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A Comparative Study Under Non-Cryogenic and Cryogenic Condition of Tool Wear and Surface Roughness in HSS T42 Single Point Cutting Tools

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This study compares the cryogenic and conventional heat treatment processes for T42 high-speed steel tools. An efficient method of enhancing the characteristics of tool material is phase transformation. The study looks at how the cryogenic procedure affects the T42 single point cutting tool's wear and roughness. It was found that when the hardness of a cryogenic tool increased, the work piece's resistance decreased. Additionally, a scanning electron microscope was used for scanning and microscopy in order to analyze the variations in microstructure features. With experimental validation, the analysis of variance (ANOVA) approach has been used to look into the process characteristics that contribute the most. The tool steel electrodes undergo the appropriate heat treatment to get the desired results. Furthermore, it was found that the experiment data most nearly matched the predicated outcome.

Keywords: HSS T42 tool steel, Tool Wear, Surface Roughness, Minitab17, Cryogenic Treatment.

1. Introduction

Sustainable manufacturing uses energy-efficient, ecologically benign, and non-polluting production techniques that are also profitable and secure for workers. Utilizing efficient resources, recycling materials, reusing machine tools, reducing waste, saving energy, extending the life of tools, broadening the managerial application of metalworking fluids and lubricating oils, and implementing life cycle assessment techniques. They have all helped the machining industry adopt sustainability [1]. The methods currently utilized for repair and restoration, including both manual methods and automated repair techniques using additive manufacturing. It has been demonstrated that automated restoration utilizing additive manufacturing is more effective and open to a wider range of restoration aspects, including materials and the construction method. [2]. A number of industrial sectors are using additive manufacturing, which is a rapidly growing technology. It offers flexibility in design and benefits for the environment and ecology. It essentially converts design files into finished items. Low productivity, poor quality, and ambiguity regarding the mechanical qualities of the finished part continue to be obstacles. [3]. An innovative strategy for process planning that supports the design of a hybrid process chain and seeks to maximize product life-to-value ratio. Using simulation and experimentation information as the enabler of a multi-criteria evaluation process, based on the precise user requirements, the method is built on the efficient production of hybrid process plan alternatives [4].

The development of a suitable process plan and the effective integration of a newly designed component into the manufacturing chain are extremely difficult tasks that demand a great deal of human experience. As a result, organized methodologies and decision-making tools are being developed and optimized [5]. Novel manufacturing technologies have been quickly developing during the past ten years and gaining ground in the manufacturing industry. They require the development of tools and support systems that will enable the fullest possible use of their potential in manufacturing applications, while lowering the demand for human expertise and raising the level of automation in the process planning stage [6]. To demonstrate the advantages of additive manufacturing in such manufacturing contexts, the research that already exists primarily looks at the aforementioned problems from an economic perspective [7]. A profile and tool mechanism is used as the throwing mechanism for the various shapes of earthenware. Using a potter's wheel to create earthen objects reduces the need for human labor. The potter's wheel tool production capacity and the size, shape, and thickness of the profile are maintained by the new system [8]. The developed a process planning algorithm that can be utilized to cut costs when comparing numerous variations of the same product by segmenting product features and applying hybrid manufacturing approaches [9]. There are two types of pottery: hand throwing, which is the only method employed, and wheel throwing, which uses equipment to create a variety of shapes for earthenware. When offered the chance to employ throwing tools on the potter's wheel, manual throwing potters handle it more skillfully and productively since they are familiar with the potter's wheel's working principles [10]. It put forth a feature-based strategy for process planning that aims to develop semi-automated and automatic operation sequencing plans for hybrid manufacturing processes with a primary goal of speeding up production. [11]

Increasing tool life and enhancing component surface integrity are the two key problems when machining difficult-to-cut metals used in critical applications. Particularly, the alloys based on nickel have particularly poor heat conductivity, which results in greater cutting temperatures and quicker tool wear. In this situation, either employing liquid nitrogen LN2 or carbon dioxide LCO2, cryogenic machining is a promising strategy that improves cooling efficiency. Cryogenic machining has reportedly been done on a variety of industrial materials, including titanium alloys and nickel-based alloys [12]. Recent developments in hydrogen storage systems are examined, along with practical difficulties. Cryogenic hydrogen is almost two times as dense as compressed hydrogen and has a storage pressure of 70 MP. Hydrogen adsorption on the active sites of activated carbon can be used to solve technical problems like material expense and explosion danger. At 77 K and 4-20 Mpa, activated carbon made from chitosan (6.77 wt%), bamboo (6.6 wt%), and African palm shell (6.5 wt%) has been found to have the highest hydrogen storage capacity. For enhancing hydrogen storage capacity in pure Si and Mg, detailed nanotechnology approaches are also described [13]. In sustainable manufacturing, tool life is one of the most important factors. Increasing the lifespan of cutting tools is essential for reducing manufacturing costs. Cutting fluids, various heat treatment methods, coatings, etc. can all be used to increase tool life during milling. Cutting fluids are seen as harmful and unfriendly to the environment once they have served their purpose. Cryogenic therapy, or sub-zero heat treatment, is used as an environmentally friendly substitute for conventional procedures to increase tool life, cutting insert wear resistance, dimensional stability, and product quality. It is accomplished by changing any remaining austenite to martensite, precipitating carbides, forming eta-carbide, forming uniform crystal structures, improving heat conductivity, and reducing chemical deterioration [14]. One of the crucial factors in sustainable manufacturing is tool life enhancement. Tool performance is a crucial consideration while cutting metal. Numerous research projects are carried out to improve the microstructural and mechanical properties of tool inserts in order to increase productivity and quality [15]. While these include hard materials as Ti, TiN, TiCN, TiAlN, AlTiN, SiNZrN, AlCrN, etc., these nano coated CNC inserts demonstrated higher efficiency and increased wear resistance. However, in harsh climatic conditions, the influence of multi-layered hard coatings made of nano composite materials is more effective [16].

