Synopsis

Gamma titanium aluminide alloy is attracting considerable interest due to their high temperature strength retention, low density (3.76 gm/cm³), good creep and oxidation resistance. TiAl based alloys are potential candidates for replacing Ti-base and Ni-based superalloys for structural applications in the range of 400°C to 800°C. This alloy is of great interest in aerospace and automobile industries. Most of these components have performed well in laboratory tests as well as in the field. Engine valves, turbine blades, airframes, seal supports and cases are some examples. But like other intermetallics these alloys are not ductile and have low fracture toughness at room temperature, which makes them difficult to fabricate. Further it is found that it is extremely difficult to machine by conventional method due to its excellent strength property. Different aspects of machining of this alloy have been investigated by several researchers. But no comprehensive research work has been reported so far in the field of Wire Electrical Discharge Machining (WEDM) of this alloy. No technology tables or charts are available for wire electrical discharge machining of such important and useful materials in industry. Therefore, it is imperative to develop a suitable technology guideline for optimum and effective machining of γ titanium aluminide alloy by WEDM.

It is already an established fact that the maximal fulfillment of the multi-criterial goals of the WEDM process may be achieved through exploring the effective combination of the various process parameters. Although strides have been made by the applied researchers in different parts of the globe to search out the machining characteristics and the related process control requirement of WEDM, a lot of further intensive research is still required for analyzing the effects of the various machining parameters, such as, pulse on time, pulse off time, pulse peak voltage, pulse peak current, dielectric flow rate and pressure, wire feed rate, wire tension, wire tool geometry, workpiece material properties, workpiece height etc. on the various machining performances like cutting speed, surface finish, wire offset setting and other product accuracy features so as to explore the optimal operating
condition of the process during machining of y-TiAl for achieving the enhanced yields in multi-criterial goals.

Thus keeping in view the above aspects and considering the demand of future technology for machining of y-TiAl the present research has been planned as follows:

(i) To develop an appropriate modeling technique of the WEDM process considering surface finish, cutting speed and dimensional deviation (wire offset) as response parameters both in single pass and multi-pass cutting operation.

(ii) To develop a suitable multi-objective optimization strategy to serve the real requirement in practice.

(iii) To develop a technology guideline in systematic manner for effective machining of gamma titanium aluminide alloy by adopting the aforesaid modeling and optimization strategy.

Keeping in view the previously mentioned objective of the WEDM process, the author has successfully designed and carried out the present set of research as stated hereinafter. Hence, the objective of the present research has been designed to be module as follows:

(i) To study existing processing technique of gamma titanium aluminide alloy and to explore the possibility of machining of this alloy by WEDM.

(ii) To apply the principles of additive model for modeling and optimization in rough cutting, a suitable orthogonal array is to be designed or selected to conduct a matrix experiments. The selected machining parameters will be pulse on time, pulse off time, pulse peak current, wire tension, servo reference voltage and dielectric flow rate for a particular job of a certain height. The experiments are to be performed by setting the various parametric combinations as statistically designed, to study the WEDM process characteristic features, like, material removal rate, surface finish and dimensional deviation phenomenon during machining of y-TiAl;
(Hi) To observe the microstructure of the material i.e. y-TiAl sample (in as received state) used for experimental study through light optical metallography.

(iv) To perform an in-depth study of the WEDM process from the point of view of analyzing the effect of different input parameters on the different machining performance criteria in rough cutting of y-TiAl, and to determine the significant factors on the machining performances as mentioned above by analysis of variance,

(v) To develop a suitable multi-objective optimization strategy using computer program that will be well suited for this process. For this purpose the problem will be formulated as a constrained optimization problem or Pareto optimization problem,

(vi) To develop a suitable technology guideline for single pass cutting (i.e. rough cutting) in handy, compact and tabular form which will be very much useful for shop floor engineer for optimal machining of gamma titanium aluminide alloy,

(vii) To observe the characteristics of the y-TiAl job surface produced by single pass WEDM. Surface topography as well as white layer will be studied through light optical metallography,

(viii) To carry out experimental investigation of multi-pass cutting (i.e. trim cutting) operation based on appropriate design of experiment and to model the trim cutting operation by both RSM and ANN tools and finally compare their performance,

(ix) To study the comparative performance of various neural network training algorithm for the purpose of modeling of trim cutting operation in wire electrical discharge machining,

(x) To study the influence of various process parameters i.e. pulse on time, pulse peak current, wire offset and dielectric flow rate in trim cutting operation during machining of y-TiAl;

(xi) To develop a suitable technology guideline for optimum machining of gamma titanium aluminide alloy in trim cutting and then carry out
optimization considering both rough and trim cutting operation in order to
explore the most appropriate machining strategy.

