Application of Cryogenic Treatment to Extend the Life of the TiAlN-Coated Tungsten Carbide Milling Cutter

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Abstract

Cutting tools are important to the manufacturing industry since they will affect production efficiency and product quality. Cryogenic treatment can improve the material properties by decreasing residual stress, stabilizing dimensional accuracy, and increasing wear resistance. The purpose of this study is to investigate the feasibility and effect of cryogenic treatment on the performance of TiAlN-coated tungsten carbide milling cutters for machining the Inconel alloy 625 in terms of different testing methods (e.g., hardness, wear resistance, residual stress, microstructure, and tool life test). Experimental results indicate that after cryogenic treatment there is less wear, the microstructure is denser, residual stress is decreased, the adhesion of coating and tungsten carbide is improved, and the tool life is effectively improved.

1. Introduction

Cutting tools play an important role in many manufacturing industries because they influence the production efficiency, quality, part accuracy, and cost. Tungsten carbide is one of the most commonly used substances in cutting tools because it offers a high degree of hardness, wear resistance, and thermal stability. The cutting tools are often coated with TiAlN because of its low thermal conductivity and high-temperature oxidation resistance. Lower thermal conductivity can increase the life of the cutting tool by preventing heat transformation to the tool.

Cryogenic treatment is an add-on process to the conventional heat treatment process to improve the material properties by decreasing the residual stress, stabilizing dimensional accuracy, and increasing hardness, fatigue resistance, wear resistance, and the life of tool. Therefore, cryogenic treatment has been widely used in the tool, cutting tool, and mold industries [1-2].

Inconel alloy 625 belongs to a group of materials that are difficult to machine because they have high chemical reactivity and a high tendency to adhere to the cutting tool, low heat conductivity, maintenance of strength at high temperature, and a low elasticity module.

There has been a report of deep cryogenic treatment at −196°C on tungsten carbide coated with TiAlN and used in cutting hot rolled anneal steel stock [2], but there is no report investigating the influence of cryogenic treatment on tungsten carbide coated with TiAlN in machining Inconel alloy 625. The purpose of this study was to investigate the feasibility and

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effect of cryogenic treatment on the performance of a TiAlN-coated tungsten carbide milling cutter for machining the Inconel alloy 625 in terms of different testing methods (e.g., hardness, residual stress, metallography, scanning electron microscope [SEM], and tool life test) and to clarify the influence of process parameters (cooling rate / soaking time) on the characteristics of the tool when performing deep cryogenic treatment at -196°C.

2. Experimental methods

2.1 Specimens preparation

The specimens were prepared to measure the hardness, test the wear resistance, and observe the microstructure before/after cryogenic treatment. To follow the standard, the specimens need to polish to below Ra 0.8 μm. The roughness was measure by Jenoptik Hommel T8000 RC. There were three specimens in this research, and the roughness of the specimens is shown in Table 1.

Table 1. Specimen roughness

Roughness of specimens (μm)	
Untreated	0.186
Process A	0.238
Process B	0.228

2.2 Cryogenic treatment

The cutting tool material in this research was WC-Co cemented carbide with a TiAlN coating. First, the tools were put into the cryogenic treatment processor (Applied Cryogenics CP-200vi) for treatment using liquid nitrogen. The details of the experiment are shown in Table 2. There were two processes (A & B) with different process parameters used in these experiments, and process B had a lower cooling rate and longer soaking time compared with process A.

Table 2. Cryogenic treatment process

Step	Process A	Process B
Cool down	-196°C (6H)	-196°C (10H)
Soaking	-196°C (6H)	-196°C (10H)
Return to room temperature	27°C (14H)	27°C (14H)
Tempering	150°C (6H)	150°C (6H)
Soaking	150°C (4H)	150°C (6H)
Return to room temperature	27°C (0.5H)	27°C (0.5H)

2.3 Hardness measurement

In this test, the ASTM E384-11 standard and Vickers hardness tester (Future-Tech FM-300) were used and there were two types of load used to separately measure the coating and tungsten carbide [3]. A 100-g load was used to measure the hardness of the coating, and a 300-g load was used to measure the hardness of the tungsten carbide.