Tungsten carbide (WC) tool inserts are the most frequently used in the majority of production industries due to their distinctive properties, which include noticeable micro-hardness, outstanding resistance to wear, good compressive strength, and stable thermal structure. In order to increase their employment in a variety of applications, major improvements in the performance of WC tools for high temperature machining are also required [17]. The findings indicate that cryogenic-LN2 outperformed cryogenic-CO2, MQL, and dry conditions in terms of technological, sustainable, and financial parameters. Compared to dry, MQL, cryogenic-CO2 conditions, LN2 aided machining significantly lowers total machining costs and energy usage. Additionally, it has been demonstrated that the LN2 cooling environment dramatically lowers machining outputs including cutting force, tool wear, and surface roughness. In comparison to dry machining settings, LN2 circumstances were determined to be the most promising since they reduced cutting force by 32.1%, tool flank wear by 33.33%, and overall energy consumption by 18%. It is important to note that contemporary lubri-cooling technologies contribute to the aerospace industry's sustainability by reducing resource consumption, providing environmental benefits, and enhancing machining capabilities [18]. In this research, the impact of tool cryogenic treatment on current, voltage, pulse on/off timing, and pulse on/off duration has been examined. A microstructural investigation was also performed to analyze the surface profile of the machined surface with non-treated and cryogenically treated tool electrodes. Optimal parameters for the lowest tool wear rate have been identified. Cryogenic copper tools have been found to have a higher rate of tool wear than non-treated copper tool electrodes. In comparison to other machining factors, the effect of current, on-time, and kind of tool electrode is found to be more prominent. On the surface that was machined using the electrode from the untreated tool, a thick recast layer with noticeable surface fissures is visible [19]. Applying the Vickers tester to evaluate hardness variation, it was found that cryogenic treatment significantly increased the surface micro hardness. Cryogenic treatment increases the tool's Vickers hardness by 2.9 HV, or 4.65%, over untreated tool hardness. The greatest material removal rate of 0.019391 g/s occurs at cutting speed of 356 rev/min and feed rate of 0.115 mm/rev. Due to the rise in tool hardness in cryogenic tools, the resistance of the work piece is at its lowest. The Material Removal Rate obtained when turning the mild steel work piece with cryogenic hardened and heat-treated tools is slightly higher [20-21]. One of the most significant issues in machining operations is the improvement of were resistance and hardness of cutting tool material. This problem can be solved by cryogenically treating tungsten carbide to increase its hardness and wear resistance. In this work, the impact of various soaking times on the cryogenic treatment of tungsten carbide is attempted to be studied. The studies were carried out on commercially available tungsten carbide at a temperature of 88K for various soaking times of 8 hours, 16 hours, 24 hours, and 30 hours. By evaluating Rockwell hardness and weight loss during wear tests, additional efforts were undertaken to quantify and corroborate the impact of various soaking periods as well as the mechanism responsible for change in the hardness and wear resistance [22].

High-Speed Steel is a preferred material for single-point cutting tools because to its great balance of hardness, toughness, and wear resistance. When employing HSS T42 cutting tools, tool wear and surface roughness are important aspects of machining operations that can happen both in non-cryogenic and cryogenic settings. HSS T42 cutting tools gradually deteriorate under non-cryogenic circumstances as a result of the high temperatures produced during machining. As a result, the tool's working temperature is greatly decreased. HSS T42 cutting tools show less wear in cryogenic temperatures than in non-cryogenic environments. The softening and chemical processes that cause tool wear are reduced to a minimum at the lower temperature. As a result, wear mechanisms are less noticeable and the tool's lifespan is increased. The tool's cutting edge is kept intact by the lower temperatures, resulting in a smoother cutting motion. Consequently, when employing HSS T42 cutting tools under cryogenic temperatures, the workpiece's surface roughness is often lower.

The machining conditions have an impact on tool wear and surface roughness in HSS T42 single-point cutting tools. Cryogenic circumstances increase surface polish while reducing wear, which can result in higher surface roughness under non-cryogenic settings. The specific needs of the machining operation, such as material, precision, and tool life, determine which of these conditions should be used. If you want to improve tool performance and surface quality, cryogenic machining can be a good choice.

