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Machining Challenges in Stainless Steel – A Review

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***Abstract:** In today's world AISI Stainless Steel contributes to almost half of the world's production and consumption for industrial purposes. Stainless Steel is most popular alloy widely used in part manufacturing due to its inherent properties like high strength, great corrosion resistant, high ductility etc. but are hard materials to machining on base performance criteria like metallurgical aspect, low thermal conductivity, chip formation, cutting tool wear and surface integrity. The surface roughness and material removal rate have been identified as quality attributes and are assumed to be directly related to performance, productivity, and production costs. In this paper study of various machining problem discussed by different researchers and their probable solution, which helps to reduce tool wear, increase corrosion resistance, high surface finish by reducing machining complexity.*

***Keywords:** Metallurgical Aspect, Corrosion Resistance, Mechanical Properties, Surface Finish, Tool Wear.*

I. INTRODUCTION

A stainless steel alloy most popular material having high strength, long-lasting, making thinner and more durable structures [1]. Stainless steel sections have been increasingly used in architectural and structural applications because of their superior corrosion resistance, ease of maintenance and pleasing appearance [2]. It shows useful performance as good strength at elevated temperatures up to about 2000ºF or 1093ºC [3].

The applications of stainless steel materials have increased enormously in various fields. The attractive combination of excellent corrosion resistance, a wide range of strength levels including strength retention at cryogenic and elevated temperatures, good formability, and an aesthetically pleasing appearance have made stainless steel materials of choice for a diverse range of applications. Stainless steels are known for their corrosion resistance along with better mechanical properties [5]. At the same time, machinability is one cumbersome issue which is being discussed by the fabricators for a quite long period. This argument is placed in relative terms to that of other alloy steels which is due to some reasons such as low heat conductivity, high built up edge tendency and high deformation hardening of most of the stainless steel varieties. Austenitic stainless steels, characterized by a high work hardened rate and low thermal conductivity [7], are used to fabricate chemical and food processing equipment, as well as machinery parts requiring high corrosion resistance [8].

The work hardening and low thermal conductivity are recognized to be responsible for the poor machinability of AISI stainless steel. In addition, they bond very strongly to the cutting tool during cutting and when the chip is broken away, it may bring with it a fragment of the tool [6].

Most of the researchers have been described various methods & tricks to machine the Stainless Steel alloy but still, it shows challenges to Stainless Steel alloy part manufacturer. However new machining methods, technology continuously developed by researchers for that purpose additional literature always needed.

This article focuses on a Metallurgical aspect of Stainless Steel and its behaviour during machining; Chip formation and Cutting Tool wear & surface integrity. These are responsible for manufacturing challenges during working with Stainless Steel alloy.

II. METALLURGICAL ASPECT OF STAINLESS STEEL

AISI (American Iron and Steel Institute) divides all standard stainless steels into four groups: Austenitic, Ferritic, Martensitic and Precipitation hardened. Austenitic types are the 200 series (three grades) and 300 series (34 grades). They contain chromium, from 15% to 26%, and nickel, up to approximately 35%, as the major alloying elements. Carbon content varies from 0.03% to 0.25%. Ferritic types are the 400 series (12 grades), which contain chromium, from 10.5% to 27 %, as the major alloying element. Carbon content varies from 0.03% to 0.20%. Martensitic types - the 400 series (12 grades) have chromium, from 11.5% to 18%, as their major alloying element. Carbon content varies from 0.15% to 1.20%. Only three grades contain nickel: 414 and 431 (2.5 % maximum) and 422 (1.0% maximum). Precipitation-hardened types are the PH series (four grades), which contain chromium, from 12% to 18%, and nickel, from 3% to 8.5%, as the major alloying elements. Carbon content varies from 0.05% to 0.09%. These PH types may be either austenitic or martensitic in the annealed condition [4].