2.4 Wear resistant test (ball on disk)

The wear resistant test (ball on disk) was performed according to the ASTM G99-17 standard [4]. This test was carried out using a 9.8-N load and a rotational rate of 0.1 m/s for 1 hour. After the test, the weight loss of each specimen was measured using a digital balance.

2.5 Microstructure observation

To observe the microstructure of the cutting tool, a SEM, and an optical microscope were used. Before observation, the specimens were grinded, polished, and etched to reveal their microstructure using a water solution mixed with 10% potassium ferricyanide for 10 to 20 seconds.

2.6 Residual stress measurement

The effect of cryogenic treatment on residual stress of the milling cutters was measured by X-ray diffraction (Bruker D8 Discover XRD). The milling cutters were scanned for a 2θ angle of 82.5° to 85.5° and using copper filter Cu K α radiation generated at 40 kV and 30 mA with steps employed at 0.025 at 30 sec per step.

2.7 Milling experiment and material

The milling test was carried out using a Tongtai MDV-508 milling machining center under wet milling conditions. The spindle speed was 800 rpm, the feed rate was 245 mm/min, the depth was 0.05 mm, and the machining method was end milling [5]. For the material, Inconel 625 alloy was used, and the workpiece size was $100\times70\times50$ mm^3. The chemical components are shown in Table 3.

After the milling test, in order to identify the wear of the milling cutter, a microscope was used to observe the wear and measure the weight loss of the milling cutter.

Table 3. Chemical composition of Inconel 625

Element (%)	Ni	Cr	Co	Mo	Nb	Al	Ti	Fe
Inconel 625	58.0	20.0 - 23.0	1.0	8.0 - 10.0	3.15 - 4.15	0.4	0.4	5.0

3. Results and discussion

3.1 Hardness results

The hardness results are listed in Table 4. Before cryogenic treatment, the hardness of the coating was measured to 2682 MHV and the hardness of the tungsten carbide was measured to 1805 MHV. From Table 4, the results indicated that the hardness of the coating increased after cryogenic treatment, and the effect of process B was better than that of process A. Based on these results, it can be concluded that the soaking time had a significant impact, with a longer soaking time obviously increasing the hardness of the coating. Varghese et al. also reported that when deep cryogenic treatment at -196°C is performed, if the treatment is up to 24 h, the hardness of tungsten carbide also increases with longer treatment time [1].

Table 4. Hardness of tungsten carbide and coating before/after cryogenic treatment

(Unit : MHV)	Untreated	Process A	Process B
Tungsten	1798.54	1799.64	1803.40
Coating	2682.26	2776.96	2919.84

3.2 Wear resistant test results

The TiAlN-coated tungsten carbide specimens were subjected to the wear test. The results of the coefficient of friction are shown in Table 5. From these results, it can be seen that after cryogenic treatment, the coefficient of friction of the coating was significantly reduced. A lower coefficient of friction can improve coating wear resistance. After the wear resistance test, the optical microscope was used to observe the surface. The results are shown in Figure 1. It can be seen that after the cryogenic treatment, the flake of the coating was remarkably reduced, and process B was obviously superior to process A. Finally, in order to accurately quantify the results, the weight of the specimen was measured using a digital balance. The results are shown in Table 6. From these results, the treated specimen weight was also reduced due to the reduction of the flake of the coating. From the above testing results, cryogenic treatment can effectively reduce the coefficient of friction, increase the adhesion between tungsten carbide and the coating, and improve the wear resistance.

Table 5. Coefficient of friction

Specimen	Coefficient of friction (μ)
Untreated	0.512
Process A	0.479
Process B	0.461

Table 6. Weight loss after wear test

Specimen	Wear weight loss (g)
Untreated	0.003
Process A	0.001
Process B	N/A
Remark : N/A indicates the weight loss beyond the limit of the digital balance.	