(xii) To perform the SEM study of the surface topography, micro-crack of the
γ-TiAl sample produced by WEDM under different trim cutting conditions
will be investigated. Characteristics of the white layer produced by
WEDM under low and high pulse energy condition will also be examined
through SEM micrograph.

The contents of thesis have been presented through chapter 1 to chapter 6 in
a well-designed manner involving exhaustive review of the past research as
highlighted in chapter 1.7. Property, application and prospect of machining of
gamma titanium aluminide alloy by WEDM in present manufacturing scenario have
been discussed elaborately in chapter 1. Fundamental features and application of
WEDM has also been discussed in this chapter. Chapter 2 explains the physics of
WEDM process and other features associated with this process. The constructional
and operational features of the WEDM system used in the present set of research
have been discussed in chapter 3.

Technique of parametric analysis and optimization for single pass cutting has
been explained in chapter 4. This chapter contains the overview of additive model
based on orthogonal experimentation. Detail discussion on formulation of multi-
objective optimization associated with WEDM process has also been discussed in
this chapter. Apart from this, the microstructure of gamma titanium aluminide and
the characteristics of WEDMed machine surface after rough cutting have also been
analyzed.

Chapter 5 presents the modeling and optimization of multi-pass cutting
operation of WEDM process. The fundamental aspects of Response Surface
Methodology (RSM) and Artificial Neural Network (ANN) have been discussed and
the issue of implementing these tools for modeling of the trim cutting operation in
WEDM has been analyzed in depth. Apart from this various training algorithms for
ANN model have been explored and their comparative performances have also been
analyzed. Finally this chapter develops a technology guideline to select real optimum machining strategy in a very systematic manner for a given machining criteria. Beside this, the surface topography and the characteristics of the white layer under different trim cutting conditions were observed and analyzed through SEM. The derived general conclusions out of the present research have been outlined in detail in chapter 6.

Within the constraints of limitations of the available resources, modeling, optimization and rigorous experimental observation based studies with wire-cut electrical discharge machining (WEDM) of y-TiAl in the present set of research investigations; the following general conclusions have been drawn:

(i) Successful utilization of the WEDM process for machining of gamma titanium aluminide alloy in manufacturing with the objective of achieving enhanced cutting speed, surface finish, geometrical accuracy and white layer characteristics depend greatly on the optimal control of the various dominant process parameters, like, pulse on time, pulse off time, pulse peak current, pulse peak voltage, wire tension, wire velocity, dielectric (water) pressure and flow rate.

(ii) The microstructure of the material i.e. y-TiAl sample (in as received state) used for present experimental study has been investigated through light optical metallography (LOM). It was typically a fully lamellar structure. The grain size varies from 100 to 150 microm. The colonies consist of alternate y and alpha2 laths. Coarsening and beginning of spheroidization of lamellae were observed in the sample. In addition to this bright appearing (3-phase was also observed on the grain boundaries.

(iii) In the present research study six control factors with three levels have been considered in rough or single pass cutting operation. The three most important criteria i.e. cutting speed, surface roughness and dimensional deviation have been considered as measure of process performance. The process has been modeled successfully using additive model in order to predict the response parameters as function of six different control
parameters. Experimental result demonstrates that machining model is quite suitable.

(iv) It is a well known fact that it is very difficult to obtain a mathematical correlation of the parametric effects on various criterial yields. Based on the experimental results parametric analysis has been carried out. The analysis of the experimental results yielded the useful outcome that the machining speed is mostly influenced by pulse on time, pulse off time and wire tension; surface finish is mostly affected by pulse on time. Peak current, wire tension and flow rate can also influence the surface finish but their effect are much less compared to pulse on time. From the trend of variation of cutting speed and surface finish with respect to different control parameters, it was observed that optimization of both these criteria simultaneously is conflicting. Thus, it is imperative that a suitable multi-objective optimization strategy is very much essential.

