Wire electro spark machining and characterization studies on Ti$_{50}$Ni$_{49}$Co$_1$, Ti$_{50}$Ni$_{45}$Co$_5$ and Ti$_{50}$Ni$_{40}$Co$_{10}$ alloys

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Abstract

The wire electrical discharge machining process (WEDM) is high demand and influenced by various input process parameters namely pulse duration, voltage, wire diameters and wire material. In this research, a smart material made of TiNiCo alloy is investigated to study the machinability using WEDM process. The pulse duration and servo voltage varied to perform the experiments on Ti$_{50}$Ni$_{49}$Co$_1$, Ti$_{50}$Ni$_{45}$Co$_5$ and Ti$_{50}$Ni$_{40}$Co$_{10}$ smart materials for bone staple applications which were designed by ELCAM software and generated G-code for machining with same software. L-25 orthogonal array used for machining of selected alloys, which is created through Taguchi design of experiment. From the experiments, an analysis was made to study the amount of material removal and average roughness as a response. Further machined areas were subjected to metallurgical characterization techniques such as surface topography, EDS analysis, residual stress calculation and wear mechanism. Tensile residual stress was noticed at higher values of outputs while lower values of residual stress at lower values of outputs which were also confirmed through microstructure and surface topography that smoother surface has been found at lower values of outputs. Moreover, the higher value of residual stress has been noticed on the machined surface of Ti$_{50}$Ni$_{40}$Co$_{10}$ alloy while lower on the machined surface of Ti$_{50}$Ni$_{49}$Co$_1$ alloy. Copper (Cu), Zinc (Zn), Carbon (C) and Oxygen (O) were found as additional elements on the machined surface during the EDS analysis of machined components for each alloy.

1. Introduction

Ti and Ni-based alloys are unique in clause of smart materials due to their superior quality in pseudoelasticity, shape memory effect, etc these alloys widely used for space applications, product of artificial intelligence, bio-implants, telecommunication, etc [1, 2]. The properties of these alloys are enriched with addition of other alloying elements so-called cobalt, silver, and copper, etc [3–6]. It has been understood from the literature that the amount of cobalt in addition to TiNi alloy can possess stable properties for bio-implants applications [7]. It is difficult to machine such smart materials through conventional manufacturing processes as they are highly sensitive towards mechanical loading and operating conditions. The response on production of smart materials is also a challenge to achieve good surface finish and bulk removal of material through conventional techniques. Therefore it has been suggested to select suitable advanced manufacturing process from the un-conventional machining process such as WEDM, EDM, Abrasive water jet cutting, and Electrochemical machining [8, 9].

In this research wire spark discharge machining process is adopted to perform machining study on TiNiCo smart materials by varying the elemental compassions. In WEDM process machining, performances are based on input process parameters such as pulse duration, servo voltage, wire speed and wire diameter are highly influencing parameters [10]. Removal of material from the work is based on spark erosion and vaporization which are highly controlled due to servo voltage and pulse durations [11]. Research on deficiency of surface quality in the form of micro-cracks, thermal stress, vast recast layer and improper material removal are existing [12, 13]. Improper machining and loss in surface quality may lead to effect on service life of the machined...
component with residual stress [14–17]. To identify the influence of process parameters experiments are defined in different combinations of process parameters to predict the responses and also to optimize best process conditions [11, 18, 19]. Articles on machining implants materials using WEDM process are limited in literature and the analysis of surface studies to be explored.

The novelty of this research is to develop TiNiCo alloy at different compositions for biomedical applications. Subsequently the machining studies are performed as per design of experiments to investigate metal rate and average roughness by varying pulse on duration and servo voltage with constant process parameters such as wire-speed, servo feed and pulse off duration. The machined surface is further investigated with SEM and XRD analysis for characterization report.