TABLE I. CHEMICAL COMPOSITION OF SOME STAINLESS STEEL

ASTM International Steel Designation	Alloy Composition (min%) from EN 10088		
	Chromium	Nickel	Molybdenum
304	17	8	-
316	16.5	10	2
316L	17	12.5	2.5

Several applications already exist worldwide for structural and non-structural components made of stainless steels, all these steels are alloys of iron, chromium, nickel and to varying degrees molybdenum. The characteristic corrosion resistance of stainless steel is dependent on the chromium content and is enhanced by additions of molybdenum and nitrogen. Nickel is added, primarily, to ensure the mechanical properties and the correct microstructure of the steel. Other alloying elements may be added to improve particular aspects of the stainless steel such as high temperature properties, enhanced strength or to facilitate particular processing routes [15].

Because of the variety of stainless steels, their machinability ratings vary from low to high. Machinability is a quality characterized by the degree of difficulty in machining a metallic work material under specified conditions. The machinability rating is expressed in percentages, with the assumption that the machinability rating of AISI 1212 free-machining carbon steel is 100%. If machinability ratings of work materials are less than 100% such work materials are more difficult to machine than AISI 1212 steel. Low machinability is attributed to austenitic steels, including 302B, 309, 309S, 314, 329, 330 and 384. Machinability ratings for these steels are only about 40% of that for AISI 1212 free-machining carbon steel. Low machinability is characterized by high tensile strength, a large spread between yield strength and ultimate tensile strength, high ductility and toughness, a high work hardening rate and low thermal conductivity. The same low machinability ratings are attributed to some martensitic steels, such as 422 (low in nickel, but containing up to 1.25% of molybdenum and tungsten and up to 0.30% of vanadium); 414 and 431 (both grades contain nickel from 1.25 to 2.5%); and 440A, 440B and 440C (no nickel, 0.75% molybdenum and from 0.60 to 1.20% carbon). Machining difficulty is influenced by hardness level, carbon content and nickel content [4].

High machinability is attributed to 430F and 430F (Se) ferritic steels, as well as to 416 and 416Se martensitic steels. Machinability ratings for these steels are about 90% of that for AISI 1212 free-machining carbon steel.

In general, austenitic steels are more difficult to machine. When machining austenitic steels, several factors should be considered:

- The cutting tool absorbs more heat, which may cause a built-up edge; users should increase the cutting speed, select positive insert geometry or use coated cermet grades to combat BUE.
- Chips are stringy and have a tendency to tangle, which makes their removal difficult; possible solutions are a higher feed rate, chip breaker geometry based on the nose radius of the insert, different lead angle or smaller nose radius of the insert.
- Chatter occurs if the cutting tool's rigidity is inadequate.
- Cut surfaces might be work hardened and more difficult to the machine if cutting is interrupted or if the feed rate is too low.

III. CORROSION RESTISTANCE

Chromium is the alloying element that imparts to stainless steels their corrosion resistance qualities. It does by combining with oxygen to form a thin, transparent chromium-oxide protective film on the metal surface (Fig. 1).

The chromium-oxide film is stable and protective in normal atmospheric or mild aqueous environments and it can be improved by higher chromium, by nickel, molybdenum, and/or other alloying elements. Chromium improves film stability, molybdenum and chromium increase resistance to chloride penetration, and nickel improves film resistance in the strong acid

environment [9]. In the event that the protective (passive) film is disturbed or even destroyed, however, it will – in the presence of oxygen in the environment – reform and continue to give maximum protection.

Material Selection for Corrosive Environment

Many variables characterize a corrosive environment – i.e. chemical and their concentration, atmospheric conditions, temperature, time, flow rate, etc. – so it is difficult to say which stainless steel to use without knowing the exact nature of the environment. However, there are guidelines.

The three most widely used stainless steel is type 304, 430 or 410, it is a good starting point in the selection process because these types are most readily available [2].

