

A review: Mechanical Properties of HSS Steel by deep Cryo-Treatment

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Abstract. Cryogenic treatment deals with heating and cooling tool piece in extreme condition so that the complete stress is relieved as to achieve zero entropy at absolute zero temperature. Exploration of the benefit of cryo-treatment for achieving improvement in wear resistance of tool steel is a topic of current research interest. This work discusses the various cryogenic treatments used so far in a manufacturing process. The optimization technique such as Taguchi method is reviewed. The present work explores the effect of cryogenic treatment done on a single point cutting tool (HSS) which helps in machining different tool materials with a better surface finish and increased tool life. Further, we propose the use of regression model and fuzzy logic based approaches for efficient optimization of process parameters. This work will act as a primer for the researchers/Industrialists and students who enter into the world of cryogenic treatment.

1. Introduction

A. Cryogenic treatment

“Cryogenic” word is taken from the two Greek words- cryo means freezing and genic means to produce. Technically, the meaning says the study of materials at very low temperature. Deep cryogenic treatment (-190°C) of steel is a deep stress relieving technology [1]. The deep cryo-treatment process makes many changes of the treated materials and it also effects on the bases of chemical composition. Involved in the material, it comprises three things; Retained austenite (FCC) turned to martensite (BCT), carbide structure precipitates and residual stress is relieved [2]. Cryo-treated materials generally improve the mechanical properties like hardness, dimensional stability, toughness, corrosion resistance and minimize the frictional behavior [3].

Many survey authors indicate that the purification of secondary carbides in metals is very advantageous over a wear resistance by cryogenic treatment. Few of them discussed on cutting tools by cryogenic but no clear idea about HSS tool by cryogenic treatment [4]. Cryogenic treatment transmits nearly 110% development of tool life. Cryo-treated tools consume less power as compared to untreated tools [5]. Under certain conditions, deep cryo treatment will not effect on carbide tools, at that time reprocessed carbides



are used [6]. The classification of heat treatment depends on soaking temperature; they are deep cryogenic processing (DCP) and shallow processing (SCP). The generally used soaking temperature varies in DCP is around (135°C to 196°C) and for shallow treatment (SCP) is around (85°C to 125°C) [7]. Have been studied that the different influencing parameters include austenite temperature, holding time, the rate of heat, cooling rate, these all determine the effect of DCT on different tool properties used in industries [8]. Conventional cooling is not effective and also hazardous to the environment, DCT is eco-friendly and non-hazardous. Liquid nitrogen can be recycled in DCT [9].

The temperature used in SCT is 100°C ; it affects the increase of hardness accomplished by a decrease in toughness. In case of DCT temperature is around 196°C , and it affects the increase in wear resistance and toughness, but hardness remarkably decreased [10]. For example vacuum arc remitting (VAR) is used to produce HY-TUF tools to eliminate non-metallic contamination but which decrease the toughness. However the effect of DCT on (HY-TUF) tools to increase the toughness [11]. For (HY-TUF) tools under DCT at 196°C , and holding time 48 hours at liquid nitrogen compares to other timing (12, 24, 72). In 1960 the idea of DCT was directly immersing metallic component and tools in liquid nitrogen (LN2) initiation of cracks on treated component due to thermal shocks and volumetric expansion was reported in many cases [12]. The increase of tools life for cutting tools is an important factor in industries. For the increase of cutting tool life and improving their properties, heat treatment parameters which were widely used for many years [13]. Many researchers discussed force acting on the cutting tool in three directions (x,y,z). Treated cutting tool required less force for operation as compared to the untreated tool, due to this effect it clearly shows the cutting parameters depends on each other. While considering the force factor CT is the one-time permanent homogeneous process that enhances the significant extension of tool lives, namely machine parts, engine, machine tools, gun barrels, etc... Not only improves the wear resistance it also improves the fatigue life of many cutting tools [14].

The effect of CT on tungsten carbide tools, the comparison was made on treated and untreated tool by plain turning, the flank and crater wear was observed for both kinds of tools. CT tool gives better performance in mechanical and physical properties as compared to untreated tool [15].

B. Effect of cryogenic on metal parameters

The conversion of retained austenite (FCC) structure to martensite (BCT) structure, by cooling treatment. Carbon atoms are trapped in forming sites during rapid transformation; as a result of CT the two main things are changed due to development of wear resistance [2].

