. [31]	Ni-Ti+TiH_2	--	Grinding	--	When the depth of cut was over 0.08 μm, a higher surface roughness has been notalised with significant wear of the abrasive grits' cutting edges, which further limits the capacity to keep its cutting ability

Table 3. Non-traditional operation of SMAs (SMA'ların geleneksel olmayan işlenmesi)

Authors	Material	Process	Parameter	Result
S. Daneshmnd. et al. [35]	Ni-Ti alloy	EDM	Pulse on/off time, discharge current, and voltage	The most meaningful parameters that alter the (MRR) are the pulse current and the pulse on time. By growing the pulse off time, MRR and SR are reduced.
V. Jatti. [39]	(NiTi), (NiCu), (BeCu) alloys	EDM	Pulse on/off duration, gap current/voltage, and electrical conductivity	By increasing the gap current, and workpiece electrical conductivity, the MRR increases. The increase in the gap voltage causes a decrease in MRR. The low electrical conductivity of the workpiece yields to lower TWR.
M. Abidi et al. [40].	Ni-Ti alloy	Micro-electrical discharge machining (MEDM)	Brass and tungsten electrodes	The brass electrode had a higher material removal rate than the tungsten electrode, as well as more tool wear and worse surface quality.

S. Hsieh et al. [43]	(Ti-Ni-Zr/Cr) SMAs	WEDM	Peak current and pulse on time	Raising the peak current and pulse on time improved the SR, also resulting in higher MRR. The volume of shifted materials effect on the surface quality.
R. Chaudhari et al. [44]	Nitinol SMA	WEDM	Pulse-on, off time and current	To achieve a higher MRR, elevated discharge energy is needed, which could be gained by increasing the rates of current, and pulse on time. To obtain a lesser (SR), lower discharge energy is demanded that might be performed by decreasing the values of the pulse-off time.
H. Soni et al. [46]	Ti-Ni-Co	WEDM	Pulse on-off duration and servo voltage	When the pulse rate was raised over time, the MRR went up, and vice versa. Surface quality was found to be poor in the presence of microvoids, micro-cracks, and micro globules when a specific combination of high pulse on time and low servo voltage was used.
H. Soni et al. [47].	$Ti_{50}Ni_{45}Co_5$ SMA	WEDM	Pulse on/off time, and servo voltage	Higher MRR, and better SR could be fulfilled by applying 125μs, 35μs, and 40V of pulse on/off time, and servo voltage respectively
H. Bisaria et al [48]	Ni-rich NiTi alloy's	WEDM	Spark gap voltage and on-off pulse duration	By raising the pulse on time and decreasing the pulse off time, surface roughness and cutting efficiency were improved.
C. Li et al. [49].	TiNi SMAs	Laser operation	Femtosecond laser and Lesser beam	The femtosecond laser creates a high ablation rate and notable recast layer. Lesser beam produces superior cutting quality at a lower cost.
M. Kong et al. [52]	TiNi SMAs	WJM	Plain and abrasive (WJM)	The (AWJM) might be a valuable and efficient approach for elements having a complicated crystal structure and phase transition.
E. Lee et al. [54]	Nitinol based SMAs	Electrochemical polishing	Acid and Neutral electrolyte	The acid electrolyte is fitting for slow down and accurate operating. The neutral electrolyte does not provide precision machining; it generates holes on the nitinol surface.

4. CHALLENGES AND OPPORTUNITIES (ZORLUKLAR VE FIRSATLAR)

In the modern-day, SMAs are new smart elements that could remember and come back to their original form by altering the surrounding conditions. Smart nature, biocompatibility, pseudo-plasticity, high corrosion, and wear resistance are some of the other unique and adaptable qualities of shape memory alloys. Because of their interesting properties, these elements have attracted plenty of attention and interest in a broad range of implementations during the last few years. Machining of these materials is required to be used in various applications. This machining could be performed in both traditional and unconventional ways. However, because of extreme strain hardening, high toughness, and large cutting pressures, conventional operating of SMAs is challenging, while during non-conventional operating the surface integrity and the accuracy of dimension are greatly enhanced as well as the machining time was reduced. Generally, each machining techniques have impediments that give advantageous or unfavorable results.

