EXPERIMENTAL INVESTIGATION ON VARIATION OF OUTPUT RESPONSES OF AS CAST TiNiCu SHAPE MEMORY ALLOYS USING WIRE EDM

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Abstract: The present research study is emphasized on investigation of machining characteristics of TiNiCu shape memory alloys using Wire EDM and analyzes the effect of input process parameters on the quality of the machined surfaces. Complications associated with the machining process results in degradation of surface quality which notably is not avoidable. But proper optimization of the process parameters may help to achieve the desired or near-perfect quality of these machined products. Experiments were conducted as per Taguchi's L16 orthogonal array considering four input parameters at four levels of operation for $Ti_{50}Ni_{40}Cu_{10}$, $Ti_{45}Ni_{45}Cu_{10}$ and $Ti_{40}Ni_{50}Cu_{10}$ shape memory alloys. Zinc coated brass wire is used as the wire electrode in this study. Material removal rate (MRR) and surface roughness (SR) of the machined samples are considered as the output responses of these alloys. Optimum MRR and SR achieved while machining these alloys are 6.9431 mm3/min and 1.060 µm respectively for $Ti_{50}Ni_{40}Cu_{10}$. Keeping in mind the productivity of the machining process, formation of recast layer of these alloys are also studied for optimum material removal rate, which led us to the conclusion that $Ti_{45}Ni_{45}Cu_{10}$ alloy exhibits a surprising aversion towards formation of recast layer as compared to its counterparts. Also, $Ti_{45}Ni_{45}Cu_{10}$ displayed least average recast layer thickness (RLT) of 9.16 µm compared to 23.93 µm and 21.65 µm for $Ti_{50}Ni_{40}Cu_{10}$ and $Ti_{40}Ni_{50}Cu_{10}$ respectively. Pulse on time (120 µs) and wire feed (10 m/min) are found as the most influential Wire EDM process parameters against pulse off time and wire feed for an optimum material removal rate and for a better surface finish, pulse on time (100 µs) and pulse off time (30 µs) against servo voltage and wire feed respectively.

Key words: Wire EDM, Shape Memory Alloy, Material Removal Rate, Surface Roughness, Recast Layer Thickness

1. INTRODUCTION

1.1 TiNi based shape memory alloys

Shape memory alloys are more popular in present days compared to traditional materials among aerospace and biomedical industries. Among all of them, TiNi alloy system are studied most extensively due to their great features and are in use in number of commercial applications. One of the basic issues related to binary TiNi alloy is its uncontrollable actuation frequency and large hysteresis, which are not useful for precise applications. These group of alloys exhibit properties which are not so refined for sensitive actuation or sensing applications. The large hysteresis is a major drawback for this group of alloys. However, when Cu is introduced to replace Ni in TiNi binary alloy system, the property of the alloy changes drastically as observed by Ishida et al.[1]. Addition of Cu decreases the hysteresis of the SMA response. These results in the decrease of transformation strain, reduction in pseudoelastic hysteresis and also reduces the sensitivity of the martensitic start temperature to composition. The small hysteresis associated with the transformation makes TiNiCu alloys an ideal choice for actuators. Among the different compositions of TiNiCu, addition of 5 to 10 at.% Cu is preferred. Addition of Cu greater than 10 at.% is most preferred as suggested by Saburi et al., [2]. However, above 10 at.% addition of Cu, the ingot becomes brittle and hence it exhibits poor machinability which is highly unfavorable for manufacturing sectors. Therefore, in this present study the copper content is kept constant at 10 at.% for all the three alloys.

1.2 TiNiCu shape memory alloys

As justified in the above section, the alloys chosen for the current investigation are $Ti_{50}Ni_{40}Cu_{10}$, $Ti_{45}Ni_{45}Cu_{10}$ and $Ti_{40}Ni_{50}Cu_{10}$. Addition of copper in TiNi shape memory alloy results in refinement of grain size and improves its usability as an actuator material as compared to the binary TiNi alloy by constraining the hysteresis response. TiNi based alloys are praised for their excellent shape memory behavior and high pseudoelasticity. Good corrosion resistance, high hardness and toughness are also some of its mentionable characteristic properties. Although, these materials are blessed with desirable properties, machining of these alloys is not an easy task. Conventional machining processes are not suitable for these alloys as they do not yield required_surface finish and dimensional accuracy required in their applications. Since they are used for their unique mechanical properties, it has to be kept in mind that the metallurgical properties, dimensional accuracy and the surface finish of the final product has to be as per requirement. As reviewed by a group of researchers [3], WEDM is regarded as the most useful method to perform machining of TiNi based SMAs. However, WEDM has its own limitations. WEDM can be used to create complex profiles of varying size which are difficult with any other machining processes. Therefore, WEDM has gained wide acceptance in industries to fulfill their demands which also inspired to carry out the current study where a relative difference in effect of WEDM machining parameters on three different TiNiCu shape memory alloys has been studied and reported.

1.3 Wire electro discharge machining of TiNiCu shape memory alloys

Wire EDM has now become a widely accepted non-traditional machining process which finds its use over a wide range of manufacturing domains. The ability to machine any electrically conductive material irrespective of the mechanical property of the target material justifies the capability and suitability for the modern manufacturing hubs. Researchers have already studied the machinability of shape memory alloys using conventional machining methods which indicated poor results [4-6]. WEDM provides better surface finish and dimensional accuracy compared to traditional machining processes and especially for difficult-to-machine Titanium-Nickel alloys. However, the working mechanism of WEDM and quality of the final product varies upon the range of input parameters fed to the machine. The study of effect of input parameters of Wire EDM process on the overall quality of the machined product is a long researched topic among researchers[7-10]. Attempts have been made to thoroughly establish a firm relation between the input parameters and output responses. Due to the complex nature of machining process of WEDM, researchers have failed to establish a universal and decisive relationship. The thermal energy dissipated by the localized electrical spark causes vaporization of small quantity of material from the workpiece which are ejected and flushed away by the dielectric fluid jet, which eventually contributes to the material loss. Although wire electro discharge machining is an excellent alternative to other conventional techniques, there are other complications associated with this technique. Recast layer formation is one of the major drawback of wire electro discharge machining process which is addressed in the current investigation in the later sections.