Retained austenite: After heat treatment, a soft grain structure always is present in a retained austenite, by applying CT. The soft grain structure transformed to hard core and it becomes durable grain structure martensite. M_2C carbide particles are formed during long soaking temperature (depending on the type of alloy element in steel). These fine particles along with large particles are closer in a matrix of metals [2]. A wide range of property improvement has been noticed.

C. Optimization

In plain turning operation, parameters are to be considered they are cutting speed (m/min), feed (mm/rev) and depth of cut (mm) these variables depends on each other one or other way. During operation selection of these parameters are very important, based on these input variables obtained desired output, so the use of optimization technique for optimization of desired values. These are surface roughness (Ra), thrust force (Ft), wear, vibration signals and so on. For these variables can be optimized by Taguchi and fuzzy logic are used in engineering analysis.

D. Method of optimization

In engineering real world many optimization methods are used based on the application, from number of decades the researcher study is going on the Taguchi method commonly used in research analysis. In this method, a special orthogonal array design to investigate the effect of machining parameter using the number of experiments. The collection of statistical and mathematical techniques is used for the modeling and analysis of the problem [13]. The effect of process parameters on machining can be optimized by Taguchi method. Result analysis of optimal values for low feed rate and depth of cut with high cutting speed is observed, the reduce of machining force and also surface roughness(Ra) [13]. In surface roughness feed rate is a more powerful factor. Taguchi method reduces the complexity and also time-consuming experiments by considering optimal cutting tool parameters to develop better precise value.

On the other hand artificial neural network (ANN) based models are developed by using non-conventional approaches. They are fuzzy logic and genetic algorithm. Recently the trend is going on fuzzy logic where the researcher developed a model and optimizes the values of cutting force and the surface roughness (Ra) while machining. So by a survey, it would be concluded that Taguchi and fuzzy logic are playing a better role in the optimization world.

II. Background

A. Process of cryogenic treatment

The complete treatment structure of steel consisting of hardening (Austenite), quenching, cryogenic and tempering. For the desired property and micro structure of steel we must follow below process. Most researchers recommended the implementation of cryogenic after quenching and before tempering in heat treatment process as shown below fig 1.

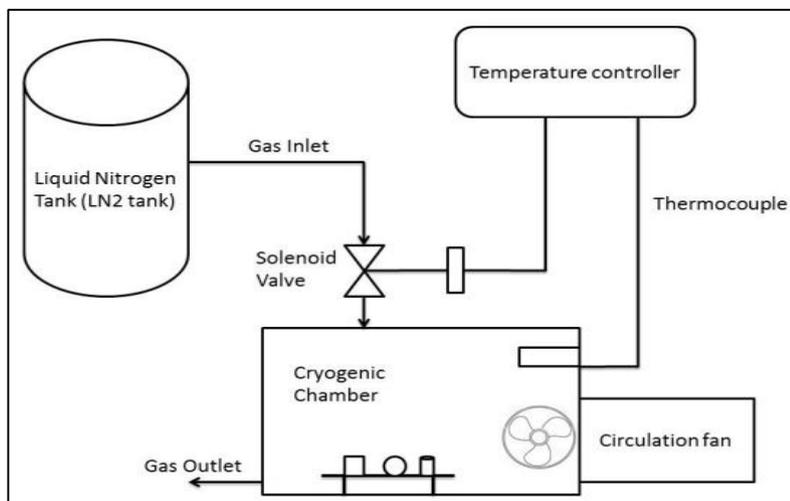


Fig.1. Cryogenic Process

1) Austenitizing: Austenite is a mixture of iron and carbon along with other components in the solution. By the process of diffusion it starts to homogenize and dissolve in the austenite solution. Due to heat treatment of steel iron the crystal changes to face-centered cubic (FCC). In austenite to martensite transformation process the beginning temperature is called martensite start

temperature (M_s). The transformation process is isothermal and smooth progress as the temperature falls to martensite finish temperature (M_f). Even after hardening, some austenite elements always present in a matrix. Higher percentage of carbon and martensite elements increases the hardness of steel. The amount of carbon at the beginning and at the end of martensite transformation affects the temperature. The temperature of M_f and M_s are lower than the room temperature which partially transform martensite in steel, and the remaining structure remains as austenite form while increasing in grain size with decreasing the temperature of M_f and M_s . It has been noticed that optimum temperature of austenitization varies from metal to metal. Suppose more number of carbides present in a matrix austenitization temperature reduces from 1070°C to 970°C in D2 steel. Further study of microstructure and hardness of D2 steel, it is subjected to DCT and CHT by increasing the austenitization temperature it affects the hardness for DCT and CHT of D2 steel. The amount of retained austenite is increased with increasing the austenitizing temperature [1].