2. Experimental Method

2.1 Sample Preparation

The pilot experiments were carried out on T42 tool steel grade. Three conventionally heat treated tool bits manufactured and supplied by Birla Precision Technologies Ltd., Indian Tool Manufacturers Division having the size ½” x ½” x 4” [12.7 mm x 12.7 mm x 101.6 mm] were selected. Analysis of given test specimens of T42 revealed chemical compositions as indicated in Table 1. Pilot experiments were conducted with non-cryo tools (Fig. 1a) and cryo tools (Fig. 1b). As tool bits were procured referring to the standard grades, the heat treatment and the chemical compositions were maintained during the manufacturing stages. The cutting tools used in the machining tests are: These tool bits were subjected to grinding operations for providing the standard single-point tool signature for turning operation. The dimensions of tool geometry provided to the specimen as given Table 2.Commonly used work piece material in turning is the steel from the revised literature, having low or medium carbon content due to its abundance. However, it was decided to select a work piece of low carbon steel material corresponding to AISI 1018. From the available diameter of bar 45 mm × 6 m AISI 1018, the specimens for machining of original diameter of 45 mm and length of 260 mm are prepared on the power hacksaw machine as shown in Fig. 1c.

Table 1 Chemical Composition of T42 Tool Steel Sample [23]

Chemical Components	wt-%
Carbon (C)	1.25%
Chromium (Cr)	4%
Molybdenum (Mo)	3.70%
Tungsten (W)	9.70%
Vanadium (V)	3.10%
Cobalt (Co)	10%

Table 2 Dimensions of tool geometry

Tool Geometry	Dimensions	Tool Geometry	Dimensions
back rake angle	10°	end cutting-edge angle	8°
side rake angle	10°	side cutting-edge angle	0°
end relief angle	10°	nose radius	0.5 mm
side relief angle	5°		

Figure 1 T42 Non-cryo and T42 cryo tool

2.2 Cryogenic Tool Preparation

Tool prepared from the procured material by incorporating geometrical features as per tool signature has to undergo cryogenic treatment. In the pilot experiment, cryogenic temperature of -185°C has been selected with initial soaking time of 2 hours. The tray containing the tool samples as per the Grade and soaking time are tagged with wires and removed from the cryogenic processor as per predefined soaking time. The tool sample has been kept in insulated boxes till the next operation i.e. tempering for 1 hour at 100°C is carried out. Accurate control of temperature and prevention of thermal shock was achieved by performing the cool-down cycle in gaseous nitrogen. Cryogenic treatment is followed by single-cycle tempering to enhance impact resistance, however, double or triple tempering cycles are sometimes used. Muffle furnace of capacity 3 kW has been deployed at 100°C for 1 hour to relieve the cooling stresses.

Figure 2 Schematic diagram for cryogenic process

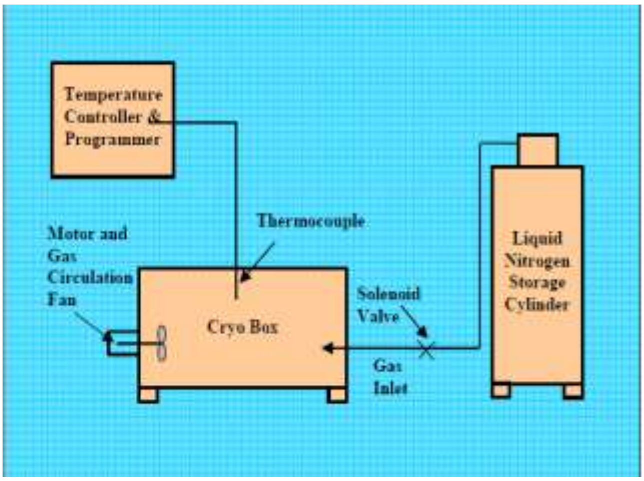


Figure 3 Cryoprocessor used for Cryogenic Treatment

2.3 Design of Experiments (DOE)

The mixed factorial design of experiment (DOE) was used in the design of the experiments. Due in large part to its time and material cost savings, DOE has emerged as a valuable technique for producing high-reliability search results [24, 25]. DOE supports the methodical investigation of many factors' effects in order to optimize the designs of processes and products. Additionally, it is useful for properly tackle the problem, prepare investigative and conclusive studies. Table 3 shown the Levels of Factors for Experimentations on Cryo-Treatment. The depth of cut, feed, and cutting speed selected as process variables for non-cryo tools. On the other hand, for cryotools, the soaking time has been identified as the fourth process parameter. In general, these components have equispaced individual values that need to be assigned at each level. Per ISO: 3685-1993 [26], the ratio between successive cutting speed values has been maintained at 1.06. The material grades determine the values chosen for feed and depth of cut. Per ISO: 3685-1993 [26], the feed to cut depth ratio is maintained at 4. Surface roughness, measured in microns (µm) and represented as Ra, is a measure of the closely spaced irregularities on the surface texture . This value indicates whether the surface is rough or smooth; an increase indicates that the surface is rough. The roughness of workpiece's surface is measured by Surf test SJ-210 manufacture by Mitutoyo. Tool wear (T_w) has been measured with a Toolmakers microscope at a magnification of × 30 specification.