2. Experimental procedure

TiNiCo smart material has been prepared using the arc melting process at vacuum conditions. The material quality achieved by standard melting process to cast a rectangular block of $50 \times 12 \times 10$ mm$^3$. Properties of the material have been presented in table 1 where mechanical properties were investigated through universal tensile machine (UTM) and phase transformation temperatures were examined by DSC analysis. Table 2 exhibit the selected input process parameters. Pulse on duration and servo voltage with their five levels have been chosen in the present study because it has been found that these process parameters were the most influential process parameters for the machining of TiNiCo alloy [20]. Hence Two process parameters approach was adopted for the experimental plan. L-25 orthogonal array has been created using Taguchi design of experiment (DOE) for the work plan. The machining process carried out on CNC based Wire EDM machine (Model Electronica ELPULS15 CNC) in a pre-defined experimental model/plan as presented in table 3. The metal removal rate was calculated using equation 1. Average roughness was measured with roughness tester SJ-301 (Mitutoyo), JEOL JSM-638OLA Scanning electron microscopy was used for SEM images. LEST OLS4100 3D laser microscope was used for surface topography and BRUKER D8 DISCOVER was used for x-ray diffraction analysis.

\[
\text{MRR} \left( \frac{\text{mm}^3}{\text{min}} \right) = \text{Cutting speed} \times \text{Kerf width} \times \text{height of workpiece} \ldots \ldots \ldots (1)
\]

Where, Kerf width (mm) = $2 \times$ spark gap (mm) + diameter of wire

3. Results and discussion

Machining of $\text{Ti}_{50}\text{Ni}_{49}\text{Co}_1$, $\text{Ti}_{50}\text{Ni}_{45}\text{Co}_5$ and $\text{Ti}_{50}\text{Ni}_{40}\text{Co}_{10}$ has been carried out and the measured responses are presented in table 4. Effects of pulse on duration and servo voltage were discussed in details in the present study. However, pulse off duration is also most influential parameter of WEDM. MRR and $Ra$ decreased with increase in the value of pulse off duration because at the higher value of pulse off duration intensity of spark will be

| Properties | $\text{Ti}_{50}\text{Ni}_{49}\text{Co}_1$ | $\text{Ti}_{50}\text{Ni}_{45}\text{Co}_5$ | $\text{Ti}_{50}\text{Ni}_{40}\text{Co}_{10}$ |
|------------|---------------------------------|---------------------------------|----------------------------------|
| Yield strength $\sigma_y$ | 170 | 250 | 574 |
| Fracture strength $\sigma_f$ | 835 | 563 | 573 |
| Elongation rate % | 29.1 | 16.9 | 11.7 |
| $M_t$ = Martensitic start ($^\circ$) | 12 | 12.91 | 13.28 |
| $M_t$ = Martensitic finish ($^\circ$) | -17.89 | -18.01 | -18.02 |
| $A_t$ = Austenitic start ($^\circ$) | 16.95 | 16.98 | 17 |
| $A_t$ = Austenitic finish ($^\circ$) | 43.97 | 43.99 | 44.01 |

| Input process parameters | Unit | Levels |
|--------------------------|------|--------|
| Pulse on duration ($T_{on}$) | $\mu$s | 105, 110, 115, 120, 125 |
| Servo voltage ($SV$) | V | 20, 30, 40, 50, 60 |
| Pulse off duration ($T_{off}$) | $\mu$s | 42 |
| Wire speed ($WS$) | m/min | 4 |
| Servo feed ($SF$) | $\mu$ | 2180 |
| Brass wire | mm | 0.25 |
Table 3. L-25 orthogonal array, for two process parameters approach.

