AN INVESTIGATION ABOUT THE MACHINABILITY OF THE NICKEL BASE ALLOY WELD INCONEL 625

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Abstract. *The nickel base alloys are known as one of the most dificult alloys to be machined despite its very low machinability. The reason for that characterist is its high ductility combined with a strong abrasive behaviour and a very sensible work harden feature. The Inconel 625 has a very small decrease in its strengh when submited into high temperature conditions, tough it can be considered as a heat resistant alloy. This type of material is often used in petrochemical plants and aerospace industry because the environment in both cases is very agressive for the mechanical and chemical behaviour of the materials employed. A very few papers have been developed to clarify which are the best conditions to machine the Inconel 625 in the milling operation with interchangeable carbide tools. This objective of this work is to contribute in this area, presenting some of the details for the milling operationg of the Inconel 625 showing a comparison among some diferent cutting conditions. The chalenge of this work is to define a satisfactory and safe parameter to machine the Inconel 625, assuring that the work harden effect will not damage the cutting tool prematurely.*

Keywords: *nickel base alloy, Inconel 625, machinability, cutting conditions, milling.*

1. Introduction

1.1 The use of super alloys

The use of super alloys in actual industry has reached an importante role in many aplications where special properties are needed. Sometimes this specials properties are obtained with the use of many diferentes materials joined all together but in many cases it is not possible to fullfil this specifications with regular materials. In these cases, the use of super alloys is the only way to stablish reasonable and successful operation conditions.

In order to clarify the need of special materials one must list the following aplications: petrochemical plants, aerospace products and biomedical technologies. The term super alloys is used inspite of the fact that one or more characteristics of this materials are strongly lower or higher than those obtained in regular materials.

The figures 1a, 1b and 1c are well known examples of the use of super alloys. The Fig. 1a shows the use of super alloys at petrochemical cracking plants. The subsea valve must protect the operation from disearable conditions like temperature gradient, stress and corrosive environment. The Fig. 1b shows the use of super alloys at aerospace products such turbine blades. This aplications has a very aggressive behaviour because the internal flow is under high temperature and the external environment is at very low temperatures. The Fig. 1c shows the use of super alloys in biomedical aplications. The use of special materials for prothesis offers a new chalenge for this industry. In this case, the material must obey a human interface conditons; wich does not accept failure in any case.

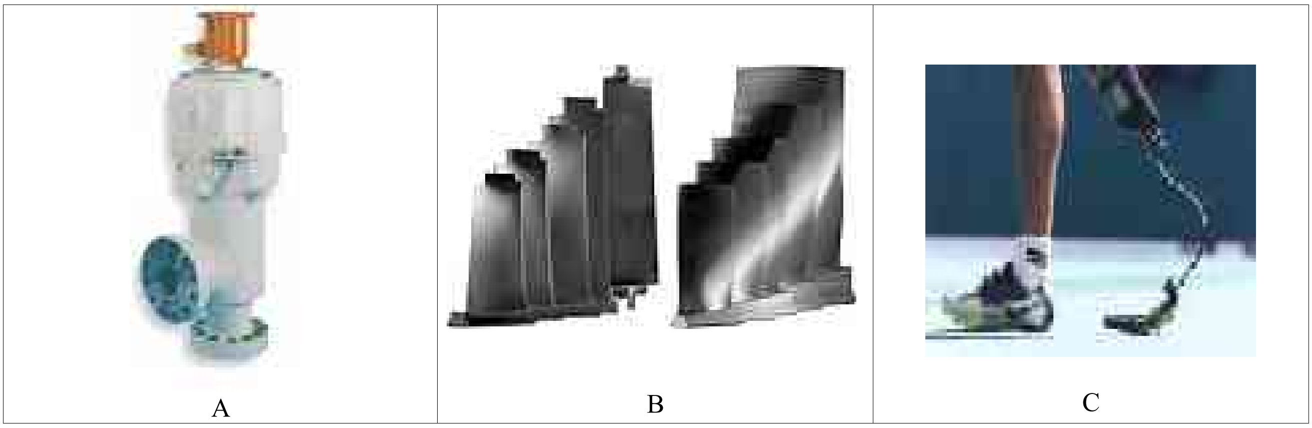

Figure 1. a) The use of super alloys at petrochemical applications: sub sea choke valve, b) The use of super alloys at aerospace products: a set of turbine blades and c) The use of super alloys at biomedical technologies: a special designed prothesis.