2) Quenching: After finishing the austenitizing temperature next falls to quenching. In quenching rapidly cooling takes place with a suitable fluid media like air, water, and oil. Once austenite is cool down to critical temperature and it starts to become martensite. The increment of the hardness, strength and wear resistance of quenched steel is depended on the cooling rate. Carbon and alloy elements are dispersed in the austenite when it is subjected to heating and cooling of steel at upper critical temperature 1200°C . The structure of the quenched steel now become a body centered tetragonal (BCT) called martensite, reheating the structure changes its results into the precipitation of fine carbides, with increase in wear resistance and toughness 20 to 30 % of austenite elements present in steel after conventional heat transform (CHT).

3) Tempering: Next step is tempering. In tempering the reheating of steels at a predetermined temperature to develop a combination of mechanical properties in steels. Transition carbides reveal micro stress in the martensite phase and to prevent cracks on the surface of the steel. The role of tempering is to reduce residual stress, increase toughness, ductility, and dimensional stability. While tempering, martensite rejects carbon elements in the form of finely divided carbide phases. The results obtained from tempering is a fine separation of carbides in a matrix where little amount of original quenched martensite retain in the structure. Hence the hardness and residual micro stresses of steels are reduced after tempering. Due to the difference in martensite contents, CT steels are much harder and brittle in nature as compared to untreated. Generally tempering temperature at 150°C to 200°C is carried out to reveal residual stresses and thermal stresses by the treatment.

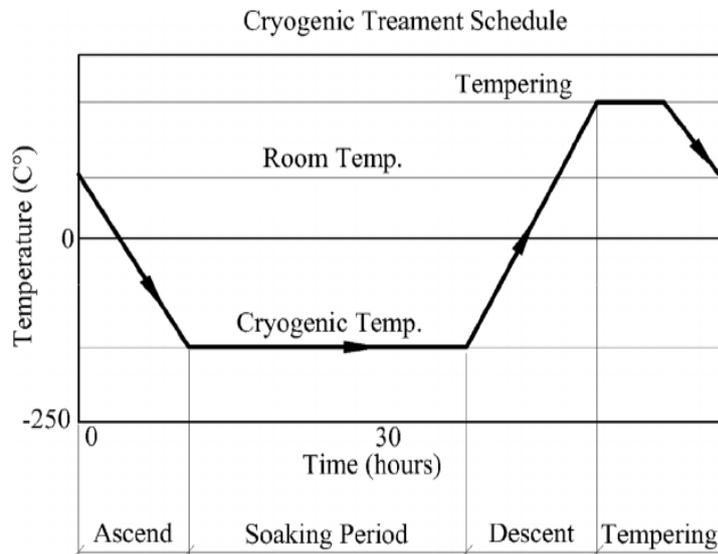


Fig. 2 Cryogenic Cycle

The above figure.2 shows temperature vs time of cryogenic treatment cycle in deep freezing of steels cryogenic temperature. Firstly treating of steel by constant cooling rate (ramp down), once it reaches the predetermined level then holding the steel at specific time (soaking Period), next bring back to room temperature at consent rate (ramp up). All these parameters affect the output of a treatment.

B. Mechanical and micro structure properties of steel

1) Micro structure: It consists of fine carbides in the matrix structure, the transformation of retained austenite (FCC) to martensite (BCT) by DCT at -196 C. By keeping the prolonged soaking time of 24 hours, effects the even distribution of martensite throughout the structure. The carbide size and shape also reduces to a minimum value. Martensite structure looks like saturated the Carbide elements in that expand more homogeneous and round in shape. Carbides are chosen from the matrix which offers more wear resistance when treated with high loads (speed, feed, depth of cut). Comparison of treated and untreated cryogenic shows clear and fine secondary carbides in a matrix, it helps to improve uniform and homogeneous structure. Obsessively increase the hardness and toughness of the steel entire structure of steel behaves very good wear resistance. Whatever changes and the micro structure will affect the life of tool under certain heat treatment.