Table 3 Levels of Factors for Experimentations on Cryo-Treatment

S. N.	Factor name	Factor symbol, Unit	Levels			
			1	2	3	4
1	Cutting Speed	V, m/min	75	80	85	90
2	Feed	f, mm/rev	0.075	0.075	0.125	0.125
3	Depth of cut	d, mm	0.3	0.3	0.5	0.5
4	Soaking Time	hours	2	4	6	8

3. Results and Discussion

3.1 Analysis of Non-Cryo HSS T42 Tools

Empirical mathematical models are developed using the Minitab17 program utilizing data from experiments with both cryo treated and non-cryotreated instruments. Fig. 4(a)-4(d) provides a summary of the performance parameters Tw and Ra for the eight experimental trials using the Non Cryo tools HSS T42. Equation 1 and Equation 2 shows the regression equation. The Tw and Ra performance parameters of the regression analysis equation for this model are listed here.

The tool wear (Tw) performance parameters of the regression analysis equation (Non-Cryo Treated HSS T42 Tool): (1)

T_w = -0.2228 + 0.002564 Speed + 0.3290 Feed + 0.1398 DOC

(Confidence level – 99 %)

The surface roughness (Ra) performance parameters of the regression analysis equation(Non-Cryo Treated HSS T42 Tool): (2)

R_a = -0.990 + 0.06203 Speed + 1.04 Feed + 0.393 DOC

(Confidence level – 95.21 %)

Figure 4 (a)

Variation in Tool wear with cutting speed (at depth of cut, d=0.3)

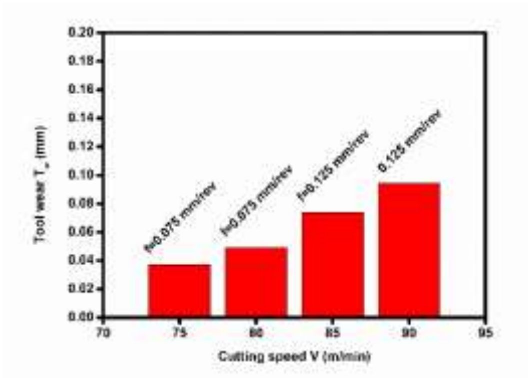


Figure 4 (b)

Variation in Tool wear with cutting speed (at depth of cut, d=0.5)

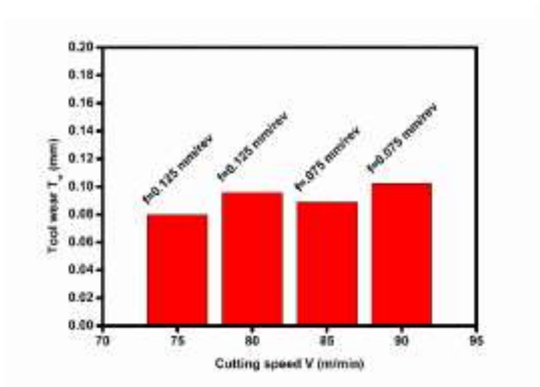


Figure 4 (c)

Variation in Surface roughness with cutting speed (at depth of cut, d=0.3)

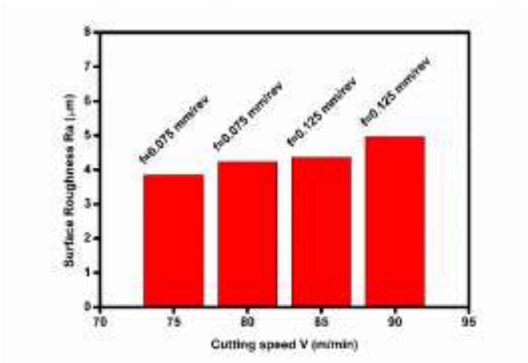


Figure 4 (d)

Variation in Surface roughness with cutting speed (at depth of cut, d=0.5)

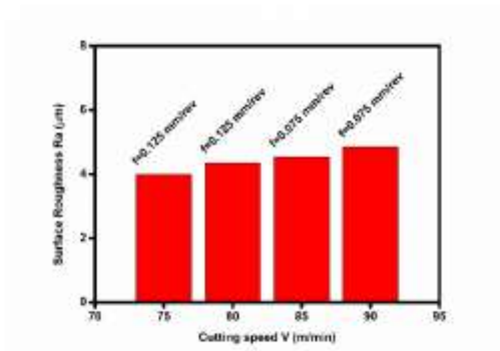


Figure 5 Main Effects Plot for tool wear (T42 Non Cryo)

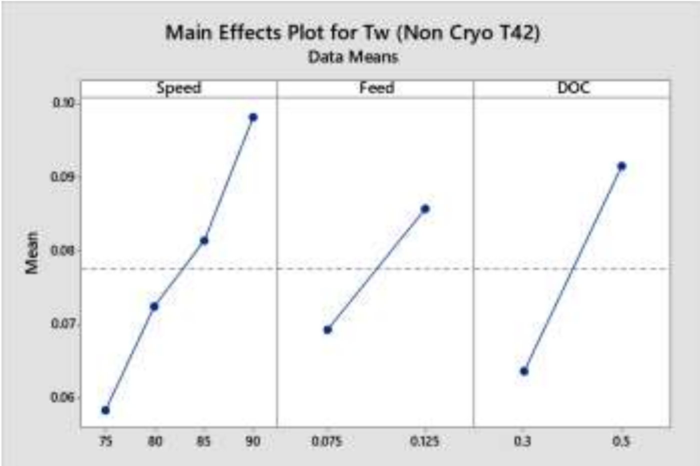


Figure 6 Main Effects Plot for Surface Roughness (T42 Non Cryo)