1.2 The machining of nickel base alloys

The main characteristic of a nickel base alloy, further its high mechanical resistance under high temperature, is its poor machinability. Following those results found by Ezugwu *et al* (1999), the nickel base alloys are the worst material to be machined.

Considering the fact that the machinability is a technological property, it is acceptable to affirm that there are no specific characteristics that can influence at the value of the machinability. The most useful aproach to understand and to define the machinability is the comprehension of the system wich this material is supposed to be machined.

An attempt to isolate the mateial properties that can influence the value of the machinability of this material is listed below. This list stablishes the properties that are commonly measured and predicted. However the machinability is not only defined by the analisys of this list because the tribological behavior of the system composed by the workpice material, the tool material and the coolant employed in this operations are not analyzed together and the dynamical behaviour of the system composed by the workpiece, the machine and tool are not analyzed too.

Isolated characteristics of the workpiece material that influnce at the machinability:

1. Hardness;
2. Stress properties;
3. Chemical compositon;
4. Microestructure;
5. Cold forming degree;
6. Work hardening stresses.

Analyzing the published material that has already been printed about nickel base alloys and trying to connect those results with the results that has been found in the experimental activities of this work becomes easy to observe that some topics are equal to several researchers and some characteristics of this material can be safely stablished, just like:

1. High mechanical resistance at elevated temperature;
2. High abrasion because its chemical elements;
3. High ductility;
4. High work hardening.

The cutting conditions practiced nowadays are the evidence that machining the Inconel 625 at every kind of machining process is still a chalenge because the economical conditons for this operation is usually not reached with speeds and feeds that go beyond 25 to 50 m/min and 0,1 mm/teeth respectivly.

Another important aspect, which must be taken place during a complete analysis of the machinability of the Inconel 625, is the tool wear and the mechanisms presented at the interaction between the tool and the workpiece material. The correct choice of the tool material and the proper geometry of the tool guarantee a reasonable part of the machining process. The four aspects listed above are determinat for a correct choice of the tool material and geometry.

When considering each of these aspects separatly for a correct choice of the tool, it is profitable to observe that the tool must offer at the same time hardness and toughness and the geometry must be as positive as possible without becoming frail.

The continuous cutting must employ one kind of analysis and the interupted cutting must employe another. It shows that the protection of the cutting edge cannot be taken as a general rule for every type of machining process. The dynamical conditions can influence a lot in this choice and no aspect must be taken separetly when defining the operation details.

1.3 The welding process of nickel base alloys

The welding process of nickel base alloys differs from many other welding processes due to its scope. The use of nickel base alloys for welding has a diferent purpouse than weld (unite) wokpieces together. Creating a protective layer over base metals is the main objetive of welding nickel base alloys.

There are some reasons for this aplications and they are based on economical and technical proofs. First of all it is possible to establish that a part wich must offer a specific chemical property in many cases does not need to be designed with a special material in its whole frame. Sometimes a protective metalic layer is enough to prevent corrosion so that the aplication of the nickel base alloy with a controled welding process is proftable for the total price analysis. Secondly, but without less importance, is the combined mechanical behaviour that can be necessary in some specific applications. Applying Inconel 625 or any other kind of super alloy weld is sometimes the only way to prevent the catastrophic damage in components wich a severe injury has been applied. For example we can show the maintenance routine that huge hydroblades must suffer. It is almost impossible to keep at hand outside the operation a hydroblabe so that a maintence in its wear must be planned and super alloys are used to fulfill these situations. The cavitation is corrected with the deposition of a super alloy without damaging the base metal.

An important aspect in the welding process of nickel base alloys is the low atomic migration between the base metal and the filler metal. The Fig.2 shows a micrography of the nickel base alloy Inconel 625 weld deposited over a sample of SAE 8630.