(v) The significant factor for dimensional deviation is only pulse on time and peak current. It is observed that both surface roughness as well as dimensional deviation are independent of the pulse off time. This aspect is very important as under certain critical machining (e.g. at sharp corners, during taper cut condition, complex profile or may be to avoid frequent wire breakage) where pulse off time can be varied as per requirement to achieve better stability and accuracy without affecting the dimensional accuracy and surface finish significantly.

(vi) Characteristics of the surface produced by maximum cutting speed in rough cutting operation were investigated. Surface topography as well as white layer was studied. Several micro cracks were observed in the white layer. The cracks mostly are perpendicular to the surface of the sample, they run across the total depth of the white layer and sometimes they continue in the layers underneath the white layer. The thickness of the white layer was around 12microm.

(vii) The WEDM process has been successfully optimized. The developed additive model was used to predict the process performance for all
possible 243 combinations of control factors. As it is a case of a multi-objective optimization problem this can be solved either by constrained optimization algorithm or by adopting the philosophy of Pareto-optimal solutions. Both methods have been tried and found suitable. Using constrained optimization technique one can select the optimum parametric combination which will result in maximum productivity while maintaining the required surface finish criterion within limit. Beside this, the program is also capable of optimizing the process under multi-constraint conditions i.e. while maintaining the surface roughness as well as internal corner radius within desired limit. By using another computer program the 20 Pareto-optimal solutions were searched out from the set of all 243 outputs. This set of 20 Pareto-optimal solutions will act as a guideline for optimum machining of y titanium aluminide alloy in rough cutting operation.

(viii) Attempts have been made further to model and optimize the WEDM process in trim cutting operation through the classical design of experiments, response surface methodology (RSM). The three important response parameters i.e. trim cutting speed; surface roughness and dimensional deviation have been expressed as function of pulse on time, peak current, flow rate and effective wire offset in trim cut. The most striking phenomenon here is that a data transformation (log transformation) improves the fit of the model considerably.

(ix) Using the same experimental data set, the process has also been modeled using ANN tool based on automated regularization. Response parameter and control factor remaining same as before. A 4-30-3 network was used. From the post training analysis goodness of the proposed ANN model was confirmed.

(x) A comparative study has been carried out between RSM and ANN model. Both this model was developed on the basis of same experimental data set. It was observed that performance of the ANN model is better compared to RSM model both in post regression analysis as well as in test data set. This
proves the superiority of the ANN model and hence it was decided to consider ANN model for trim cutting operation in WEDM.

(xi) Attempt has been made to further improve the ANN model. As it is a case of function approximation problem from a limited set of experimental data, it appears that both early stopping and Bayesian regularization are promising candidates. Additional set of experiment has been carried out to create validation data set which is essential to carry out early stopping method of training. After carrying out the training, it was observed that both methods can model the process but Bayesian regularization performs better compared to early stopping not only in post regression analysis but also in test data set.

(xii) It was further observed that present ANN model based on automated regularization gives better prediction performance than earlier one. The probable reason is that later has more number of experimental data for its training. This is an important advantage of ANN model. Because the model is open and there is always a scope to enhance the prediction performance of the model by incorporating additional training data. The final ANN model based on Bayesian regularization using additional training data set has been considered for further analysis due to its best prediction performance.

(xiii) Based on the developed ANN model various control factors have been studied at a time to establish the trend of variation for various machining criteria with various control parameters. From the various response surfaces, it was observed that cutting speed, surface finish and dimensional deviation increase with increase in pulse on time and peak current. Cutting speed and dimensional deviation decrease and increase respectively with increase in effective wire offset. Surface roughness is not so significantly affected by effective wire offset. Cutting speed, surface finish and dimensional deviation have an optimum value for a particular flow rate and this effect is particularly predominant at higher value of pulse on time.
Based on the developed ANN model 44 Pareto optimal solutions were searched out to develop the technology guideline for trim cutting operation. It was observed that the surface quality decreases as the cutting speed increases and they varies almost linearly up to surface roughness value 1.52 μm and cutting speed 14.01 mm/min. Beyond this value of cutting speed, surface roughness deteriorates drastically with increase in cutting speed.