| Run | A  | B  | Pulse on duration | Servo voltage |
|-----|----|----|-------------------|---------------|
| 1   | 1  | 1  | 105               | 20            |
| 2   | 1  | 2  | 105               | 30            |
| 3   | 1  | 3  | 105               | 40            |
| 4   | 1  | 4  | 105               | 50            |
| 5   | 1  | 5  | 105               | 60            |
| 6   | 2  | 1  | 110               | 20            |
| 7   | 2  | 2  | 110               | 30            |
| 8   | 2  | 3  | 110               | 40            |
| 9   | 2  | 4  | 110               | 50            |
| 10  | 2  | 5  | 110               | 60            |
| 11  | 3  | 1  | 115               | 20            |
| 12  | 3  | 2  | 115               | 30            |
| 13  | 3  | 3  | 115               | 40            |
| 14  | 3  | 4  | 115               | 50            |
| 15  | 3  | 5  | 115               | 60            |
| 16  | 4  | 1  | 120               | 20            |
| 17  | 4  | 2  | 120               | 30            |
| 18  | 4  | 3  | 120               | 40            |
| 19  | 4  | 4  | 120               | 50            |
| 20  | 4  | 5  | 120               | 60            |
| 21  | 5  | 1  | 125               | 20            |
| 22  | 5  | 2  | 125               | 30            |
| 23  | 5  | 3  | 125               | 40            |
| 24  | 5  | 4  | 125               | 50            |
| 25  | 5  | 5  | 125               | 60            |

Table 4. Machining responses of each alloy.

| Run | Ti50Ni49Co1 | Ti50Ni45Co5 | Ti50Ni40Co10 |
|-----|-------------|-------------|--------------|
|     | Ra          | MRR         | Ra           | MRR         | Ra          | MRR         |
| 1   | 1.68        | 4.62        | 1.51         | 3.71        | 1.84        | 3.51        |
| 2   | 1.61        | 3.64        | 1.46         | 3.12        | 1.72        | 3.06        |
| 3   | 1.48        | 2.99        | 1.33         | 2.28        | 1.58        | 2.41        |
| 4   | 1.27        | 2.6         | 1.3          | 1.69        | 1.26        | 1.69        |
| 5   | 1.04        | 1.49        | 1.02         | 1.11        | 1.18        | 1.04        |
| 6   | 2.1         | 5.27        | 2.29         | 4.42        | 1.98        | 3.71        |
| 7   | 2.07        | 5.14        | 2.2          | 3.19        | 1.84        | 3.06        |
| 8   | 1.89        | 3.58        | 2.03         | 2.21        | 1.67        | 2.28        |
| 9   | 1.68        | 2.73        | 1.96         | 1.69        | 1.49        | 1.63        |
| 10  | 1.18        | 1.83        | 1.67         | 1.24        | 1.2         | 1.11        |
| 11  | 2.63        | 7.8         | 2.72         | 6.18        | 2.45        | 5.92        |
| 12  | 2.51        | 6.18        | 2.26         | 5.01        | 2.31        | 4.81        |
| 13  | 2.13        | 4.16        | 2.15         | 3.71        | 2.26        | 3.51        |
| 14  | 1.85        | 2.99        | 2.1          | 2.86        | 2.15        | 2.41        |
| 15  | 1.73        | 2.54        | 2.05         | 1.82        | 1.78        | 1.63        |
| 16  | 2.82        | 9.23        | 2.99         | 8.32        | 3.41        | 8.78        |
| 17  | 2.76        | 7.15        | 2.77         | 6.31        | 3.12        | 6.31        |
| 18  | 2.4         | 5.97        | 2.53         | 5.58        | 2.2         | 5.04        |
| 19  | 2.4         | 3.97        | 2.53         | 3.58        | 2.2         | 3.84        |
| 20  | 2.27        | 2.8         | 2.32         | 2.34        | 2.17        | 2.47        |
| 21  | 3.87        | 11.51       | 3.42         | 9.43        | 3.63        | 9.68        |
| 22  | 3.63        | 9.04        | 3.2          | 8.65        | 3.3         | 6.55        |
| 23  | 3.25        | 8.13        | 3.07         | 8.06        | 2.45        | 5.6         |
| 24  | 2.66        | 5.27        | 2.41         | 5.2         | 2.26        | 4.9         |
| 25  | 2.31        | 3.45        | 2.17         | 3.38        | 2.13        | 2.99        |
reduced in the machining zone, which results in fewer amounts which will be removed from the work surface which leads to the lower MRR. At the same time at the higher value of pulse off duration the spark intensity is less, there is much time for flushing during the machining hence most of the melted material will be removed through flushing from the surface of work material and leads to the lower value of average roughness. Similar work was presented by others researchers during the machining of TiNiCo shape memory alloy [20].