2) Mechanical properties: Many researchers says about steels and alloys but we cannot describe easily, so better is to summaries the results obtained from published journals so we will get the clear picture of these properties (wear resistance, hardness, tensile and bending, thermal fatigue resistance, fatigue resistance and fracture toughness).

a) Wear Resistance: Reciprocal in contact machining components subjected to wear and tear property, such as gears, bearings, machine tools, piston seals, etc. From the micro structure changes related to CT, austenite reduction and carbide precipitation improve over a resistance by an increase of hardness of steel. More enhancement of wear resistance in tool steels, one of the most AISI M2 HSS tool widely used in

turning, drilling and milling cutters. This property not only improves tool steels but also play important role in sliding and rolling contact, in different fields like oil drilling, mining, automotive sectors etc.. Researchers agree with the reason the behind the improvement of wear resistance. The carbide precipitation of steel with an increase in hardness and strength of martensite matrix, rather than elimination of austenite element in the matrix. Wear rate of M2 steel can be compared by treating four different combinations,

Quenching then double tempering (A)

Quenching, double tempering then DCT (B)

Quenching, DCT then tempering (C)

Quenching, DCT then double tempering (D)

Sample (B) shows the less reduction in wear rate (51%) compared with sample (A), against 35% and 45% for (D) and (C) samples respectively. The researcher can conclude that DCT is better to carry out after tempering process [16].

b) Hardness: Hardness is related to wear resistance; this property is measured by indentation tests. This test depends on the type of penetrator shape, the commonly used methods are Vickers and rock-well test. The first method is to perform micro and macro indentation, the second one can be performed only macro indentation tests; it depends on the type of load used. The CT plays a role in hardness of tool steel. However, as compared to wear results the hardness test results depend on the different materials. Authors suggested that carbides role in the matrix to achieve retained austenite of structure by increasing the hardness and toughness in HSS.

c) Tensile and bending strength: Only a few results have been found on tensile and bending strength, before CT and after CT. Actually, the tensile property could not affect much as compared to hardness and wear resistance in tool steels. Unchanged retained austenite does not affect the static property while considering the small precipitation of carbide which play important role in carburized steel-815M17 noticed that slight reduction in tensile strength, subjected to CT and also conventionally treated [16].

d) Fatigue resistance: Materials and mechanical engineering the topic fatigue is a trend of research from the beginning of the 20th century. All the micro structure changes of CT it depends on the fatigue behavior a fine hard carbide in an austenite matrix can be blocking of low-stress amplitude, for fatigue properties of CT stress cannot be investigated by authors. The study of cold rolled steel of two different DCT: rapidly immersion in a liquid nitrogen for 1 hour, controlled cooling slowly and 30 min soaking time. The result of bending test of treated and untreated shows no difference in fatigue limit, and small DCT dispersion has been found.

e) Thermal fatigue resistance: In an internal combustion engine, the composition of thermal and mechanical cycles is a basic required operation and it will be more interesting to conduct a CT effect analysis on thermo-mechanical fatigue behavior of the component. The preliminary test about DCT effect on pure thermal fatigue properties, without mechanical loads, has been published till now. The rotating disk subjected to cyclic induction-warming and water cooling a crack network has generated on the surface. Later measuring those thermal crack density ρ , mean crack length l_m and maximum crack length P_{max} , authors computed the pyrocracking factor C . The DCT disk showed a pyrocracking factor of 0.6 μm versus 1.18 μm of untreated. The reason for this drop is the crack density which has minimized from $3.49 mm^{-1}$ to $1.53 mm^{-1}$. For both treated and untreated Specimen mean crack length and maximum crack length almost remained same [16].

C.Optimization method

1) Taguchi method: Taguchi method is a robust design process, for all noise factors response sensitivity is least. By considering “signals to noise” ratio (S/N ratio) as the performance measure. The availability of mathematical analysis to support the above. Each process characteristics have a nominal Value Taguchi method reduces the target value and models to the nominal value. Taguchi allows functions very approximate and the quality loss in most cases, for variety of problems we found that different S/N ratios 3 important ratios are given below:

Large-the-better

$$S/N \text{ ratio } (\eta) = -10 \log_{(10)} \left(\frac{1}{n} \sum_{i=0}^n \frac{1}{Y_i} \right) \quad (1)$$

n = number of replication

Nominal-the-best

$$S/N \text{ ratio } (\eta) = -10 \log_{(10)} (\mu^2/\sigma^2) \quad (2)$$

μ = mean, σ = standard deviation

Smaller-the-better

$$S/N \text{ ratio } (\eta) = -10 \log_{(10)} (1/n \sum_{i=0}^n Y_i^2) \quad (3)$$