Further, this process has been successfully modeled as a constraint optimization problem. A program was developed that will enable one in selecting the optimum parametric combination which will result in maximum productivity (cutting speed) while maintaining the required surface finish criterion within limit. Beside this, the program is also capable of optimizing the machining process (under multi-constraint conditions) while maintaining the surface finish as well as effective wire offset as per requirement.

Finally, the strategy to select appropriate machining operation (rough or trim cutting operation) has been proposed in a very systematic manner. Optimization was carried out considering both rough and finish cutting operations in order to search out the true optimal parametric combinations. It was observed that trim cutting is more productive if the required surface finish is below the critical Ra value of 2.85μm. On the other hand if the surface finish requirement is above 2.85μm then rough cutting is more productive. This combined technology setting is extremely useful for true optimal machining of gamma titanium aluminide. Further this table may help in selection of process parameter in fully automated way. Thus, the present research findings may be considered as a quantum jump toward computer aided process planning (CAPP).

Comparative analysis of the WEDMed surface topography produced with high \( (I_p(A) \times T_{ON}(\mu s) = 90 \times 0.85) \) and low pulse energy \( (I_p(A) \times T_{ON}(\mu s) = 70 \times 0.25) \) was carried out. It was apparent from the SEM micrographs that the surface produced by low pulse energy is much smoother. From the
SEM micrographs it was seen that higher pulse energy produces a larger crater, approximately 40-50μm and lower pulse energy produces smaller crater, approximately 20-25μm. Typical overlapping layers were also observed from micrographs. The small spherical debris particles and very small pock marks were also identified from those figures. In both cases their diameter lies in the range of 2-4μm. Apart from these the most significant fact to be observed was the presence of micro-cracks on the surface under high pulse energy condition. No such micro crack was observed with low pulse energy during trim cutting operation. From the above observation by the Scanning Electron photomicrographs, it can be concluded that higher pulse energy is undesirable because of occurrence of micro-cracks on the surface.

(xviii) Apart from surface topography, edge produced by rough and trim cutting operation has also been investigated by using light optical microscope. It was observed from the micrographs that surface and edge produced by lower pulse energy is comparatively smoother.

(xix) White layer obtained under different trim cutting conditions have been examined thoroughly. Lower pulse energy in trim cutting results in thinner white layer compared to rough cutting operation. It was observed in trim cutting operation that the white layer depth decrease with decrease in pulse energy. (i.e. white layer depth is 10μm and 3μm when Ip(A)×T_on(μs) = 90×0.85 and Ip(A)×T_on(μs) = 70×0.25, respectively) It was noted that the characteristics of the white layer produced in trim cutting under high pulse energy condition are similar to the white layer produced under rough cutting condition. Maximum crack depth varies in the range of 10-15μm. Apart from this some globular voids were observed. These voids appear as pock mark when surface topography was examined through SEM. This perhaps occurs due to the presence of entrapped micro gas bubbles. Again the characteristics of the white layer produced under low pulse energy condition were also examined. A comparatively smooth surface was observed without the presence of any micro cracks. Thus, it is apparent
that an investigation, leading to selection of the optimum peak current and pulse duration which would assure absence of micro cracks, is very much desired.

Hence, it is believed that the present set of research findings will not only be opening up new insights to the fundamental and applied research in the area of the WEDM of gamma titanium aluminide but also be quite useful to the manufacturing Industries and tool rooms for taking a quantum jump to the arena of the present day needs of varieties of other electrically conductive material machining irrespective of their hardness, toughness, micro-structural properties, configurational aspects in the changing scenario of physical requirements for products or parts.

Through the experimental analysis and test results, author also attempts to justify the uniqueness of the research work in exploring the optimal parametric combinations of the WEDM process for achieving optimal machining performance characteristics during machining of y-TiAl both in the single pass and multi-pass cutting. The author expects that the present research findings will provide a lot of insights to the elementary and applied researchers and manufacturing engineers in clear understanding of the influence of various parametric features of wire electrical discharge machining and also give a direction and guidance to the practical manufacturing engineers for fulfilling their present day needs of the aerospace, aeronautics, automobile industries for effective machining of gamma titanium aluminide alloy.

Author also believes that the present set of research with the proposed future research direction on wire electrical discharge machining of gamma titanium aluminide is an important contribution of original nature, which will provide a great impetus for effective utilization of this material in modern manufacturing industries.