3.1. EDS analysis of as-cast material
Energy Dispersive x-ray Spectroscopy (EDS) analysis has been carried out to confirm the chemical constituents for each alloy and can be seen in figure 1. The recorded EDS spectrums have clearly exhibited that the appropriate amounts of elemental constituents present within the alloying configurations.

3.2. Effects of each experimental run on MRR for each alloy
Figure 2 exhibits the effects of each experimental run on MRR for each alloy. Black colour indicates the MRR for Ti50Ni49Co1 alloy, similarly red colour for Ti50Ni45Co5 alloy and blue colour for Ti50Ni40Co10 alloy are indicated in figure 2. It can be seen that MRR decreases up to experiment no 5 because SV increases with constant Ton. When it comes to experiment no. 6 again MRR increases then further it decreases until experiment run 10 because SV increases. A similar trend has been noticed after every five experiments. MRR decreases with an increment in SV because increase in SV results in larger spark gap thereby reducing the spark intensity and eventually lesser amount of material is removed from the surface of the workpiece. Others researchers [21] also observed similar kind of results during the wire EDM of High- strength low-alloy steel (HSLA). Additionally, during the machining of Ti50Ni40Co10 alloy at the run no. 21 and 22 noticed more frequent wire breakage due to
higher \( T_{\text{on}} \) and lower SV. Hence it can be said that combinations of 125 \( \mu \text{s} \) \( T_{\text{on}} \) and 20–30 V SV are not suitable parameters for the machining of Ti50Ni40Co10 alloy.

### 3.3. Effects of each experimental run on Ra for each alloy

The effect of each experimental run Ra is given in figure 3. Black colour indicates the MRR for Ti50Ni49Co1 alloy, similarly, red colour for Ti50Ni45Co5 alloy and blue colour for Ti50Ni40Co10 alloy respectively. It has been noticed that Ra decreasing from 1 to 5 experiments, same as observed during 6 to 10, 11 to 15, 16 to 20 and 21 to 25 experiments due to increment of the value of SV constant pulse on duration and after each five experiment \( T_{\text{on}} \) is increased and further it is constant for five experiments. Ra was decreased with increased SV because at the higher SV, small quantity of material melted from the surface of workpiece which can be easily flushed away from surface by dielectric fluid leading to low Ra. Same as reported by others researchers [22]. Moreover, higher value of servo voltage will increase the spark gap, which is responsible to reduce the intensity of sparks, which results in lesser amount of material that will be melted in the machining zone, therefore material removal rate will be less. On the other hand, an average roughness will be less at higher value of servo voltage because most of melted material cleaned from the surface of work material during machining which was also confirmed by scanning electron microscopy and can be seen in figure 3. Similar investigations have been observed during the wire spark discharge machining of Inconel 706 for Aerospace applications [17].

The trend of the process parameters on the outputs was found to be similar for each alloy. However, material removal rate and surface roughness were decreasing when percentage of cobalt is increasing in the TiNi shape memory alloy during the machining. Moreover, this trend has not been followed during some experimental run and it can depend on several parameters such as porosity inside the developed material and machining errors.