2. EXPERIMENTAL DETAILS

2.1 Casting of TiNiCu shape memory alloy

In the current investigation, three different TiNiCu shape memory alloys have been used which are $Ti_{50}Ni_{40}Cu_{10}$, $Ti_{45}Ni_{45}Cu_{10}$ and $Ti_{40}Ni_{50}Cu_{10}$. They have been prepared by using Vacuum TIG Arc Melting technique. Titanium, Nickel and Copper are availed from commercial sources bearing purity of 99.97%, 99.98% and 99.89% respectively. These raw materials are procured in rod form for ease of cutting and weighing. They are cut into small pieces and placed into button crucibles weighing 8 grams each. Each sample was melted and re-melted six times each to maintain homogeneity to finally obtain a bar sample as shown in figure 1. The bar is obtained by melting of three buttons which is further considered for wire electro discharge machining study. Table 1 denotes the alloy composition, weight and density of the prepared alloys.

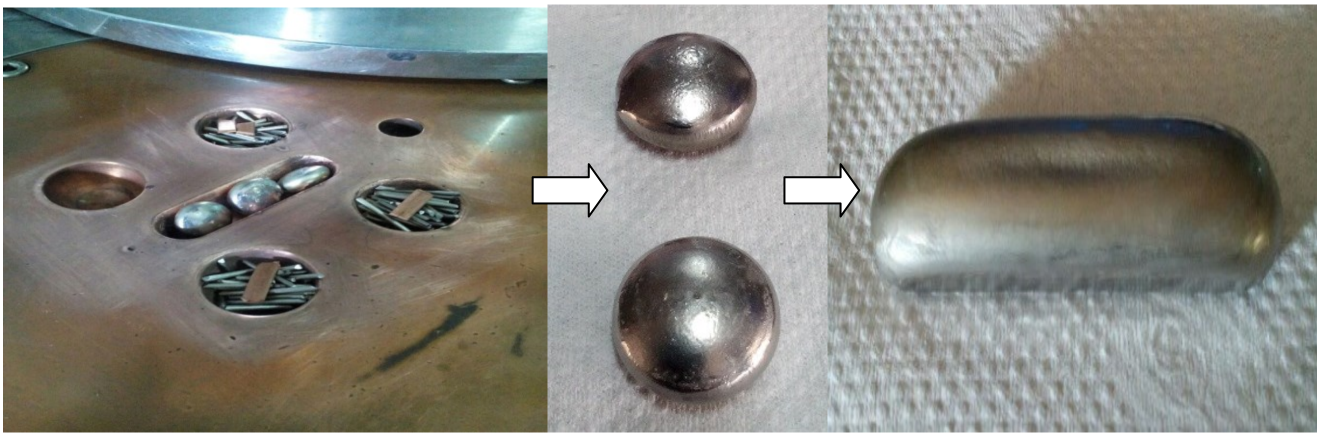


Fig. 1. As cast TiNiCu shape memory alloys

Table 1. Specifications of as cast TiNiCu shape memory alloys

Alloy (at.%)	Symbol	Weight (gms)	Density (gm/c.c.)
$Ti_{50}Ni_{40}Cu_{10}$	TNC11	8	6.14711
$Ti_{45}Ni_{45}Cu_{10}$	TNC12	8	6.36003
$Ti_{40}Ni_{50}Cu_{10}$	TNC13	8	6.58823

2.2 Wire Electro Discharge Machining

Wire cut EDM machine, ELPULS 15, manufactured by Electronica India has been used in the current study to machine the ternary TiNiCu shape memory alloys. Zinc coated brass wire of diameter 250 µm was used as the wire electrode. De-ionized water is used as the dielectric fluid in this study. The machining operation is designed using Taguchi's L16 orthogonal array for the ease of machining study as it helps in minimizing the number of experiments and thus effectively reduces overall machining cost. The L16 orthogonal array is presented in table 2. For WEDM study, four input parameters were selected, which are pulse on time, pulse off time, servo voltage and wire feed. The range of parameters was chosen each at four different levels based on machine capability. The details of the parameters can be found in table 3.

Table 2. Taguchi's L16 Orthogonal Array

Trial No.	T_{on}	T_{off}	SV	WF
1	100	20	15	4
2	100	30	30	6
3	100	40	45	8
4	100	50	60	10
5	110	20	45	6
6	110	30	60	4
7	110	40	15	10
8	110	50	30	8
9	120	20	60	8
10	120	30	45	10
11	120	40	30	4
12	120	50	15	6
13	130	20	30	10
14	130	30	15	8
15	130	40	60	6
16	130	50	45	4

Table 3. Input parameters and their levels

Parameters	Symbol	Level 1	Level 2	Level 3	Level 4
Pulse on time (µs)	T_{on}	100	110	120	130
Pulse off time (µs)	T_{off}	20	30	40	50
Servo voltage (V)	SV	15	30	45	60
Wire feed (m/min)	WF	4	6	8	10

2.3 MATERIAL REMOVAL RATE, SURFACE ROUGHNESS AND RECAST LAYER

2.3.1 Material Removal Rate

The material removal rate in WED machining is determined from relating the measured weight loss after machining with the time taken for each sample. The concerned relation is expressed in the equation below:

$$\text{MRR} = \frac{w_f - w_i}{\rho \times t} x1000 \qquad \textbf{(1)}$$

MRR = Material Removal Rate (in mm^3/min)
w_f = final weight (in gm, after machining)
w_i = initial weight (in gm, before machining)
ρ = density of the alloy (in gm/c.c)
t = time taken (in minutes)

2.3.2 Surface Roughness

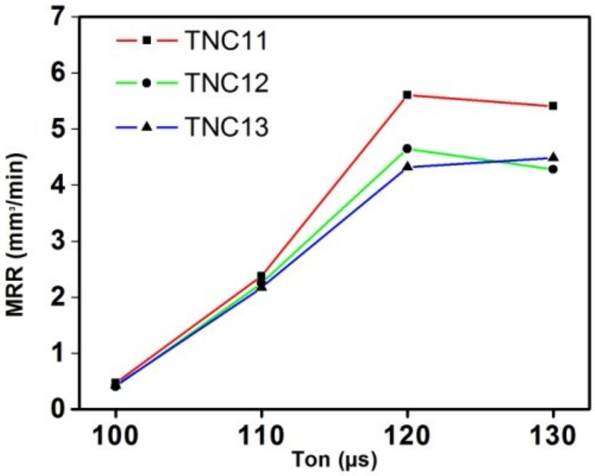
The surface roughness of the machined surfaces is noted using Mitutoyo SJ-301 surface roughness tester. For better accuracy, the surface roughness denoted, is the arithmetic mean of each sample measured at six different locations. 0.25mm/s was considered as the stylus speed and the evaluation length was 4.0 mm for each sample.