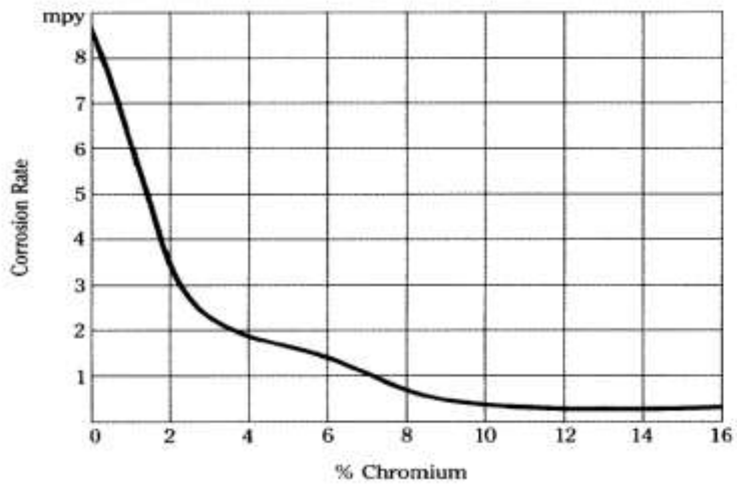


Fig.1. Effect of Chromium Content on Corrosion Rate [9]

Type 304 serves a wide range of applications. It withstands ordinarily rusting in architecture, it is strongly resistant in food – processing environments (except possibly for high – temp. condition involving high acid and chloride contents), it resists organic chemicals, dyestuffs, and a wide variety of inorganic chemicals. It resists nitric acid well and sulphuric acid at moderate temperature and concentrations.

Type 316 contains slightly more nickel than type 304 and 2-3 % Molybdenum, giving it better resistance to corrosion than type 304, especially in chloride environments that tend to cause pitting. It was developed for use in sulphite pulp mills because it resists sulphuric acid compounds. It uses has been broadened, however to handling many chemicals in process industries.

Type 317 contains 3-4 % molybdenum and more chromium than type 316 for even better resistance to pitting.

Type 430 has lower alloy contains than type 304 and is used for highly polished trim application in the mild atmosphere. It is also used in nitric acid and food processing.

Type 410 has the lowest alloy contains the three general purposes stainless steel and is selected for highly stressed parts needing the combination of strength and corrosion resistance, such as fasteners. It resists corrosion in the mild atmosphere, steam, and many mild chemical environments.

IV. MECHANICAL PROPERTIES

The stress-strain behaviour of austenitic steels in a tensile test differs from that of carbon steels. Stainless steels are also characterized by:

- A high degree of plasticity between the proof stress and the ultimate tensile stress.
- Very good low temperature toughness.
- A degree of anisotropy.

Given the relatively recent emergence of stainless steel as a structural material, efforts have been made to maintain consistency with Carbon steel design guidance. However, unlike carbon steel, stainless steel exhibits a rounded non-linear stress-strain relationship with no strictly defined yield point (Fig. 2). Hence, no sharp behavioural transition occurs at any specified stress. This complexity is overcome by defining the yield point as the stress level corresponding to 0.2 % permanent strain $\varepsilon_{0.2}$ and assuming bilinear stress-strain behaviour for stainless steel as for carbon steel. The substantial differences in the structural response between the two materials are neglected in favour of simplicity, generally resulting in conservative slenderness limits for stainless steel cross-sections [2]. Stainless steel exhibits a rounded stress-strain relationship with no sharply defined yield point as illustrated in Fig. 2.

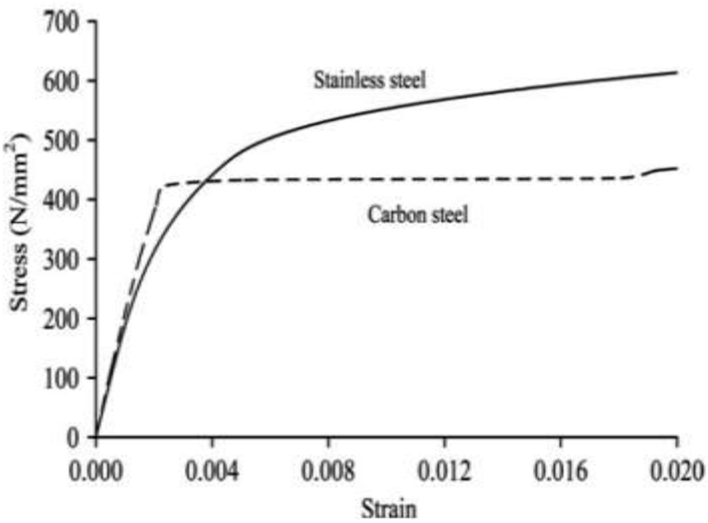


Fig. 2. Indicative Stainless Steel and Carbon Steel Stress-Strain Behaviour [2]