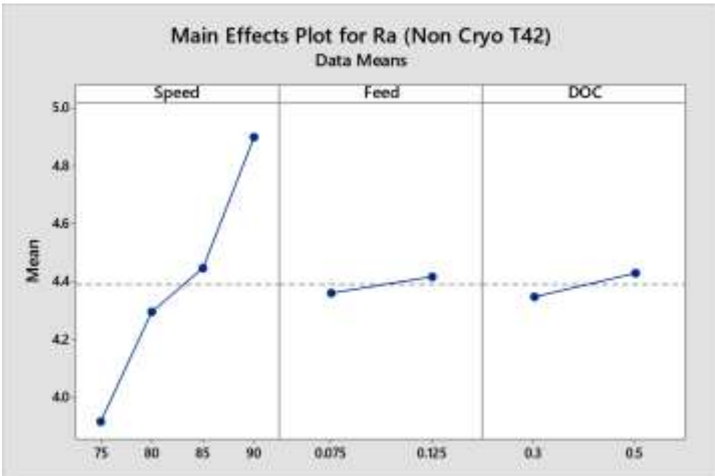


Fig.5 shows the graph of the main effects for each of the factors which have been considered in this study. As the value of cutting speed, feed and depth of cut are increased, tool wear is found increased. This could be because of overheating of tool and due to failure in self-erosion. Fig.6 clearly shows that Cutting speed is the most notable parameter whereas feed and doc are having less significance for performance parameter R_a.

Figure 7 Microstructure Image of Non-Cryo H.S.S. T42 Material

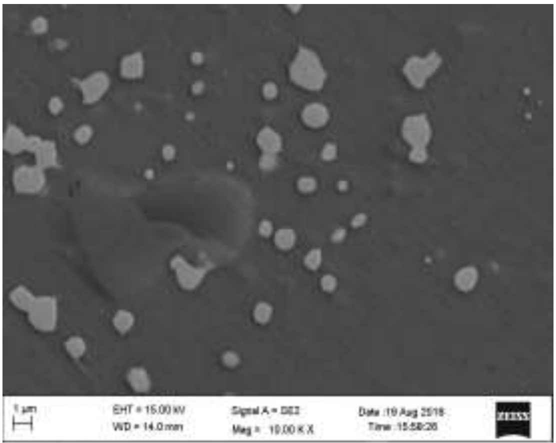
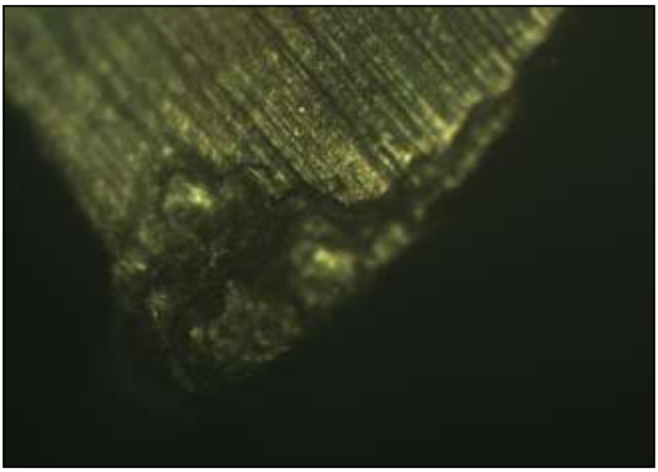


Fig.7 shows the Microstructure Image of Non Cryogenically Treated H.S.S. T42 material with 10000 X Magnification. The image clearly shows Clustering of carbides at certain areas or points and majority of carbides are observed to be spherical in shape.

Wearing out of tool tip of non-cryo T42 tool sample has been depicted through Fig.8.

Figure 8 Photograph showing Tool Wear for T42 Non-Cryo



3.2 Analysis of Cryo-Treated HSS T42 Tool

A Minitab package 17 has been utilized to design and analysis of the experiment. Fig. 9(a)-9(d) summarizes design of experiment (DOE) results for T_w of machined work piece by T 42 cryo tool. Also, Fig. 10(a)-10(d) summarizes design of experiment (DOE) results for R_a of machined work piece by T 42 cryo tool. Equation 3 and Equation 4 shows the regression equation for this model (Cryo T42). Regression Analysis equation for this model are summarized above for T_w and R_a performance parameters.