2.3.3 Recast Layer

Recast layer formed during wire electro discharge machining of the as cast TiNiCu shape memory alloys have been observed and measured using Scanning Electron Microscope (SEM-JEOL). The machined samples were cold mounted using epoxy in such a way that the transverse section of the samples can be polished with ease to a mirror finish. Thereafter, the machined samples were etched for 30 seconds each. The etchant used is a mixture of 2 ml of Hydrogen Fluoride with 10 ml Nitric Acid diluted with 20ml of distilled water. The recast layer thickness of the machined samples was measured carefully at nine different locations of each sample. The detailed observation is discussed in the later section.

3. RESULTS AND DISCUSSIONS

3.1 Effect of process parameters on Material Removal Rate



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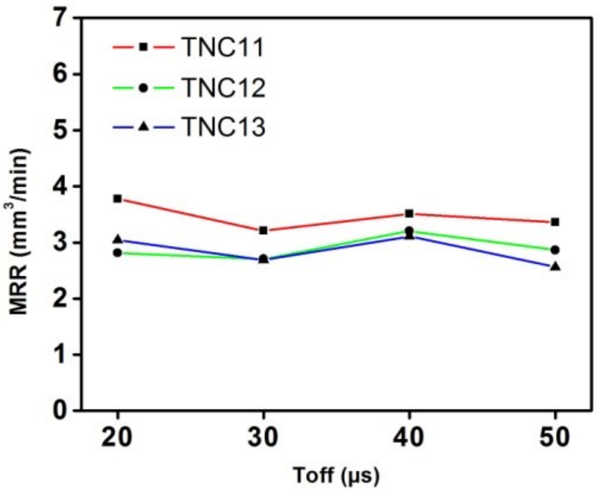

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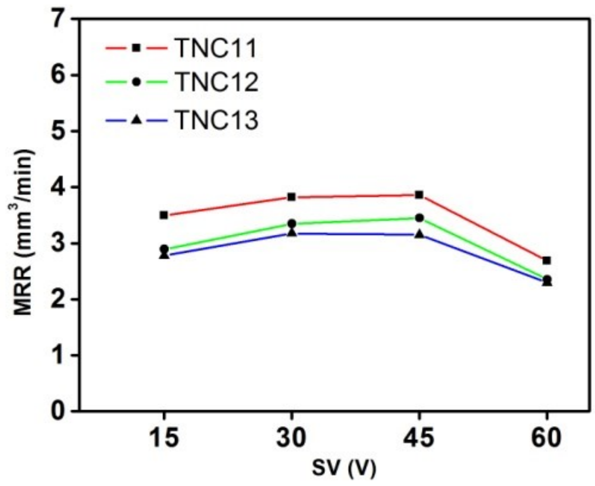

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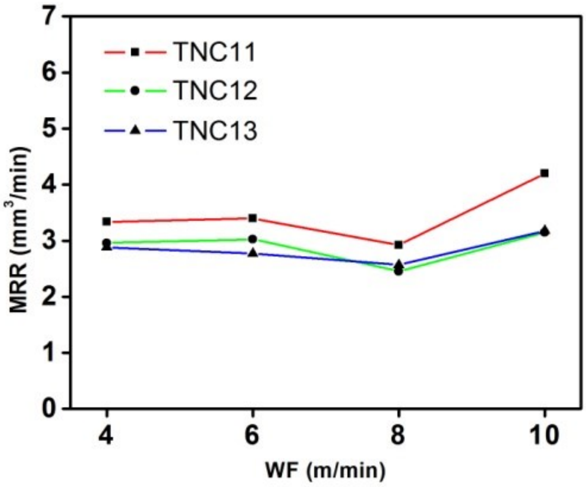

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Fig. 2. A-Effect of T_{on} on MRR, B-Effect of T_{off} on MRR, C-Effect of SV on MRR, D-Effect of WF on MRR

3.1.1 Effect of Pulse on time on MRR

In wire electro discharge machining, effect of pulse on time on MRR is quite consistent which can be justified from figure 2A. With an increase in pulse on time duration, MRR gradually increases upto 120 µs for all the alloys and then attains a constant behavior upto 130 µs as can be seen in figure 2A. At 120 µs, TNC11 exhibits 20% and 29% more material removal rate as compared to TNC12 and TNC13 respectively. The results are similar with the findings of other researchers working with WEDM productivity and surface integrity [9, 11] where they have studied its effect upto three levels of pulse on time. This characteristic drop in MRR at the fourth level (130 µs) in all the three alloys is due to increased vibration of wire electrode which affects the net spark gap and eventually lowers the MRR. At higher wire vibration, the wire electrode becomes incapable of maintaining uniform spark gap at given period of time, causes multiple spark generation sites and therefore discharge sparks become uneven which lead to lesser melting of material resulting in lower material removal rate, [24]. The degradation of the machined surface due to high energy discharge sparking in case of TNC11 can be justified by observing the formation of thicker recast layer as shown in figure 4A and 5A.