Traditionally its stress-strain relationship has been described by Ramberg-Osgood model. Ramberg and Osgood proposed the expression is given in equation (1) for the description of material stress-strain behaviour, where E_0 is Young's modulus and K and n are constants.

$$\varepsilon = \frac{\sigma}{E_0} + K\left(\frac{\sigma}{E_0}\right)^n$$

V. BEHAVIOR AT ELEVATED TEMPERATURE

At both room temperature and elevated temperature, the material characteristics of stainless steel differ from those of carbon steel due to the high alloy content. At room temperature, stainless steel displays a more rounded stress-strain response than carbon steel and no sharply defined yield point, together with a higher ratio of ultimate to yield stress and greater ductility

(Fig. 3). At elevated temperatures, stainless steel generally exhibits better retention of strength and stiffness in comparison to carbon steel [2].

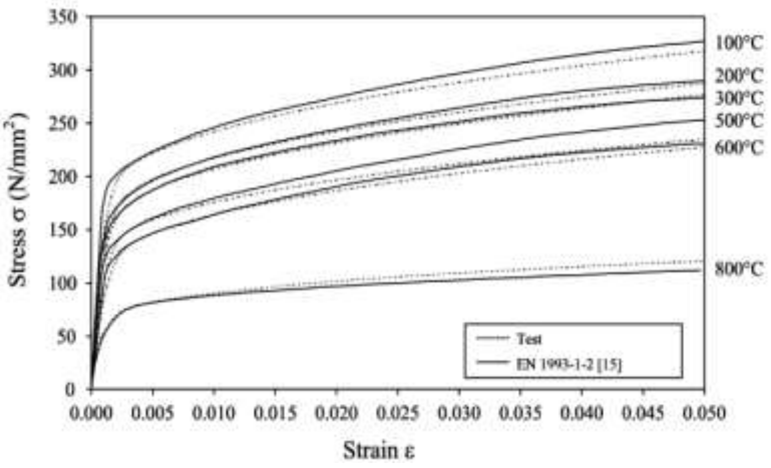


Fig. 3: Stress-Strain Curve for Austenitic Steel at Elevated Temperature [2]

VI. SURFACE INTEGRITY

In a machining operation, the quality of surface finish is an important requirement for many turned work-pieces. Thus, the choice of optimized cutting parameters is very important for controlling the required surface quality [10]. Machining of difficult-to-machine materials such as high alloy steels, SS304, Titanium, and alloys usually results in the poor surface finish, irregular tool wear, built-up-edge (BUE) and premature tool failure. This is due to high strength, high fracture toughness, high fatigue and corrosion resistivity [11]. Many researchers have focused on the surface roughness of hard material like Stainless Steel, Titanium, etc. even though they have some good properties. The presence of built-up-edge will cause an increase in tool wear rate and deteriorate the surface integrity of the work. Low thermal conductivity together with high strength and high heat capacity has made Stainless Steel a difficult-to- machine material. The work hardening capability of stainless steel together with mechanical and thermal properties results in severe tool wear and low surface quality of the machined surface [11].

The surface parameter used to evaluate surface roughness is the roughness average (Ra). The roughness average is the area between the roughness profile and its central line, or the integral of the absolute value of the roughness profile height over the evaluation length. There are a large number of factors influencing the surface roughness shown in Fig.4.