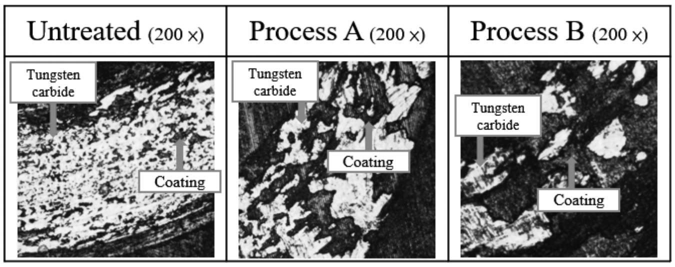

Figure 1. Observed surface after the wear resistance test

3.3 Metallography and SEM analysis

In this section, the optical microscope and scanning election microscope were used to identify the microstructure change and observe the adhesion between tungsten carbide and the coating. The metallography results are shown in Figure 2, which need to be complied with the ASTM B657-11 standard to define the α phase and β phase [6-7]. The chemical components of the α phase and β phase are listed in Tables 7 and 8. Due to the high tungsten content of the α phase, it can provide improved hardness and strength, and the high cobalt content of the β phase can provide superior toughness and corrosion resistance [7-8]. By comparing the metallography images with the different processes in Figure 2, it can be seen that after cryogenic treatment, the α phase (black points) and β phase (white points) of tungsten carbide were increased and the average grain size was reduced from 1.5 μm (untreated), to 1.0 μm (process A) and to 0.8 μm (process B).

The SEM images are shown in Figure 3, which also shows that after cryogenic treatment, the α phase (black points) and the β phase (white points) were increased and more uniform.

Adhesion between the tungsten carbide and the TiAlN coating was observed by SEM, and the results are shown in Figure 4. Comparing the SEM images in Figure 4, we found that the coating layer increases in thickness because of the cryogenic treatment and process B has a more profound effect than process A. Although the mechanism of the finding is currently unclear, it is obvious that the adhesion between tungsten carbide and the coating improves after cryogenic treatment, which was verified from the results in Figure 1 and Tables 5 and 6.

Table 7. Chemical components of α phase

Chemical components of α phase		
Element	Mass %	Atomic %
C	3.60	35.58
Co	1.32	2.65
W	94.43	60.93
Nb	0.65	0.84

Table 8. Chemical components of β phase

Chemical components of β phase		
Element	Mass %	Atomic %
C	4.79	37.75
Co	5.09	8.18
W	74.96	38.61
Nb	15.16	15.45