### 3.4. Microstructures

Surface characterization is performed over maximum and minimum response on MRR and Ra to discuss the material behaviour. Figure 4 shows the micro images of the machined surface at different process conditions. Lower values of outputs found at run number 5 (\( T_{\text{on}} 105 \mu \text{s} \) and SV 60 V) and higher values of outputs are found at the run number 21 (\( T_{\text{on}} 125 \mu \text{s} \) and SV 20 V) for all three alloys. From this observation, it can be say that the trend of MRR and Ra were constant with same process parameters for all three alloys but the values of these outputs were not constant which are reduced with the increased percentage of Co in TiNi alloy. The smoother surface has been found the Ti50Ni49Co1 alloy comparatively while higher MRR has been noticed during the machining of Ti50Ni49Co1 composition as exiting in figures 2 and 3. microstructure images (figure 4) of machined surface also confirmed the same statement. Figure 4(a) for Ti50Ni49Co1 alloy, figure 4(c) for Ti50Ni45Co5 alloy, and figure 4(e) for Ti50Ni40Co10 alloy respectively indicate the microstructures at the experiment number 5. The surface exhibits with fewer micro globules, melted drops and micro-cracks due to lower \( T_{\text{on}} \) (105 \( \mu \text{s} \)) and higher SV (60 V) during the machining. This is due to process condition and heat
intensity resulting in less amount of spark created in the machining zone and less amount of material was removed from the surface of workpiece and leading to the surface defects. Figure 4(b) for Ti50Ni49Co1 alloy, figure 4(d) for Ti50Ni45Co5 alloy, and figure 4(f) for Ti50Ni40Co10 alloy respectively exhibits the microstructures. These show that there are more microcracks, melted drops, micro globules on the machined surface comparatively due to higher $T_{on}$ (125 $\mu$s) and lower $SV$ (20 V). At high $T_{on}$, spark intensity is high, more amount of spark is produced in the machining zone, very less time is there to remove the melted materials form the machined component. Only some amount of melt can be removed from the machined surface, the rest of the materials are resolidify on machined surface in the form of microcracks, melted drops and micro globules on the machined surface, these leads to the higher MRR. Moreover this leads to high temperatures experienced continuously in the machining zone, some melting has occurred white oxide particles are also observed during the microstructure study. In addition thermal cracks are observed over the surface of the component machined at lower $SV$ compared to higher levels. It also leads to influence on surface roughness with craters due to rapid solidification of fused metal under dielectric medium [23].

3.5. Surface topography

Surface topography has been carried out at lower and higher values of MRR and Ra for all three alloys. Figure 5(a) for Ti50Ni49Co1 alloy, figure 5(c) for Ti50Ni45Co5 alloy and figure 5(e) for Ti50Ni40Co10 alloy respectively exhibit the surface topographical analysis at lower values of outputs while figure 5(b) for Ti50Ni49Co1 alloy, figure 5(d) for Ti50Ni45Co5 alloy and figure 5(f) for Ti50Ni40Co10 alloy respectively show surface topographical analysis at higher values of MRR and Ra. From figures 5(a), (c) and (e) smooth surface...
found comparatively while figures 5 (b), (d) and (f) exhibit rough surface comparatively due to higher $T_{on}$ (125 μs) and lower SV (20 V) because at high $T_{on}$ spark intensity is high more amount of spark is produced in the machining zone. Very less time is there to remove the melted materials form the machined component only some amount of melted can be removed from the machined surface, rest of the materials are resolidify on machined surface in the form of microcracks, melted drops, micro globules on the machined surface which also leads to the higher MRR. Better surface finish has been found at higher servo voltage and surface quality was poor as lower values of servo voltage because of lesser spark intensity. But, at higher servo voltage, the spark gap widens and reduces the intensity of the spark. This, in turn, increases the flushing and forms the microcavities on the machined surface leading to a smoother surface of the machined components as shown in figure 5. The same is noticed during the microstructural analysis of machined surface and can be seen in figure 4. Moreover, this leads to high temperatures experienced continuously in the machining zone, some melting has occurred, white
oxide particles are observed during the microstructure study. Due to higher $T_{on}$ and lower SV, tensile residual stress exhibit on the machined surface (figure 7) of machined components. Similar work was presented by Sharma et al [24] during the wire spark discharge machining of Inconel 706.