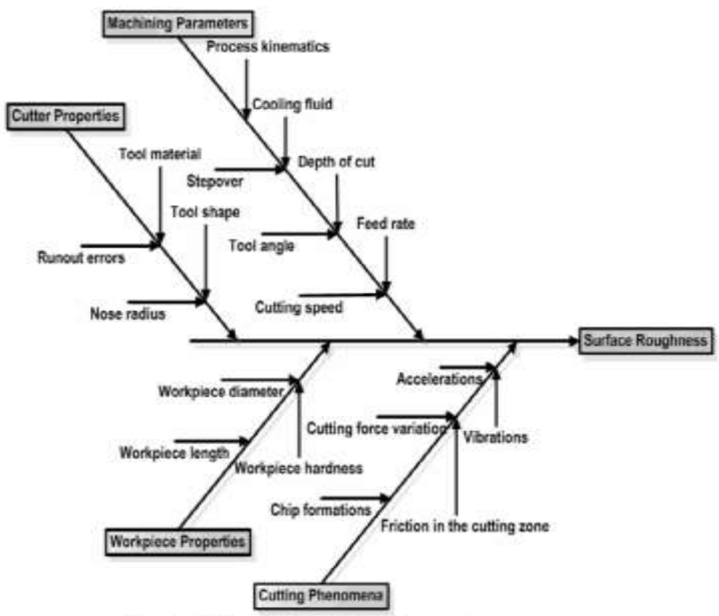


Fig.4: Fish Bone Diagram for Surface Roughness Parameters [12]

Ra is the area between the roughness profile and its mean line, or the integral of the absolute profile height over the evaluation length as shown in Fig.5.

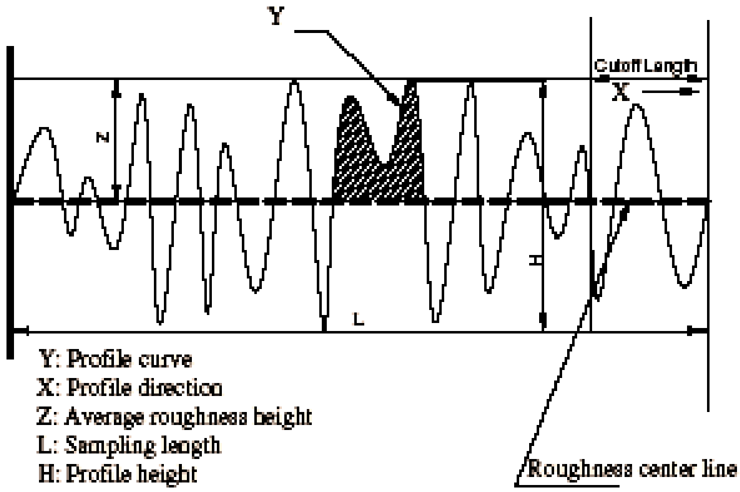


Fig.5: Surface Roughness Profile [12]

Therefore, the Ra is specified by this equation:

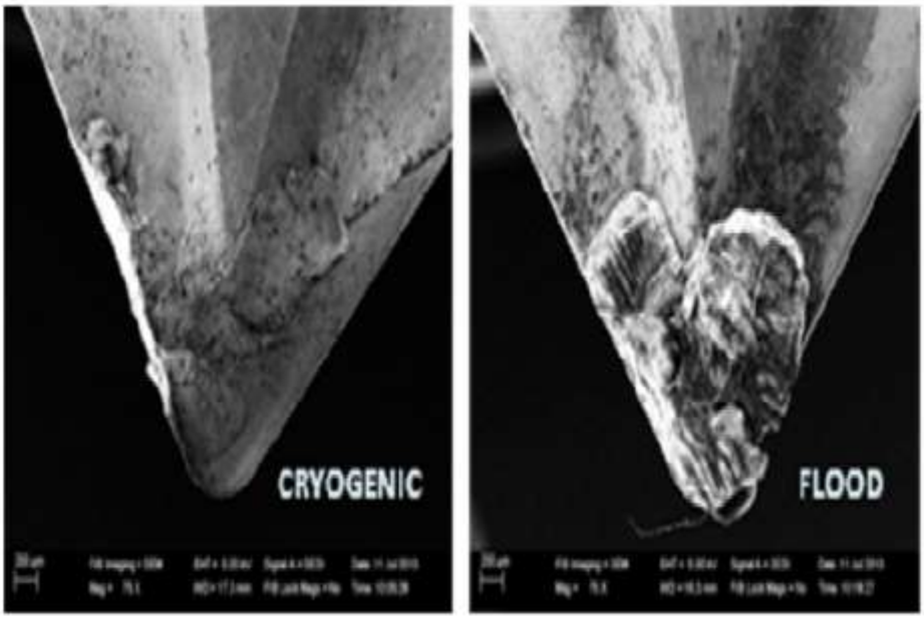
$$Ra = \frac{1}{L}\int_{0}^{L} |Y(x)|\, dx.$$