3.1.2 Effect of Pulse off time on MRR

Out of the three TiNiCu alloys investigated, TNC11 exhibited quantitative performance in terms of material removal rate and as usual affinity for higher surface roughness. Similar trend in results have been reported by Ravindranadh et al., [12] which can be explained by the fact that with increasing pulse off time, the time available for spark discharge per cycle is reduced that lowers the MRR, which is evident from the effects plot as depicted in figure 2B. At 20V, TNC11 show 34% and 24% more material removal rate as compared to TNC12 and TNC13. From table 6, it can be justified that the average recast layer thickness of the samples machined using higher pulse off time is less as compared to samples machined with lower pulse off time. Nonetheless, it is imperative to discuss the behavioral similarity between TNC11 and TNC13 along the entire input range when T_{off} is in play which can be inferred from the periodic drop and rise in response and typical 'distributed-yet-different' behavior of intermediate TNC12 alloy. TNC12 seems a little shifted from the usual response and shares equal weight at both initial and final range of the parameter under discussion. In all the alloys, MRR seems to be optimum during shorter pulse off duration of 20 µs which is due to increased number of discharges in a single spark cycle of (120-150) µs. These results match with the findings of Liao [13] and Ramakrishnan [14]. For further reference, table 4 represents the material removal rate of the machined samples of the chosen TiNiCu shape memory alloys.

3.1.3 Effect of Servo voltage on MRR

Servo voltage applied as one of the major input parameters in wire electro discharge machining, helps in maintaining an uniform spark gap between the workpiece and the wire electrode during machining process. Lower spark gap results in more number of sparks per unit time and hence, high MRR and vice versa. As this can be seen from figure 2C, with increasing servo voltage, material removal rate eventually decreases. But it can also be noted that there is a small increment of MRR between 30V and 45V which has happened due to higher discharge energy per spark which is also observed by Bijo et al., [15] but after 45V upto 60V, MRR reduces drastically due to lower discharge spark energy caused due to higher spark gap. The net drop is material removal rate for TNC11, TNC12 and TNC13 are 23%, 18% and 17% respectively. It can be observed in figure 2C, that material removal rate and surface roughness fairly converges for all the chosen alloys at 60V. Even though these variations are observed in these alloys, the overall pattern is similar in nature and match with the findings of Tarng et al. [16].

3.1.4 Effect of Wire feed on MRR

Effect of wire feed on output responses during wire electro discharge machining seems to have more intensity at higher feed rate for all the alloys investigated. Even though material removal rate and surface roughness seems to be in proportion, as observed in figure 2D and 3D, there is a characteristic drop in their behavior at wire feed rate of 8 m/min as compared to 4 m/min which accounts for around 12%, 17% and 10% drop in material removal rate for TNC11, TNC12 and TNC13 shape memory alloy. This steady decrement in material removal rate for wire feed rate upto 8 m/min is observed due to rise in uneven sparking at the machining zone caused due to higher feed rate and hence lower material removal rate alongside lesser crater formation leading to lower surface roughness, thereafter a sudden rise is observed.

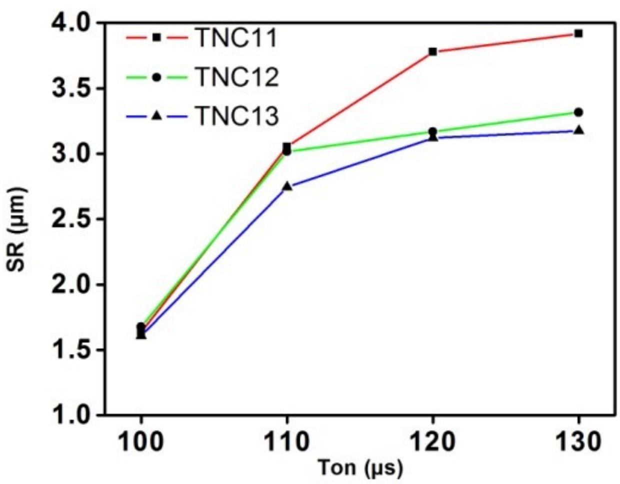
Table 4. MRR of TNC11, TNC12 and TNC13

Trial No.	TNC11 MRR (mm^3/min)	TNC12 MRR (mm^3/min)	TNC13 MRR (mm^3/min)
1	0.5035	0.3089	0.3289
2	0.4912	0.6058	0.7185
3	0.5028	0.5353	0.4722
4	0.3783	0.1782	0.1720
5	3.0709	2.9449	2.8546
6	1.3545	1.2899	1.2566
7	3.1813	3.0684	2.8983
8	1.9036	1.6969	1.6789
9	4.5906	3.8409	3.8848
10	6.2902	5.1844	4.5319
11	5.9339	5.1117	5.2050
12	5.6022	4.4569	3.6491
13	6.9431	4.1567	5.0981
14	4.6995	3.7436	4.2376
15	4.4203	4.0982	3.8599
16	5.5606	5.1294	4.7399

However, the net increment in MRR for TNC11, TNC12 and TNC13 at wire feed rate of 10 m/min considering the entire range of input parameter are 25%, 6% and 10% respectively.

This increase in material removal rate is caused due to better flushing of the molten material from the machining zone by the fast moving wire electrode which previously tend to accumulate due to lower wire feed rate. This happens due to increased wire tension at higher wire feed rate as confirmed by Amitesh et al., [17].

3.2 Effect of process parameters on Surface Roughness



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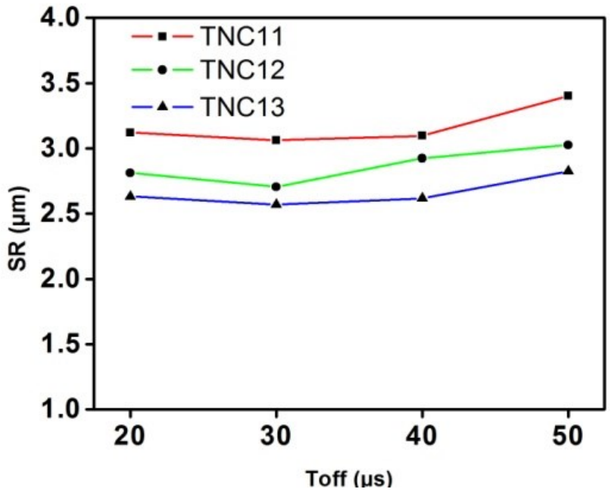