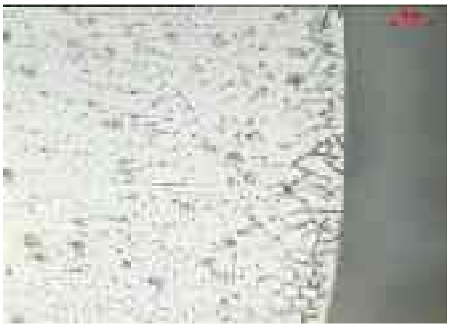

Figure 2. Micrography of the nickel base alloy weld Inconel 625 deposited with arc welding process.

The micrography of the figure 2 was obtained with a etcthing solution of 100ml of HF with 100ml of HNO_3. The imersion time was 5 minutes. The base metal was consumed and the focus was not possible (right side of the picture). The scale shows the proportion of the atomic migration from the steel into the weld metal (left side of the picture). The total layer of the welded material for the efective mechanical and chemical behaviour of the part produced was 18mm.

1.4 Chemical composition and mechanical properties of the Inconel 625 nickel base alloy

The graphs presented at the figures 3 and 4 exemplify the characteristics listed at 1.1 and 1.2. The table 1 presents the chemical composition of this alloy.

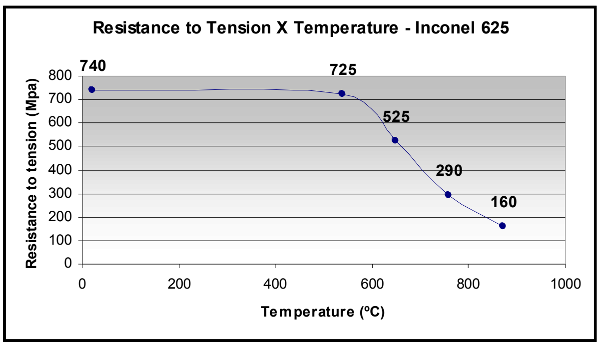

Figure 3. Resistance to tension X Temperature.

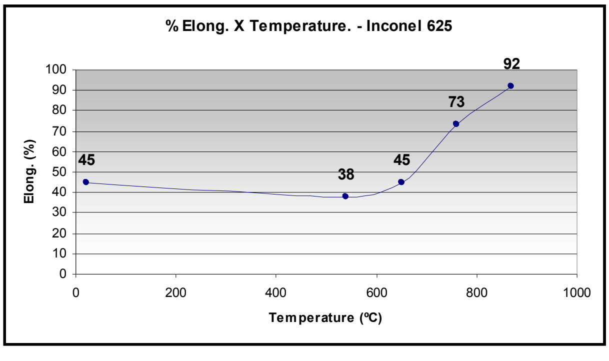

Figure 4. % Elongation X Temperature.

Table 1. Chemical composition of the Inconel 625 weld.

Chemical element	Cr	Fe	Mo	Nb+Ta	C	Mn	Si	P	S	Al	Ti	Co	Ni
Min.	20	0	8	3,15	0	0	0	0	0	0	0	0	58
Max	23	5	10	4,15	0,1	0,5	0,5	0,015	0,015	0,4	0,4	1	---

The nickel base alloy Inconel 625 is an austenitic matriz reinforced with several types of carbides. This alloy is known as a Ni-Cr-Mo alloy and it is obtained by induction vacuum foundry methods. There some explanations for the high mechanical resistance behaviour of this alloy and the major aspects are listed below.

1. Matrix Alloy (γ) – It´s the solid solution CFC with a high percentage of alloying elements;
2. Primary Gama phase ($\gamma^`$) – It happens by the precipitation of high fractions of Al and Ti accordingly to the nickel austenit. It is an inter-metallic that increases the mechanical resistance of the alloys as soon as the temperature increases.
3. Carbides – Carbon is added to react with the refratory and reactive elementes resulting in the formation of the prymary MC. During the expositon at long periods, the MC is decomposed into two types of carbides ($M_{23}C_6$ and M_6C), localyzed at grain boundary, providing an increase at the stress resistance of the alloy.
4. Grain Boundary – A thin film of carbides and other lower chemical elements forms it in order to provided a higher fracture resistence at medium and elevated temperatures.
5. TCP-Topologically Close Packed phases– They are secondary phases μ, σ and δ that provide mechanical resistance to the alloy. Their structure is tetragonal and their interaction occurs by the geometrical and chemical affinity with the CFC matrix alloy.