VII. TOOL WEAR

The extent of cutting tool wear depends on the tool material and geometry, work piece material, cutting parameters, cutting fluids and machine-tool characteristics. An increase in tool wear was noticed with increasing the cutting speed, while at the same time, a decrease in tool wear was observed with increasing the cutting feed. Machining operations of austenitic stainless steels are usually accompanied by a number of difficulties such as irregular wear and built-up-edge (BUE) on the tool flank face and crater face, respectively. The presence of BUE will cause an increase in tool wear rate and deterioration of the surface integrity of the work. The poor machinability of this material is usually accounted for some reasons such as having very low heat conductivity, high ductility, high tensile strength, high fracture toughness and high work hardening rate. Work hardening of stainless steels is caused by a previous severe cutting operation by a worn tool. Work hardening will cause increased rates of tool wear and damage [13].

Tool life decreases with improper edge formation. So edge preparation has an important effect on tool life. The principal-cutting edge, which performs the primary work during turning, is formed by the intersection of the rake and the side flank surfaces. The intersection of the side relief and end relief surfaces produce the end cutting edge. The point at which the side and end-cutting edges converge is called the tool nose. It is the scrawniest part of the tool and determines the overall strength of the cutting edge. As a result, in order to increase its strength, the tool point is given a cutting edge that is circular or is in the form of a transitional cutting edge [14].

In cryogenic machining, a super cold medium, usually liquefied gases, is directed into the cutting zone in order to reduce the cutting zone temperature and cool down the tool and/or work piece. The cryogen medium absorbs the heat from the cutting zone and evaporates into the atmosphere. Spraying cryogenic coolant at the cutting zone could reduce the chip-tool interface temperature and thus reduce the chemical reaction between the cutting tool and chips. This reduces the adhesion and diffusion wear of the cutting tool hence increase the tool life [11].



(a) Cryogenic Insert **(b) Flood Insert**

The improvement in tool life can be attributed to:

- Reduction in chip-tool interface temperature,
- Better integrity of cutting edge due to reduction in tool wear rate,
- Reduction in thermal softening.

Thermal softening is a phenomenon occurring due to the degradation of strength and hardness at high temperatures. The SS304 is work hardening material which in turn increases the thermal softening. Thermal softening can be reduced by reducing the temperature at the tool-work piece interface using cryogenic coolant [11].

VIII. COCLUSION

From reviewing literature, experimental results give a keen tool for efficient machining of Stainless Steel were identified.

- Cryogenic coolant showed better surface finish due to the reduction in tool wear as compared to Conventional flood coolant.
- The increase in cutting speed caused a dramatic reduction in tool life. Feed variation at high cutting speeds has a small effect on tool life.
- Surface finish is directly depending upon machining conditions. Good surface finish obtained at a minimum depth of cut, maximum spindle speed, with low cutting speed.

It is observed that all researchers have focused on the effect of depth of cut, feed rate and cutting speed on various parameters like surface roughness, tool wear, for hard, ductile materials like stainless steel, MS, etc. Also, they provide a suitable solution for that.

IX. ACKNOWLEDGEMENT

As per the reviewed literature, experimental investigations about Stainless Steel, more research work are needed in following areas for easy machining.

- Lubricants and their effect on Stainless Steel alloy.
- Cutting tool material.
- Techniques of Chip formation.

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