3.6. Recast layer thickness
Recast layer thickness measurement has been carried out at lower and higher values of outputs. Figure 6 indicates the recast layer thickness of the machined surface. Figure 6(a) for Ti$_{50}$Ni$_{49}$Co$_{1}$ alloy, figure 6(c) for Ti$_{50}$Ni$_{45}$Co$_{5}$ alloy and figure 6(e) for Ti$_{50}$Ni$_{40}$Co$_{10}$ alloy respectively shows recast layer thickness at lower values of outputs while figure 6(b) for Ti$_{50}$Ni$_{49}$Co$_{1}$ alloy, figure 6(d) for Ti$_{50}$Ni$_{40}$Co$_{5}$ alloy and figure 6(f) for Ti$_{50}$Ni$_{40}$Co$_{10}$ alloy respectively exhibit the recast layer thickness at higher values of outputs. During wire EDM, rapid heating and quenching of the molten material by the dielectric fluid causes the formation of a solidified layer and gets deposited on the machined surface, which makes harder surface of machined component. At lower values of outputs 4.2 $\mu$m for Ti$_{50}$Ni$_{49}$Co$_{1}$, 4.6 $\mu$m for Ti$_{50}$Ni$_{45}$Co$_{5}$ and 4.9 $\mu$m for Ti$_{50}$Ni$_{40}$Co$_{10}$ alloy observed while at higher values of outputs 30 $\mu$m for Ti$_{50}$Ni$_{49}$Co$_{1}$, 32 $\mu$m for Ti$_{50}$Ni$_{45}$Co$_{5}$ and 35 $\mu$m for Ti$_{50}$Ni$_{40}$Co$_{10}$ alloy were reported. Thicker recast layer has been noted at the lower values of outputs because these lower values are obtained at the 125 $\mu$s $T_{on}$ and 20 V SV. At high pulse of duration the energy for the spark discharge is more and material inclined towards machining and at end of spark discharge the volume of recast layer will be strong. The thin-film of the recast layer was noticed from figure 6(b), figures 6(d) and (f) due to lower $T_{on}$ (105 $\mu$s) and higher SV (60 V). Similar results have been reported by another researcher [24] during WED machining of Inconel 706. Moreover, thicker recast layer has been found during the machining of
Ti$_{50}$Ni$_{49}$Co$_{10}$ comparatively thinner recast layer has been observed during the machining of Ti$_{50}$Ni$_{49}$Co$_{1}$, which is also confirmed during the residual stress analysis that very less residual stress has been reported on the machined surface of Ti$_{50}$Ni$_{49}$Co$_{1}$ alloy at the same higher values of residual stresses has been seen during the machining of Ti$_{50}$Ni$_{49}$Co$_{10}$ which can be seen in the figure 7. This is due to the hardness of the workpiece because with the less percentage of Co in TiNi hardness was more of machined surface but by increasing the Co percentage in TiNi microhardness is decreasing.

3.7. Residual stresses analysis
While machining the surface stress (Residual component) may be compressive and elongated. The compression component may be due to the mechanical loads and elongation may be the effect of spark produced on plastic deformation. The outcome of this is revealed on drastic metallurgical transformation [25, 26]. Tensile stress was noticed during wire spark discharge machining or in the recast layer zone further it decrease toward the heat-affected zone because of high intensity of spark energy comes in the picture in machining area [27]. Residual stress has been measured on the machined surface which can be seen in figure 7 at lower and higher value of outputs. Tensile residual has been found on the machined surface of all three alloys. Minimum residual stress has been observed on the machined surface of Ti$_{50}$Ni$_{49}$Co$_{1}$ alloy while maximum stress has seen on the machined surface of Ti$_{50}$Ni$_{49}$Co$_{10}$ alloy. It was also observed that at lower values of Ra and MRR having less residual stress while at the higher values of these output residual stress increased in tensile nature due to the higher values of T$_{on}$ and lower values of the SV because at the higher value of T$_{on}$ more energy of spark has been produced. At the same time lower values of SV very less spark gap result in more melting and solidification of melted material on machined surface during the machining zone which leads to higher tensile residual stresses on the surface. Compressive stresses can be related to sample thickness since residual stresses within plastically deformed layers are equilibrated with elastic stresses in the core of the material. Higher values of microhardness also corroborate the presence of compressive residual stress on the recast layer. The surface morphology of machined surface (figure 4), with few micro cracks and thinner recast layer (figure 6), implies the absence of tensile residual stresses due to low discharge energy. The minimal amount of residual tensile stress in the thin recast layer was equilibrated by rest of the material. Similar kind of observation has been reported by Soo et al [28] during machining (WEDM) of Ti–6Al–2Sn–4Zr–6Mo alloy. Cong et al [29] observed compressive residual stresses deeper in the WED machined surface, below the recast layer.