To minimize the mean square error of the nominal-the-best one of the target value. Adjust the target and mean by the various method to a constrained optimization problem. One more major tool is orthogonal array design model, is used to design many parameters by a single response. It contains both inner and outer array, inner array defines control factors including 'n' number of variables. Experts can control the design of each inner array is replicated according to the outer array, another design based on noise variables it cannot be controlled by control factors directly [17].

2) ANOVA: ANOVA acts as an investigator, used in a design parameter for investigation purpose, weather parameters are significant or not. ANOVA table model is widely used for test the significance of model factors, few test is to be conducted in order to test the results by control factors (how it affect). For example; F-test is computed, when “problem F” is less than 0.05, the significant interaction with control factors to be noticed. The effect of cutting speed, heat treatment and feed on Re and Ra has been predicted by applying an ANOVA with 95% efficiency [13].

II. Review

Ref . No	Materials	Parameters	Performance Measure	Methodology	Technique	Results
1	Nimonic 90	Vc=40 f=0.05 ap=0.5	Roughness, Tool Wear	Tool Dynamo meter	XRD	CT coated tool reduces the cutting force by 17%, wear behavior of treated tool is good.
2	Ti-6AL-	Vc=70	Tool,flank,	SEM	Graph	CT by LN2 the growth of tool

	4V alloy	f=0.02	crater wear			wears at moderate cutting velocity of 70m/sec.
3	(PCBN TOOL)	Vc=2.23 f=0.1 ap=0.5	Tool wear, cutting force, chip morphology	Dynamometer	Graph	Changing the condition parameters it affects the life of tool.
4	Tungsten carbide tool	Vc=150 f=0.1 ap=1	flank wear	microscope	graph CT	Improves the life of cutting tool by choosing suitable parameters.
5	Ti-6Al-4V	Vc=220 f=0.045 ap=1	Tool wear cutting force roughness	force sensors	Graph	Reduction in cutting temperature due to compressed Cooling air is used for treatment.
6	M2 HSS tool	Vc=35	Flank Wear	Lathe-SEM	SEM	M2 HSS tool performance by DCT shows more consistence as compare to SCT.
7	HSS Tool	Vc=88 f=0.06 ap=1	Micro structure	Lathe-SEM	SEM Graph	HSS cutting tool by CT results shows marginally increase as compared to untreated.
8	M2 HSS Tool	Vc=630 f=0.05 ap=1.25	Surface Roughness	Lathe-Graph	Taguchi ANOVA	Verify the result obtained from the test, in CE the value of surface roughness found to be 2.4 μ
9	M2 HSS Tool	Vc=35.5 Tc=10-30min	Flank wear	Lathe-Data analysis	Fuzzy Logic, NN	With the help of Fuzzy logic modeling can be done, and also online control problem can be done simultaneously.
10	Nimonic 90 Aerospace Alloy	Vc=40 f=0.08 ap=0.5	Tool Wear, Cutting force	Dynamometer	SEM Graph	CT Treated tool shows better performance than untreated tool.
11	HY-TUF	DCT Tempering	Surface Morphology	SEM	SEM Graph	DCT doesn't affect the young's modulus (206Gpa).
12	HSS Tool (S400)	Vc=180 Tc=3.6	Tool wear, Surface Finish	Dynamometer	Graph	tool With the suitable parameters CT gives better tool life than untreated
13	HSS Tool	V=10.5 f=0.15 ap=1	wear, surface Roughness	Lathe-analysis	Graph	CT can increase the cutting force it can be reduce by secondary LN2.
14	HSS	Vc=360 f=0.6 ap=0.2	Surface Roughness	Lathe-analysis	Graph	The performance of SPCT can be improved by CT and also increase the surface finish.
15	M2 HSS	Vc=149 f=0.2	Tool life	Lathe-analysis	Graph	(DCT and SCT) improve the HSS tool life and cutting

		ap=1.6				performance also been increased.
16	HSS	Machining Time MRR	Hardness Micro structure	FEA	Graph	Tool life of DCT HSS cutting tool is increased compared to untreated tool.
17	M2 Tool	Cryogenic Time	Wear, Tool life	Cryogenic cycle	Graph	Laboratory test results, gives better performance in case of wear and tool life.