5. CONCLUSIONS (SONUÇLAR)

In this article review, several traditional, non-traditional technical techniques of Nitinol - Titanium-based alloys, over with their statements, have been briefly reviewed. Furthermore, the challenges of operation these SMAs typically were also studied. Multiple functions on non-traditional ways of machining such as EDM, WEDM, WJM, and AWJM have been highlighted in this review. Furthermore, the numerous machining methods and the work element were employed by the researcher have been displayed. Finally, subsequent conclusions are formed after reviewing the earlier mentioned literature:

- The significant obstacle faced in the operating of SMAs is the work hardening. However, the most suitable cutting speed range for carbide cutting tools in turning is (15-30m/min). In contrast, coated carbides could be utilized up to (50m/min). Also, the most extended tool life could be provided by ranges of feeds (0.18-0.25 mm/rev), and Positive rake angles are advised to be utilized. A surface with the lowest roughness could be achieved by the usage of a cryogenic machining manner. Usually, the most predominant failure forms are notching and flank wear. Traditional lubricant equipment appears to provide higher life of tool than high-pressure lubricant equipment at most operating situations.
- Cutting speeds (20-30 m/min) and feed rates (0.10-0.15 mm/tooth) were found to be the optimum for most nickel-based composites during milling. Nevertheless, the most applied cutting tool is (K20) carbide grades. Moreover, (CVD) coated instruments function better than (PVD). Down-cutting milling is considered as a favored system since it decreases the influence of work hardening. In addition, the dominant form of instrument breakdown for uncoated carbides is fracture and chipping, Despite the fact that tool crash is influenced by flank wear as well.
- For finer surface integrity in the drilling technique, the range of 20-50 m/min for cutting rate, and 20-6000 rpm for spindle velocity were the most reasonable operating factors.
- The velocity during the micro-drilling process shall not be more than VC = 30 m/min. Due to excessive work-hardening, a slower cut-rate produces chipping of the cutting edge. Faster speeds improve adhesive mechanisms once more.
- Generally, when machining shape memory alloys, the shared act of strain and fatigue hardening has a significant hardening influence and reduces the cutting rate. As a consequence, specimen integrity is reduced, and wear rate is too high, even with modified cutting settings and appropriate cutting equipment. Those properties could as well have an effect on the form of memory characteristics.
- The most substantial parameters that influence the rate of removed materials (MRR) during the EDM test are the pulse current and the pulse on time. In the meanwhile, an increase in these two variables grows the MRR. Additionally, the surface roughness (SR) can be impacted negatively by growing the pulse current and the pulse off time. Finally, structural modifications in the operated surface depend on the machining variables and the thermal features of the tested material, as melting point and thermal conductivity.
- The (EDM) manner is the predominant option in the non-traditional machining of SMAs. It is obviously visible from the number of investigations conducted on that process by various investigators.
- For femtosecond laser machining, the usage of lower beam turns higher quality in the cutting and lower economic cost.

- In comparison to micro-milling processes, the water jet machining was considered more useful in regard to the time of cutting, the thermal attraction of the specimen, and operation costs.
- Finally, high sensitivity to temperature variations, unique chemical reactivity, chip creation, and phase transformation over machining of SMAs considered as causes for engineers to select non-traditional techniques of machining these alloys, essentially to avoid high wastage of element during operating, also has confirmed to be extremely economical as opposed to traditional modes of operating.

6. FUTURE SCOPE (GELECEK KAPSAMI)

The greatest number of public procedures were investigated for traditional operations on SMAs utilizing the turning procedure within dry and cryogenic situations. The turning operation was documented to assess the formability and surface-integrity properties of SMAs like micro-hardness and surface roughness by adjusting cutting quickness, depth, and feed of cutting. During the traditional operation technique, narrow experimentations are implemented to enhance the microstructure and governance of the phase transformation temperature for SMAs.

The application of coating was being used to evaluate tool life and enhancement during the processing of SMAs materials by lowering the temperature during the machining process. Likewise, constructing a texture on the tool rake face is another way to dramatically increase the tool life. Textures may be utilized efficiently to minimize the heat while machining by withstanding the lubrication effect via its groove surface. Like these techniques are not made with SMAs processing. Similarly, research is needed to extend tool life through multilayer coating, tool holder, and insert improvements.

The earlier machinability investigations of non-traditional processes have been done on SMAs that are manufactured by various approaches such as traditional tungsten, vacuum arc melt techniques, melting and remelting methodologies. However, relatively limited studies have been published on the EDM and WEDM operations of shape memory alloys manufactured by powder metallurgy.

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