The Inconel 625 alloy can be strenghtened by use use of diferents methods. The most common methods are:

- Solid solution treatment;
- Hardening by precipitation;
- Hardening by dispersion;
- Heat treatments;

It is important to notice that among the effect of chemical elements presented at Table1, the aluminum has a very particular influence in this alloy. Diferently from its influence at other alloys, the presence of aluminiun guarantees the higher influence at the increase of the mechanical resistance. In many cases, the titaniun is added to moderate the influence of the aluminiun, because it can frails if his proportion is not controlled.

The presence of carbides must be observed by the aspect of machinability as one of the worst factor to be overcome. The high melting point of this particles and their high abrasive profile influences the lower machinability. It is useful to remind that the tool material is composed by carbides and some of them has the same composition.

Despite the welding process, slag and hardness gradient may appear along the welded profile. This influence must be taken as an important consideration, and the specification of the tool material and geometry must contemplate this factors.

2. Experimental Methodology

The methodology purposed to investigate the mechanical behaviour of the workpiece material and its influence at the tool life was the face milling process. The experiments were divided into two sets of experiments. The reason for this division was the search for a better identification of the best condition to machine this material and what could be done to improve this result. The general conditions for the first and the second set of experiments are listed bellow:

- Face mill with 63 mm of diameter;
- 7 cutting edges;
- Tool material – Cemented carbide P20-P45 coated with PVD TiAlN;
- Tool gemetry – Axial rake: 16º; Radial rake: 9º; Lead angle: 90º;
- Wokpiece material – A SAE 8620 25mm plate covered with a 18mm multilayer weld of Inconel 625 applied with a shielded electrode arc weld process. The conditions for the welding deposition was:
  Circuit Current =140 to 150 A
  Power supply= 24 to 26 V DC
  Electrode diameter= 4mm
  Depositon displacement speed=10 to 13 inches/min
- Machine tool – A vertical CNC milling center with 25 kW spindle power;
- Coolant conditions – An 8 to 9% mineral base cutting fluid water solution applied along the total contact lenght and ahead of the cutting point in order to avoid improper cut of the chips already removed;

- Depth of cut =2mm;
- Engagement of the milling cutter = 42mm.

The Fig. 5 shows the experimental set.

Figure 5 – Experimental set.

The Table 2 and Table 3 show the cutting conditions for each experiment done.

Table 2. First set of experiments to be executed.

Experiment number	Cutting Speed (m/min)	Feed (mm/teeth)	Cutting	Use of Coolant
1	30	0,065	Up milling	Yes
2	30	0,1	Up milling	Yes
3	45	0,065	Up milling	Yes
4	45	0,1	Up milling	Yes
5	30	0,065	Down milling	Yes
6	30	0,1	Down milling	Yes
7	45	0,065	Down milling	Yes
8	45	0,1	Down milling	Yes

Table 3. Second set of experiments to be executed.

Experiment number	Cutting Conditons	Use of Coolant
9	Best result of the first set of experiments	Yes
10	Best result of the first set of experiments	No

3. Results

3. 1 Results of the first set of experiments

In order to observe the diference provided by the two diferent milling strategies the results were divided into two graphs. Figure 6 shows the results to the up milling strategy and the figure 7 shows the results to the down milling strategy.