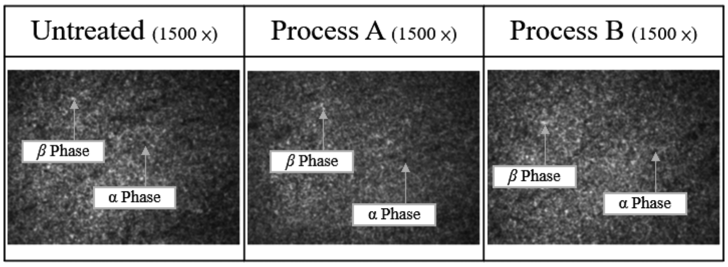

Figure 2. Microstructures for different cryogenic treatment processes

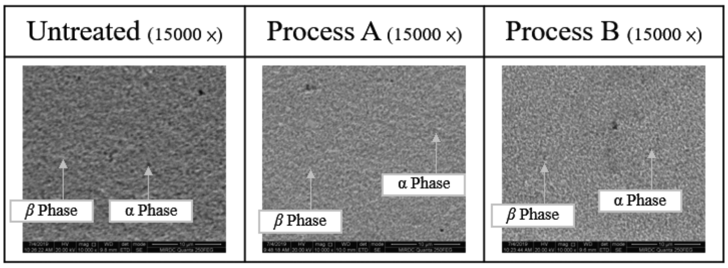

Figure 3. SEM images for different cryogenic treatment processes

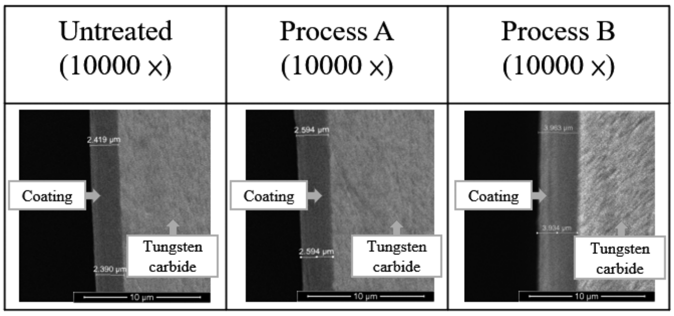

Figure 4. Adhesion between tungsten carbide and coating

3.4 Residual stress results

Residual stress results are shown in Table 9. Compared with an untreated and a treated milling cutter, the residual stresses were reduced by 3% and 9% for process A and B, respectively. Lower residual stress can improve the cutter dimension stability and increase the machining performance.

Table 9. Residual stress between different cryogenic treatment processes

	Value (MPa)	Rate of reduction
Untreated	-968.8	-
Process A	-936.7	-3%
Process B	-875.5	-9%

3.5 Tool life test results

This test used a total of two sets of milling cutters, which were divided into untreated, process A, and process B. The tool life testing results are shown in Figure 5. The untreated milling cutter edge was damaged at 26 minutes. At the same time, there was no obvious edge cracking for either process A and process B. These results show that after cryogenic treatment, there is a significant improvement on the tool life of the milling cutter. To compare the tool life between processes A and B, the milling test continued with the same milling parameters. As shown in Figure 6, the milling cutter edge of process A was damaged at 179 minutes, while at the same time, the milling cutter of process B could continue to be used for machining. From the above test results, it can be proven that the cryogenic treatment can prolong the tool life of the milling cutter and that the process parameters (lower cooling rate and longer soaking time) have a better effect in this study.

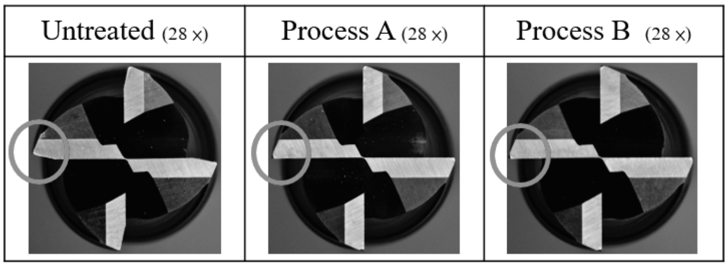

Figure 5. Cutting edge observed after a total milling time of 26 minutes

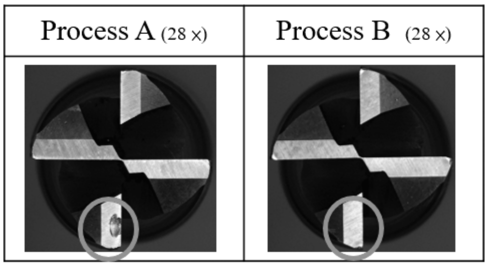

Figure 6. Cutting edge observed after a total milling time of 179 minutes

4. Conclusions

In this study, the hardness test, wear test, microstructure observation, residual stress, and tool life test confirmed that cryogenic treatment provides a significant improvement in the tool life of the TiAlN-coated milling cutter. The tool life was extended from 26 minutes to 179 minutes, an overall increase of nearly 7 times. This is a very valuable and original result, and the main conclusions of this research are as follows:

- The hardness of the coating was improved and the adhesion between the coating and the tungsten carbide was enhanced. This phenomenon can prevent coating damage from the tungsten carbide and avoid cutting heat conduction to the milling cutter, thereby extending the tool life.
- After cryogenic treatment, the precipitation of the α phase and β phase was increased, which can increase the wear resistance. In addition, the microstructure was denser than that of the untreated one.
- The residual stress of the tungsten carbide was reduced after cryogenic treatment, which can improve the dimension accuracy, reduce the deformation, and increase the performance and tool life of the milling cutter.
- The experimental results indicate that a lower cooling rate with a longer soaking time improves performance.

Further research needs to be conducted to explore the optimal cryogenic process and to clarify the mechanism and the relationships between cryogenic treatment and adhesion.

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