The tool wear (Tw) performance parameters of the regression analysis equation (CryoTreated HSS T42 Tool): (3)

T_w = -0.02144 - 0.000228 Soaking Time Hrs. + 0.001388 Speed + 0.0110 Feed

+ 0.00388 DOC

Confidence level – 96.33 %

The surface roughness (Ra) performance parameters of the regression analysis equation(Cryo Treated HSS T42 Tool): (4)

R_a = 2.1297 - 0.014566 Soaking Time Hrs. + 0.00076 Speed + 7.342 Feed + 0.5285 DOC

Confidence level – 99.19 %

Figure 9(a)
Variation in Tool wear with cutting speed (at soaking time 2hrs)

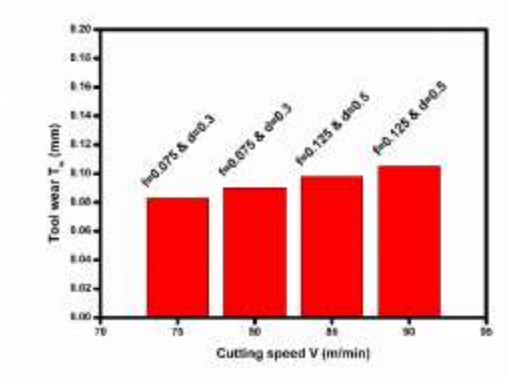


Figure 9(b)
Variation in Tool wear with cutting speed (at soaking time 4hrs)

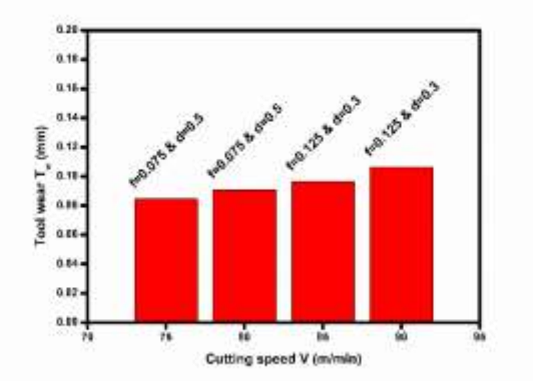


Figure 9(c)

Variation in Tool wear with cutting speed (at soaking time 6hrs)

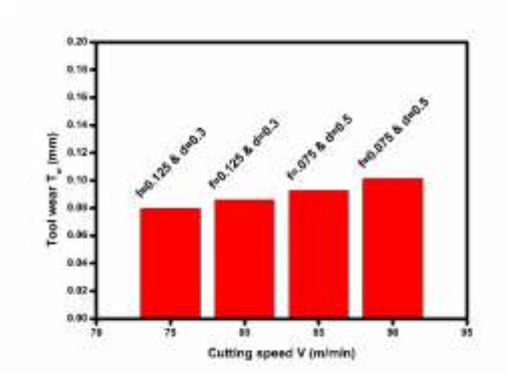


Figure 9(d)

Variation in Tool wear with cutting speed (at soaking time 8hrs)

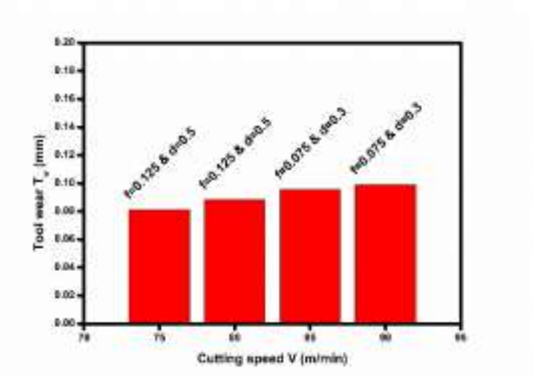


Figure 10(a)
Variation in Surface roughness with cutting speed (at soaking time 2hrs)

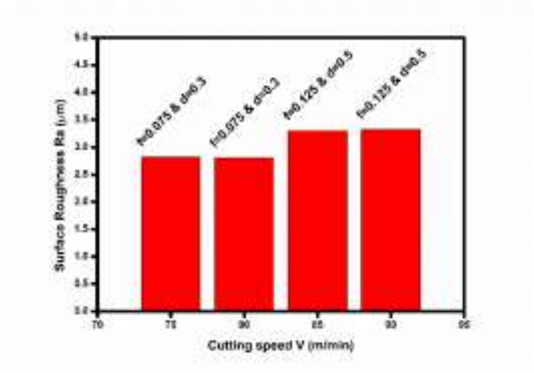


Figure 10(b)
Variation in Surface roughness with cutting speed (at soaking time 4hrs)

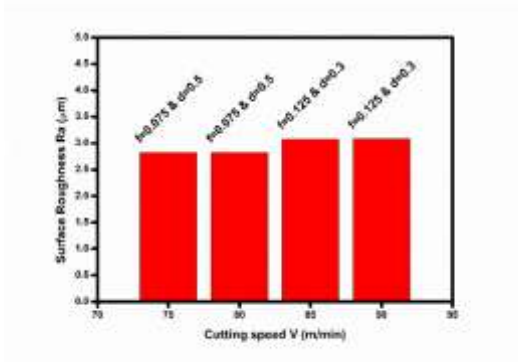


Figure 10(c)
Variation in Surface roughness with cutting speed (at soaking time 6hrs)

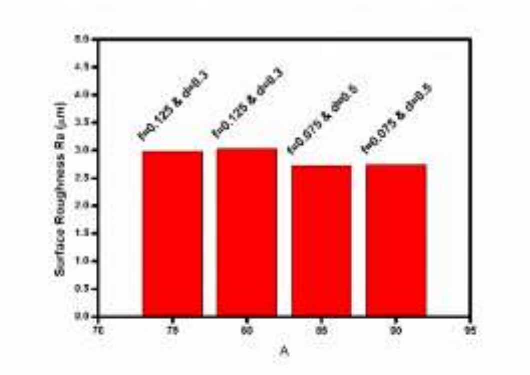


Figure 10(d)
Variation in Surface roughness with cutting speed (at soaking time 8hrs)