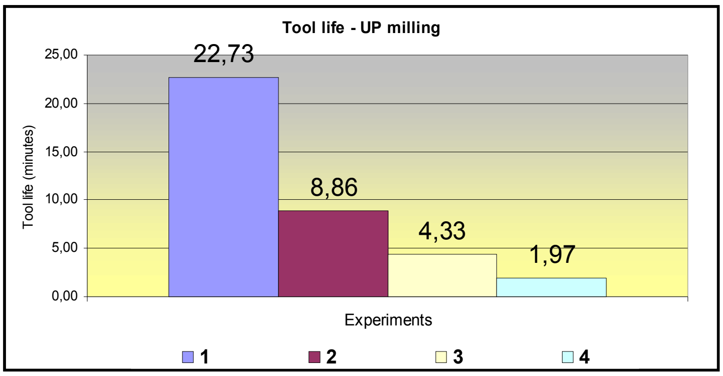

Figure 6 – Results of the experiments 1 to 4.

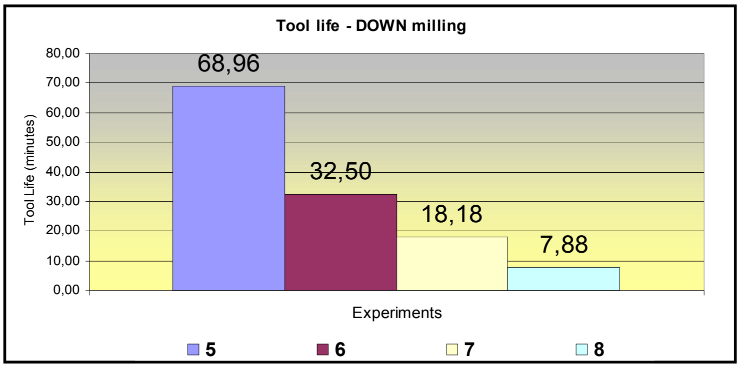

Figure 7 – Results of the experiments 5 to 8

The adopted criteria for both sets of experiments was the flank wear established as 0,3mm or any cutting edge breakage in one or more inserts at once. The wear observations was made locally and the wear evolutive behavior was subject of a further paper developed by the same researchers.

3. 2 Results of the second set of experiments

The graph shown at Fig.8 is following the experiments planning (Table 3) and it is the reproduction of the best result of the first set of experiments. As one can see it is the reproduction of the experiment number 5 with and without coolant.

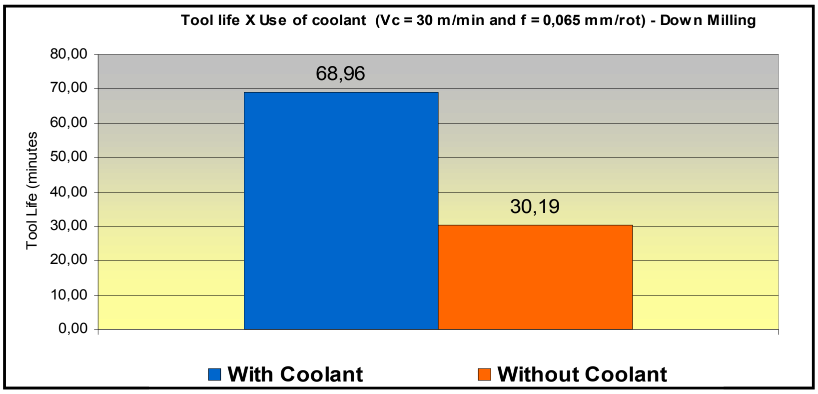

Figure 8 – Results of the experiments 9 and 10.

4. Discussion

4. 1 First set of experiments

The Table 4 shows the percentage of increase at the tool life when the milling strategy was changed. It is noticeable that the down milling strategy showed a better performance at the tool life than the up milling strategy.

Table 4 - Percentage of increase in tool life.

Similar experiments	Tool life Up milling	Tool life down milling	% of increase
1 and 5	22,73	68,96	203,43
2 and 6	8,86	32,50	266,67
3 and 7	4,33	18,18	320,10
4 and 8	1,97	7,88	300,00

The reason for this increase is layed on the fact that the work hardening behaviour of this material was higher when the cutting edge penetrated softly at the workpiece material. This characteristic happens at up milling strategy because the chip width rises from zero up to its maximum value during the evolution of the up milling and the uncut material that remains at the workpiece offers to the new cutting edge that reaches this strenghtened point an elevated mechanical resistance.