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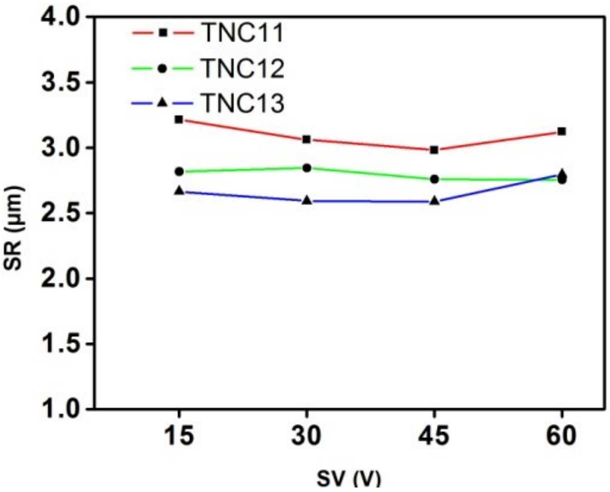

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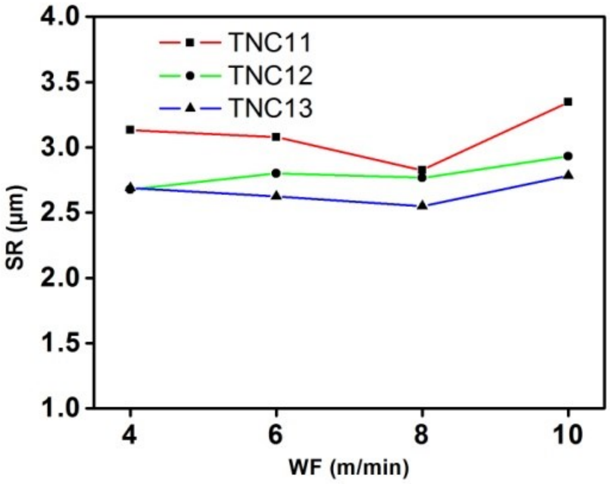

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Fig. 3. A-Effect of T_{on} on SR, B-Effect of T_{off} on SR C-Effect of SV on SR, D-Effect of WF on SR

3.2.1 Effect of Pulse on time on SR

The trend of surface roughness in all these alloys is similar to the findings of other researchers who emphasized these output responses considering same parameters at hand [11, 12] but only at three levels. They also reported a rise in surface roughness with increasing pulse on time caused due to increase in discharge energy of each spark creating larger craters which contributes to increased roughness of machined surfaces. Surface quality in terms of roughness in case of TNC12 and TNC13 have a tendency to converge and remain stable at high pulse on time unlike TNC11 which exhibits a dramatic increase compared to its counterparts as shown in figure 3A which may be due to change in its material property which can be justified by the findings of Hsieh et al., [18], where the material removal rate is related to the melting temperature and thermal conductivity of the material. According to their findings, higher material removal rate is due to lower thermal conductivity of the material which makes it easy to melt off the material from the surface compared to its counterparts which adds to surface roughness which is also observed in the current investigation. The net increment in surface roughness for TNC11, TNC12 and TNC13 starting from 110 µs to 130 µs are 28%, 9% and 15% respectively. For further reference, table 5 represents the surface roughness of the machined samples of the chosen TiNiCu shape memory alloys.

3.2.2 Effect of Pulse off time on SR

As discussed earlier, similarity in behavior of TNC11 and TNC13 is also observed in case of surface roughness. Whereas in case of TNC12, the magnitude of machined surface quality in terms of roughness seems to be attaining a median value and exhibiting a 'wobbled' distribution as the net change is only 7.5%. However, the surface roughness is least affected by pulse off time for upto 40 µs and remains maximum at shorter pulse off time. Although, beyond 40 µs, surface starts to exhibit an increment in roughness which is evident from figure 3B that can be explained by the contribution of longer dielectric quenching time that eventually re-solidifies more molten material at its surface. The net change in surface roughness due to variation in pulse off time for alloys TNC11, TNC12 and TNC13 are 8.9%, 7.5% and 7.3% respectively which proves that pulse off time as a process parameter have least effect on surface quality of the machined samples. The variation in behavior of the surface roughness of the chosen alloys is due to the difference in their thermal conductivity and melting temperature which is justified by considering the findings of the researchers, [18-20].

3.2.3 Effect of Servo voltage on SR

The variation in surface quality of wire electro discharge machined samples with respect to varying servo voltage is almost consistent in nature. Along the entire range of servo voltage applied, surface roughness of the machined samples does not exhibit any major fluctuations as evident from figure 3C. At low servo voltage, spark gap is minimum which results in intense spark discharge due to which machined surface suffers heavy degradation due to formation of larger craters which generally decreases with increasing servo voltage. As discussed earlier and inferred by the researchers [11, 17], the results obtained in the current investigation is in accordance with the published data. This collective change in overall behavior for both material removal rate and surface finish for TNC11 and TNC13 are same, however in TNC12, its net change is almost equal which is only 2.2% as compared to 2.8% and 4.9% for TNC11 and TNC13 respectively. Although TNC11 and TNC13 exhibits similarity in their behavior along the entire input range, TNC12 and TNC13 surprisingly converge at higher servo voltage in case of both MRR and SR which confirms that when the spark gap is too large, effect of discharge sparks are almost equal irrespective of the material property.

3.2.4 Effect of Wire feed on SR

A few researchers have investigated the effect of Wire EDM parameters on output responses based on three levels of input parameters [12, 14, 15, 17, 21]. It is very difficult to find literature based on four levels. Therefore, a detailed study regarding the further implications of wire feed rate is inevitable and it is attempted in the current investigation. In case of material removal rate, alloy TNC11 and TNC12 display similarity in behavior whereas it is alloy TNC11 and TNC13 which shares similar pattern in case of surface roughness as seen in figure 3D. The net change in surface roughness for TNC11, TNC12 and TNC13 are 6.7%, 9.5% and 3.5% respectively. This increase in surface roughness beyond 8 m/min is due to increased wire vibration caused due to higher wire feed rate that leads to uneven sparking and crater formation that eventually leads to higher surface roughness. TNC11 is most affected by wire feed rate in terms of surface quality and exhibits average surface roughness of 3.346 µm at wire feed rate of 10 m/min. Alloy TNC12 seems to be least affected by the change in wire feed rate throughout the experiments and is evident from 'almost linear' behavior of its effects plot represented in figure 3D. However, its counterpart alloys exhibit considerable change and variation along the range of wire feed rate which follow a similar pattern which can be related to the difference in material property that leads to the variation in their responses, and it is confirmed by Hsieh et al.[18] and is already discussed earlier.