3.8. EDS analysis of machined surface
Figure 8 exhibits the EDS analysis of the machined surface where figure 8(a) for Ti$_{50}$Ni$_{49}$Co$_{1}$, figure 8(b) for Ti$_{50}$Ni$_{49}$Co$_{5}$ alloy and figure 8(c) for Ti$_{50}$Ni$_{49}$Co$_{10}$ alloy. From figure 8 it has been found that all figures 8(a)–(c) clearly indicates the Ti, Ni and Co materials on the machined surface of all three alloys. But through EDX analysis, other elements were observed on the machined surface such as Copper (Cu), Zinc (Zn), Carbon (C) and...
Oxygen (O) due to the machining process. The residuals of copper (Cu) and Zinc (Zn) were recognized in all three alloys. This might be because of the melting and solidification of the wire material during spark erosion in WEDM process. The presence of oxygen in these alloys was observed because of oxidation as a result of high temperature involved in the WEDM process. Although EDX results showed that carbon (C) and oxygen (O) exists in all three alloys; these elements were observed due to the fact that dielectric fluid normally contains carbon (C) from minute minerals present and oxygen (O) from water molecules. Same was noticed by kumar et al [30] during the machining of pure titanium using wire spark discharge machining process.

4. Conclusions

- During this study, it has been proved that $T_{\text{on}}$ and SV both are most influential process parameters of wire EDM process.
- Lower values of MRR and Ra have been noticed at the 105 $\mu$s $T_{\text{on}}$ and 60 V SV while higher values of these outputs at 125 $\mu$s $T_{\text{on}}$ and 20 V SV.
- It was observed during this study that by increasing the percentage of Co in TiNi alloy, both MRR and Ra are decreasing. This is because at the same process parameters machining of a higher percentage of Co in TiNi alloy became difficult which is noticed in form of frequent wire breakage during the machining of higher percentage of Co mixed TiNi alloy.
- The effect of each experimental run on MRR and Ra has been investigated and it was found that minimum values of these outputs were recorded at 105 $\mu$s $T_{\text{on}}$ and 60 V SV while maximum values at 125 $\mu$s $T_{\text{on}}$ and 20 V SV.
- More microcracks, micro globules and craters have been observed at the higher $T_{\text{on}}$ and lower SV. A similar trend has been noticed for the selected alloys.
- The smoother surface was obtained for samples machined at lower $T_{\text{on}}$ and higher SV during surface topography analysis.
- At lower values of outputs 4.2 $\mu$m for Ti$_{50}$Ni$_{49}$Co$_1$, 4.6 $\mu$m for Ti$_{50}$Ni$_{45}$Co$_5$ and 4.9 $\mu$m for Ti$_{50}$Ni$_{40}$Co$_{10}$ alloy observed while at higher values of outputs 30 $\mu$m for Ti$_{50}$Ni$_{49}$Co$_1$, 32 $\mu$m for Ti$_{50}$Ni$_{45}$Co$_5$ and 35 $\mu$m for Ti$_{50}$Ni$_{40}$Co$_{10}$ alloy were reported.
- The higher value of residual stress has been noticed on the machined surface of Ti$_{50}$Ni$_{49}$Co$_{10}$ alloy while lower on the machined surface of Ti$_{50}$Ni$_{49}$Co$_1$ alloy.
Copper (Cu), Zinc (Zn), Carbon (C) and Oxygen (O) were found additional elements on the machined surface during the EDS analysis of machined components for each alloy.

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