An important fact that must be pointed during the analysis of the graphs shown at Fig. 6 and Fig.7 is that the increase of the cuting speed had a prior influence at the tool wear than the increase of the feed.

The strategy that showed the best performance was the down milling. The tool geometry had an important influence at the work hardening behaviour because the attrition presented at the beginning of the cutting edge penetration did not happen with the same intensity with the down milling strategy. The use of high positive cutting edges is favorable and no chip at the cutting edge was identified with the down milling. The chip of the cutting edge was predicted but the hardness of the material was not enough harmful to cause it.

4. 2 Second set of experiments

The Table 5 shows the percentage of decrease at the tool life when the best result of the first set of experiments was performed with or without coolant.

Table 5 – % of decrease in tool life without the use of coolant

Similar experiments	Tool life	% of decrease
9	68,18	
10	30,19	55,72

It can be observed a severe reduction at the tool life when the coolant was eliminated. The reasons for that is the increase of process temperature, the friction ratio and the adhesion of the workpiece material on the rake face and the clearence face of the tool.

There are many researchers who deny the existance of coolant at the metal cutting zone during the milling process. It is a fact that the temperature gradient is higher when coolant is applied at the face milling however it was noticeable that even with a higher temperature gradient the tool life was almost two times higher.

4. 3 Tool wear mechanisms

It was necessary to identify the tool wear mechanisms in order to conclude the analysis of the results. At this time a special analysis was done with scanning electronic microscopy and the results can be seen at Figure 9 and Figure 10.

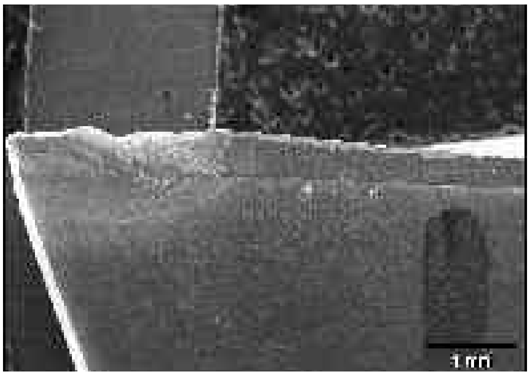

Figure 9 – Tool profile after experiment 5 (20X).

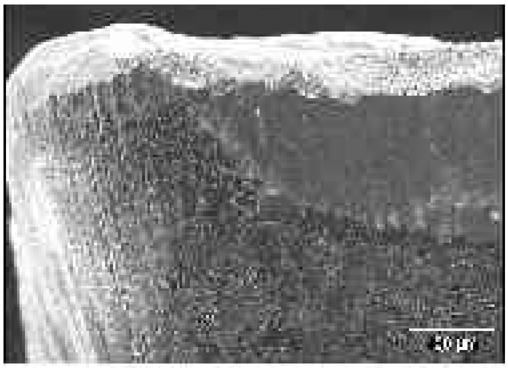

Figure 10 – Detail of the tool nose of Fig.9 (200X).

The figure 9 shows the total profile of the tool wear. It can be identified an expressive notch wear at the depth of aprox. 2mm. It can be seen a considerable flank wear caused by the abrasive feature of the workpiece material and an adhesion behavior of the Inconel 625 over the clearance face (Figure 10). A stick-and-slip mechanism is purpoused to explain the harmfull influence of the adhesion and the presence of diferent carbides at the worpiece material explains the abrasive behavior of the flank wear.

5. Conclusions

The specification of face milling conditions must be done after a proper analysis of the worpiece material that will be machined. The understanding of the microstructure is important to prevent premature tool wear because the tool material must diffuse into the workpiece material and vice-versa despite their similar composition. The tool geometry and the milling strategy are strictly related and the exact point to penetrate the cutting edge into the workpiece material must be predicted and obeyed during the process.

The use of coolant is a prior condition to machine this type of material even tough the increase of the temperature gradient.

It is important to observe the strenghtening of this alloy at high temperatures and the melting point of the chemical elements that constitute the tool material and the workpiece material. The understanding of the wear mechanisms has a prior importance because the maximum productivity will only be reached if this aspcet is known.

6. Acknowledgements

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