Table 5. SR of TNC11, TNC12 and TNC13

Trial No.	TNC11 SR (µm)	TNC12 SR (µm)	TNC13 SR (µm)
1	1.852	1.633	1.527
2	1.303	1.337	1.309
3	1.060	1.477	1.46
4	2.322	2.256	2.128
5	3.052	3.198	2.703
6	2.595	2.272	2.898
7	3.475	3.233	2.723
8	3.090	3.362	2.648
9	3.612	2.987	3.015
10	3.617	3.042	2.995
11	3.888	3.483	3.135
12	3.992	3.163	3.335
13	3.968	3.197	3.281
14	3.540	3.243	3.076
15	3.960	3.505	3.148
16	4.197	3.322	3.193

3.3 Recast layer study

Recast layer formation during wire electro discharge machining is inevitable. However, with modest and optimized setting of input parameters, it is possible to reduce the thickness of the recast layer. In the current investigation, effort has been laid to understand the effect of process parameters yielding optimum MRR on the formation and structure of recast layer on the machined TiNiCu shape memory alloys. Samples exhibiting optimum MRR for each of the alloys are considered for the recast layer study which lead us to the samples machined with the input process parameters as depicted in table 6 where obtained recast layer thickness and corresponding surface roughness of the machined samples during wire electro discharge machining have also been reported.

Table 6. Average RLT for high MRR and corresponding SR of machined surfaces

Alloy	Samples at optimum MRR			
	Input Parameters	**MRR** (mm^3/min)	**Average RLT** (µm)	**Average SR** (µm)
TNC11	T_{on} : 130 µs T_{off} : 20 µs SV : 30V WF : 10 m/min	6.9431	23.93	3.968
TNC12	T_{on} : 120 µs T_{off} : 30 µs SV : 45V WF : 10 m/min	5.1844	9.16	3.042
TNC13	T_{on} : 120 µs T_{off} : 40 µs SV : 30V WF : 4 m/min	5.2050	21.65	3.135

It has to be noted that it is not necessary for the samples exhibiting optimum MRR to yield poor surface roughness as well. The corresponding SEM micrograph of the samples has been shown in figure 4.

Study of the samples with thicker recast layer carry much more importance than the samples with thinner recast layer, because recast layer tend to change the material property as its metallurgical properties are different as compared to the bulk material and their presence heavily influence the shape recoverability of the machined TiNiCu samples. In addition, these samples can also be considered for further study after elimination of the recast layer using trim cut technique in wire electro discharge machining. Out of the three alloys considered for the experimental study, TNC11 exhibits a higher affinity for recast layer formation as compared to TNC12 and TNC13 under similar machining conditions which can be justified from the data provided in figure 5 where SEM micrographs have been presented for samples machined by using similar input parameters during wire electro discharge machining. As evident from figure 4A, the recast layer thickness of TNC11 is higher at optimum MRR input setting as compared to TNC12 and TNC13, depicted in figure 4B and 4C. Average recast layer thickness of TNC11 at optimum MRR setting is around 23.93 µm compared to TNC12's 9.16 µm and TNC13's 21.65 µm. Such thicker recast layer formation can also be associated with the usage of zinc coated brass wire used in the current investigation. As observed by Sharma et al. [23], zinc coated brass wire yielded thicker recast layer as compared to pure brass wire during machining of Inconel 706. Corrugated surface of bulk material in case of TNC12 and TNC13 exhibits much lesser recast layer which can be acknowledged from figure 4B and 4C, this is may be due to good flushing conditions but such difference in recast layer morphology as compared to alloy TNC11 is due to the difference in their material property due to variation in Ni content resulting into difference in $\lambda_{\Theta}K_T$ (λ_{Θ}=melting temperature, K_T=thermal conductivity) value of the chosen alloys as established by Hsieh et al. [18]. The group of researchers have established that $Ti_{50}Ni_{49.5}Cr_{0.5}$ have higher affinity for recast layer formation as compared to $Ti_{35.5}Ni_{49.5}Zr_{15}$ due to smaller $\lambda_{\Theta}K_T$ value, which is in accordance with the results obtained in the current investigation. The reason for such behavior can be greatly related to the difference in their inherent material property as discussed in the previous section. While TNC11 is more susceptible to recast layer formation, TNC12 and TNC13 resist the same which can be justified due to increased thermal conductivity as observed by Ramachandran et al. [19, 20]. It has been observed by them that with increasing Ni content in binary TiNi alloy, the thermal conductivity of the alloys exhibit a periodic rise and drop which is also applicable for Cu-doped TiNi alloys. In the current investigation, TNC11 exhibited thicker recast layer followed by TNC13 and TNC12 under same machining parameters as evident from figure 5. The reason behind such intermediate behavior of TNC12 can be explained by its higher thermal conductivity with respect to TNC11 and TNC13. Ramachandran et al.[19] observed similar behavior in thermal conductivity where TiNi alloy doped at 5%, 7.5% and 10% Cu exhibited substantial increment in thermal conductivity and then suddenly drops beyond 10% Cu addition. These results were also similar with their study using Ni-rich TiNi alloys [20]. Due to such nominal behavior of TNC12 in case of recast layer formation, it can also be observed that surface roughness of the aforementioned is also minimum as compared to its counterparts which is evident from the data provided in figure 4. To justify the varying behavior of the chosen materials, from figure 5 it is proved that under similar machining conditions, TNC12 follow similar trend in results. Such desirable response of TNC12 in terms of MRR, SR and RLT makes it more qualified for further study.