Were, V_c = Cutting velocity, f = Feed rate, a_p = Depth of cut, MRR= Material removal rate, SEM= Scanning electron microscopy XRD= X-ray powder diffraction, NN= Neural network, CT= Cryogenic Treatment, DCT = Deep cryogenic Treatment, SCT= Shallow cryogenic treatment, LN2= Liquid nitrogen gas.

M.pellizzari [52] He prepared AISI M2 HSS tool for investigation, the properties of M2 HSS tool by DCT can be investigated that only small variation in fracture toughness is introduced. A reduction in wear rate of 32% was noticed by CHT and further more reduction of 49% before double tempering temperature.

A.V Pradeep [55] for his investigation, HSS tool (S400) most widely used tool in industries. Turning operation was done on lathe by using both treated and non-treated tool at three variant speeds (180,300 and 530) and time interval of 3minutes till the blunt nose radius is noticed.

P.V Gopal Krishna [56] in this work, author discussed about tool wear portion of face and flank. Life stability of HSS drill bit was studied by DCT, different grades of material was used such as EN36, AISI 1040 and AA6041 and respective improvement of 38%,90% and 140%.

K.Harish [60] in this paper author says about experimentation was carried out on uncoated carbide inserts (TTR and TTS) with untreated and treated. In his experimentation he evaluates the temperature at different machining condition. Resulting much improvement in tool and cutting performance.

Tejinderpal [63] Tungsten carbide inserts used commonly for machining of stainless steel (304H).In this work study on surface roughness during turning operation. The comparison between machining of DCT, SCT and untreated tool, to achieve optimum parameters of all these condition, resulting treated tool improves the hardness and toughness of tool as compared to untreated tool.

K.Amini [72] in recent trend cryogenic treatment has been used for finishing operation between quenching and tempering process on tools for the improvement of hardness and wear resistance. Results shows that CT before coating and CT after coating leads to an increase in hardness grade of 33% and 60% respectively.

IV. Discussion

A. Enhancement of tool material machining characteristics

Further study can be achieved by using liquid to solid phase change during solidification of steel by DCT, also further requires a study on an addition of alloying elements on to the wear characteristics of AISI grade steel [6]. Further implementation of adaptive control of CNC for higher productivity and standard product manufacturing automation domain. Also, the fuzzy model can be improved by including neural networks. Further, the extent of work to the evaluation of cutting temperature and estimation of tungsten alloy under DCT and optimization of cutting parameters of best efficiency [18].

B. Experts system with application

1) Regression model: A model describes about relation between dependent and independent variables. For example relationship between road accidents and rash driving by a driver is studied by regression analysis. For creative analysis one can develop a new regression based on the application or user needs to select the combination of parameters above. Commonly used regression are Linear regression, Logistic, polynomial, step wise, ridge, etc... Generally, all users for the analysis of engineering problems regression model is used in mini-tab software worldwide.

2) Fuzzy logic model: Fuzzy model design, the selection of suitable membership function, the parameter is taken into consideration as per the requirement. The design of input membership functions are speed, feed, and depth of cut. For Gaussian membership, three levels are selected high, medium and low. The role of the editor is to interpret the unit between input and output parameter as per obtained result. From the experiment, if we use more membership function to get more accurate value [80]. Classification of two fuzzy systems are: fuzzy mathematical model (ex: fuzzy K mean clustering), fuzzy logic model (ex: fuzzy decision support system).

V. Conclusion

The Conclusion of this paper concludes that the Cryo-heat treatment processes follows these steps Austenite, Quenching, DCT, and Tempering cycle process. Useful work has been reported by many authors, but further study on austenitizing temperature, martensitizing, soaking time, soaking temperature, carbide precipitation and tempering zone optimization of all these parameters which obviously increase the quality of products and also life of components. Cryogenic stabilizes and refines crystal structure and scatter of carbon elements throughout the material, resulting outcome is stronger and more durable material. Cryo-treated alloy and metals will enhance more durability, wear resistance. Plastic shows stronger and composite behave better strength and hardness. Cryogenic is Eco-friendly because of its non-hazards effect to the environment. Future study can be done on milling cutters, dry machining treated and non-treated, wet machining treated and non-treated.

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