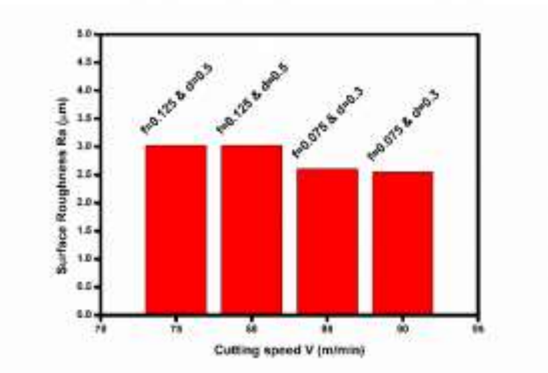


Figure 11 Main Effects Plot for tool wear (T42 Cryo)

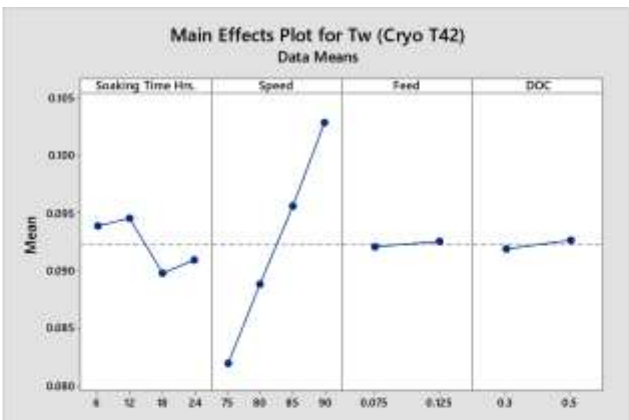


Figure 12 Main Effects Plot for Surface Roughness (T42 Cryo)

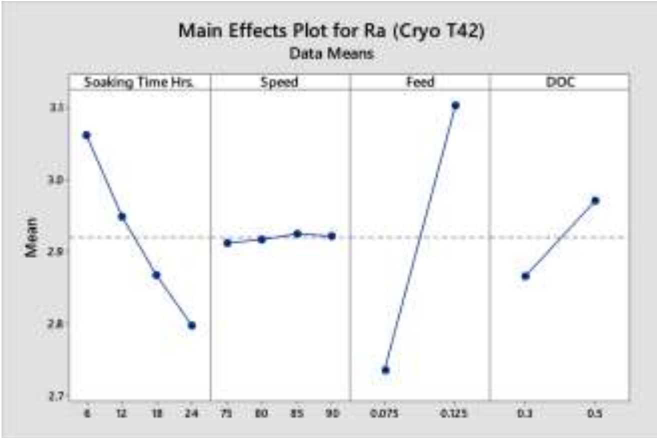


Fig. 11 and Fig. 12 shows the main effects for T_w and R_a respectively for the tool cryo T42. The most influential factor over T_w is cutting speed whereas for the performance parameters R_a feed rate plays important role.

Figure 13 Microstructure Image of Cryo-treated H.S.S. T42 with Soaking Time 8 hours

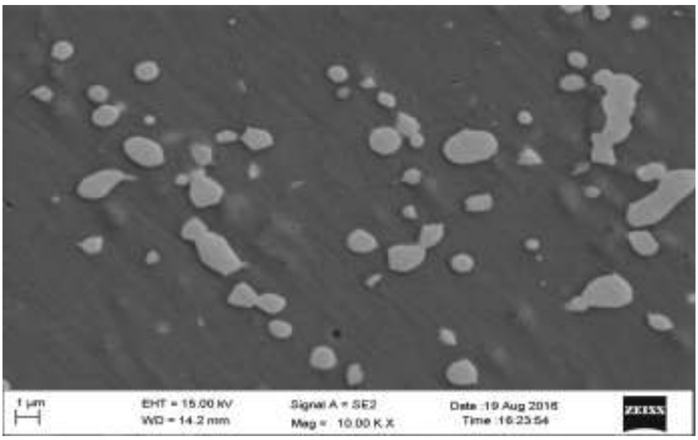
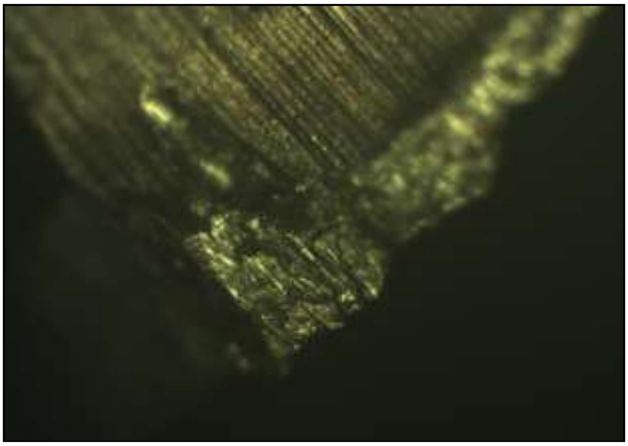


Fig. 13 shows Microstructure Image of Cryogenically Treated H.S.S. T42 material with soaking time 8 hours with 10000 X Magnification. Most uniformly distributed spherical shaped carbides are observed in the microstructure. Few Spherical shaped types of carbide are seen attached to some irregular shaped carbide. The carbide size seems to increase at and above this soaking temperature.