3.4 Behavioral Summary

In the previous sections, the effect of the Wire EDM process parameters namely, T_{on} (pulse on time), T_{off} (pulse off time), SV (servo voltage) and WF (wire feed) on MRR (material removal rate) and SR (surface roughness) has been discussed. The effects plot for the chosen TiNiCu shape memory alloys have been plotted and merged together to understand the difference in their behavior under similar machining conditions. It has been noted that TNC11 and TNC13 exhibited optimum MRR of 6.9431 mm^3/min and 5.2050 mm^3/min with corresponding surface roughness of 3.968 µm and 3.135 µm respectively compared to TNC12's material removal rate of 5.1844 mm^3/min bearing surface roughness of 3.042 µm. However, in case of recast layer formation, TNC11 exhibited thicker recast layer (23.93 µm by average) compared to TNC12 (9.16 µm) and TNC13 (21.65 µm). Therefore, it is affirmative that TNC12 exhibits nominal behavior in all the cases. Therefore, it is more advantageous to study an alloy with a nominal behavior to understand the effect of parameters used to machine the as cast shape memory alloys. Since TNC12 provides us with favorable results by bearing intermediate position among the chosen TiNiCu shape memory alloys, it can be considered for further study by using ANOVA to apprehend the machining parameters that influence the machining rate and surface quality which is discussed in the next section.

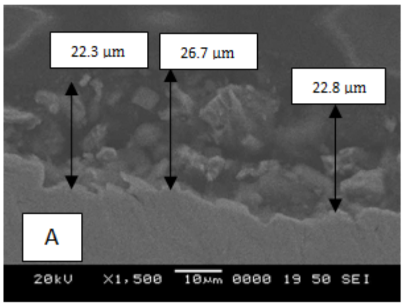
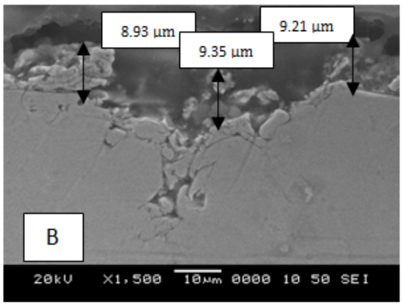
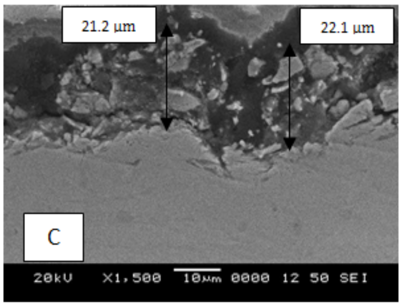
Recast layer thickness at optimum MRR		
TNC11	**TNC12**	**TNC13**
Input Parameters T_{on} : 130 µs T_{off} : 20 µs SV : 30V WF : 10 m/min	**Input Parameters** T_{on} : 120 µs T_{off} : 30 µs SV : 45V WF : 10 m/min	**Input Parameters** T_{on} : 120 µs T_{off} : 40 µs SV : 30V WF : 4 m/min
		
Avg. RLT : 23.93 µm	Avg. RLT : 9.16 µm	Avg. RLT : 21.65 µm
MRR : 6.9431 mm^3/min SR : 3.968 µm	MRR : 5.1844 mm^3/min SR : 3.042 µm	MRR : 5.2050 mm^3/min SR : 3.135 µm

Fig. 4. SEM micrograph of TiNiCu machined samples at high MRR

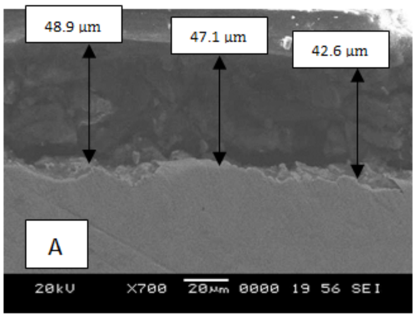
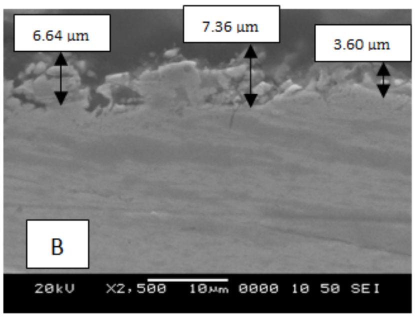
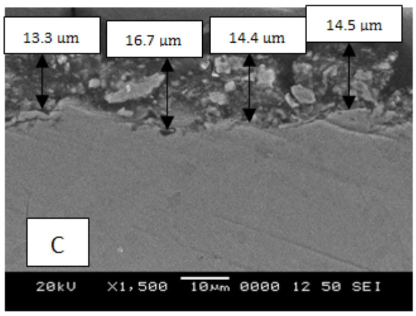
Recast layer thickness at similar machining parameters (T_{on}:120 µs, T_{off}: 40 µs, SV: 30V, WF: 4m/min)		
TNC11	**TNC12**	**TNC13**
		
Avg. RLT : 46.2 µm	Avg. RLT : 5.87 µm	Avg. RLT : 14.73 µm
MRR : 5.9339 mm^3/min SR : 3.888 µm	MRR : 5.1117 mm^3/min SR : 3.483 µm	MRR : 5.2050 mm^3/min SR : 3.135 µm

Fig. 5. SEM micrograph of TiNiCu samples at similar machining parameters

3.5 Analysis of Variance

Researchers have analyzed the experimental data using ANOVA to comprehend the most influencing process parameters that affect the output responses of wire electro discharge machining [9, 13, 22]. By the help of ANOVA, the most influencing parameters contributing in the machining of alloy TNC12 can be identified as it is our material of interest. With the help of the analysis of variance it is possible to establish the statistically significant process parameters of Wire EDM process and the percentage contribution of these parameters on the material removal rate and surface roughness. The relative importance of the Wire EDM process parameters with respect to the material removal rate and surface roughness were investigated to determine optimum combinations of machining parameters by using ANOVA. The ANOVA results obtained from Minitab 17.1.0 are presented in table 7 and 8 which represent the ANOVA results for MRR and SR respectively for TNC12 shape memory alloy. F-test provides the user a decision at some confidence level as to whether these estimates are significantly different.

A larger F-value indicates a significant change on output response caused due to variation in process parameters.