When compared with wear observed in non-cryo tool, cryogenic treatment undertaken with soaking period of 8 hrs has resulted in reduced wear of tool tip as seen in Fig. 14.

Figure 14 Photograph showing Tool wear of Cryo-treated H.S.S. T42 with Soaking Time 8 hours



3.3 Validation

Validation is the process of evaluating the final product to check the authenticity of performed experiments. Statistically regression equation provides the relation between process parameters and performance parameter. Thus, there is good unison between predicted and experimental outputs. It also observed that the experimental (Expt.) and predicted (Pred.) values of performance parameters are with least % error, therefore the model can be validated. It has been observed that average tool wear and average surface finish are -30.7635% and -27.1249% respectively.

Fig.15(a) show comparison of experimental with predicted tool wear of (Non-Cryo) T42 Tool. It has observed that 5.92 % error found at cutting speed 85 m/min, feed 0.125 mm/rev and depth of cut 0.3 mm. Whereas the surface roughness of non-cryogenic T42 HSS tools, maximum error of 3.78% has been obtained at cutting speed 85 m/min, feed 0.125 mm/rev and depth of cut 0.3 mm as shown in Fig.15(b). Furthermore, after the cryogenic treatment has been done to T42 HSS high speed steels. It has been found that maximum 4.17 % error in the wear tool of cryogenic T42 HSS tools are observed at soaking time 8 hr., cutting speed 85 m/min, feed 0.125 mm/rev and depth of cut 0.3 mm as shown in Fig. 16(a). However, the surface roughness of cryogenic T42 HSS tools, maximum error of 1.87% has been obtained at cutting speed 85 m/min, feed 0.125 mm/rev and depth of cut 0.3 mm as shown in Fig. 16(b). T42 HSS has been newly developed material by European company. Some of the advantages of cryogenic treatment incorporate longer part life, less failure due to cracking; reduced coefficient of friction and easier machining are realized from the series of experiments conducted.

Figure 15(a)
Validation with experimental and predicated Tool wear of (Non-Cryo) T42 Tool

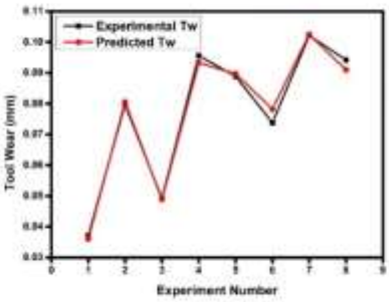


Figure 15(b)
Validation with experimental and predicated surface roughness of (Non-Cryo) T42 Tool

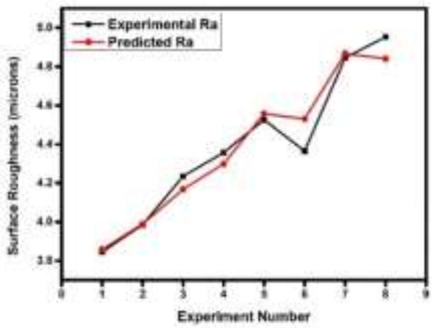


Figure 16(a)
Validation with experimental and predicated Tool wear of (Cryo) T42 Tool

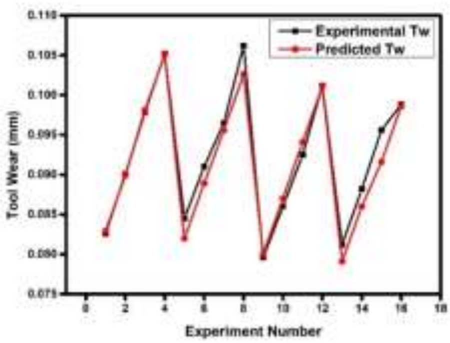
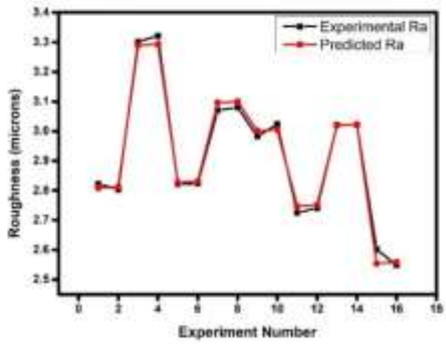


Figure 16(b)
Validation with experimental and predicated surface roughness of (Cryo) T42 Tool



4. Conclusions

In this study, T42 (Tungsten HSS) steel has been used as an electrode tool in both cryogenic and non-cryogenic settings. T42 HSS cryogenic and non-cryogenic tools have been used for CNC turning operations. The process parameters for non-cryogenic tools were cutting speed, feed, and depth of cut. On the other hand, soaking time is a fourth parameter for the cryogenic treatment instrument. With the use of the statistical program Minitab 17, a DoE table was created. For this investigation, the effects of both cryogenic and non-cryogenic tools have been investigated for the performance criteria of tool wear and surface roughness.

Furthermore, a comparison between the experimental and predicted outcomes was also conducted. It was determined that the experiment data most closely matched the predicted outcomes.

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