Table 7. Result of ANOVA for Material Removal Rate of TNC12

Source	DF	SS	MS	F	P	% P
T_{on}	3	46.4170	15.4723	**69.30**	0.003	91.91
T_{off}	3	0.5539	0.1846	0.83	0.560	1.09
SV	3	1.1171	0.3724	1.67	0.342	2.21
WF	3	2.4057	0.8019	**3.59**	0.161	4.76

DF-Degree of freedom, SS-Sum of squares, MS-Mean square, F-F test value, P-P test value, %P-Percentage contribution

Table 8. Result of ANOVA for Surface Roughness of TNC12

Source	DF	SS	MS	F	P	% P
T_{on}	3	6.85433	2.28478	**11.58**	0.037	86.52
T_{off}	3	0.70031	0.23344	**1.18**	0.447	8.84
SV	3	0.13351	0.04450	0.23	0.874	1.68
WF	3	0.2338	0.00779	0.04	0.988	2.95

DF-Degree of freedom, SS-Sum of squares, MS-Mean square, F-F test value, P-P test value, %P-Percentage contribution

According to table 7, T_{on} and WF are the two most influencing parameters while material removal rate is concerned followed by T_{off} and SV which is also evident from the effects plot as depicted in figure 6A. Percentage contribution of pulse on time and wire feed rate on material removal rate while machining TNC12 are 91.91% and 4.76% respectively. The significance of the aforementioned process parameters can also be justified from the effects plot depicted in figure 2A and 2D, where net change in MRR varies from 0.1782 mm^3/min to 5.1844 mm^3/min. Whereas, in case of surface roughness, T_{on} and T_{off} are the most influencing parameters followed by SV and WF as evident from table 8 and figure 6B. Percentage contribution of pulse on time and pulse off time on surface roughness are 86.52% and 8.84% respectively which can be justified accordingly from figure 3A and 3B. High surface finish can be observed in low pulse on setting and does not vary much while pulse off time is concerned. Throughout the entire range of pulse off time applied while machining, the variation in surface roughness is negligible which is in accordance with the obtained ANOVA results. The corresponding F-values of the specific process parameters signify the above drawn conclusion and the sum of squares helped us in achieving the percentage contribution of the respective factors for 'higher the better' MRR condition and 'lower the better' SR condition.

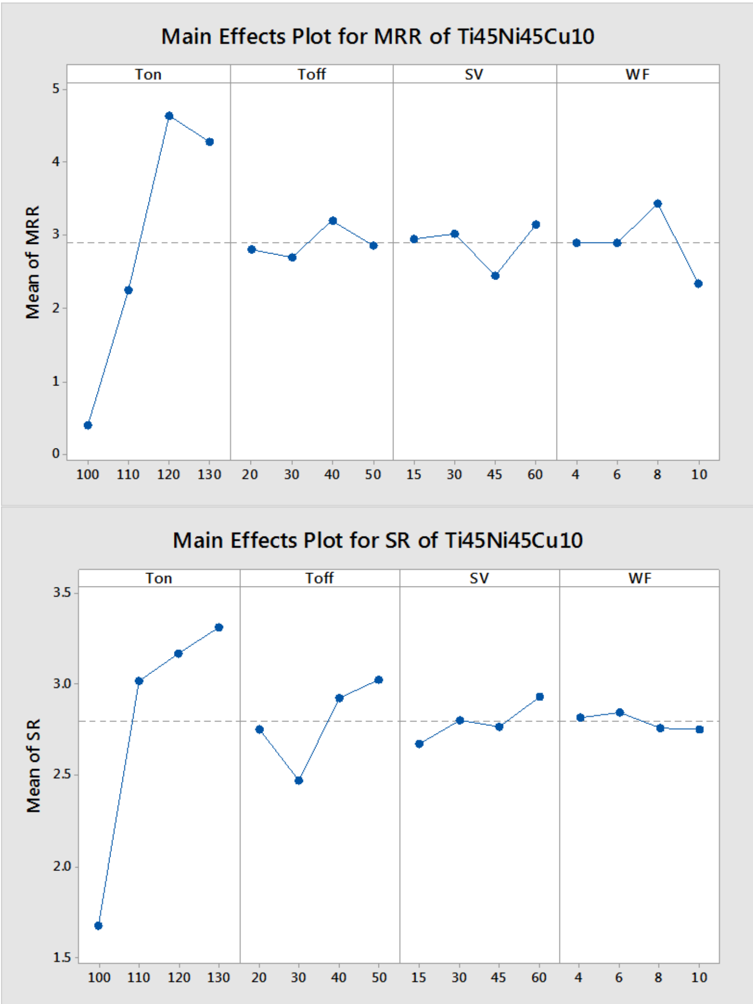


Fig. 6. Effects plot for A-MRR, B-SR for TNC12 shape memory alloy

4. CONCLUSIONS

Experimental investigation of wire electro discharge machining on $Ti_{50}Ni_{40}Cu_{10}$, $Ti_{45}Ni_{45}Cu_{10}$ and $Ti_{40}Ni_{50}Cu_{10}$ as cast shape memory alloys has been carried out. Material removal rate and surface roughness of the machined samples are also studied to draw out the difference in behavior the alloys exhibit under similar machining conditions. Further, recast layer thickness of the machined samples exhibiting optimum MRR of each of the alloys have been measured to understand the behavior of its formation and the following conclusions have been drawn:

TNC11 exhibited exceptional affinity for high material removal rate which reaches upto 6.9431 mm3/min compared to 4.1567 mm^3/min for TNC12 and 5.0981 mm^3/min for TNC13 respectively under similar machining conditions caused due to lower thermal conductivity compared to its counterparts.

In case of surface roughness, TNC11 demonstrated poor surface roughness of 4.197 µm compared to 3.322 µm and 3.193 µm for TNC12 and TNC13 respectively under similar machining conditions which proves it is more susceptible to surface alterations and higher surface roughness during wire electro discharge machining operation compared to its counterparts.

Unlike TNC11, TNC12 and TNC13 displayed surprising aversion to formation of recast layer. TNC11 exhibited as usual affinity for recast layer formation and scored highest average thickness of 23.93 µm at high MRR settings compared to 9.16 µm and 21.65 µm for TNC12 and TNC13 respectively.

TNC12 proves to be a suitable material for further study as it provides favorable results in terms of both material removal rate and surface roughness at optimum MRR input settings and exhibits poor affinity towards formation of recast layer.

As per ANOVA results, it is evident that T_{on} and WF are the most influencing process parameters bearing percentage contribution of 91.91% and 4.76% to machine TNC12 when MRR is concerned and in case of surface roughness it is T_{on} and T_{off} whose percentage contributions are 86.52% and 8.84% respectively.

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