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# ENHANCEMENT OF MECHANICAL AND BALLISTIC PROPERTIES OF QUENCHED AND TEMPERED HIGH STRENGTH LOW ALLOY STEEL WELDMENTS

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## Abstract

HSLA Quenched& Tempered Steel Weldments are prone to number of Welding defects as regards to Mechanical & Ballistic properties. In this investigation an attempt has been made to device such Welding methodology which gives sound Weldment by keeping the adequate Mechanical and Ballistic properties intact. Extensive Literature survey reveals that up till now Hard faced layer was deposited in between the Austenitic Stainless Steel Welding layers of Q & T HSLA Steel Weldments for good Ballistic & Mechanical properties but this didn't work well. This study focuses on the shortfall of the previous studies. On the basis of which there has been proposed a strategy to eliminate cracks and defects in weldments by depositing soft Buttering layer in between the base metal and Hard faced layer Low hydrogen ferrite consumables have been recommended to apply the Buttering layer. The results obtained are in good agreement with the already published research.

**Keywords:** High strength low alloy steel, Austenitic stainless steel, Low hydrogen ferriticsteel, Buttering layer.

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## 1.Introduction

Mostly it is very essential it is very much necessary to minimize the Mass & Volume of the Structure but keeping the adequate Mechanical & Ballistic Properties intact. This design philosophy led to the use of the Quenched and Tempered High Strength and Low Alloy Steel . But off course as every structure needs the fabrication or joining process such as welding. Therefore it is very adequate to emphasize on the weldability of HSLA steel Weldments.

Applications of the design philosophy includes the Turret and Hulls of Combat vehicles, Landing Gear, Earth Moving Equipments, Mining Equipments and Mortar Casings. A literature survey indicates that basic requirements in such types of structures are good Impact and Ballistic properties with adequate Strength[1].Therefore basic requirements in the welding of Q & T HSLA Steel in various application can be summarized, as under:

1. Adequate Mechanical Properties and Strength.
2. Good Ballistic Properties.
3. No Cracking and Deformation at all.
4. Free of welding Defects.

Previous studies have explored that softening phenomenon occur in the Heat Affected Zones of these steels during welding, which led to the poor ballistic properties of these Weldments. Remedy for this type of problem could be the "Control of Heat Input" and use of High energy efficient welding processes [2-7].Moreover Martensitic structure of these types of steels increases the chances of cracking. This type of cracking acts like a main spalling factor in the engineering structure of the High Strength Low Alloy Steels and also decreases the Ballistic performance [5,6].Moreover defects such as Deformation, Blow Holes and Porosity are also the part of Hurdle in welding of these steels [8-12].The type of cracks which appear in the welded structure of HSLA are shown in Fig.1 and 2.

Although some work has been done in order to improve the Mechanical Properties of Q & T HSLA Steel Weldments but very less information is available on the Hardfacing of Q & T Armor Steel weldments and their evaluation for ballistic performance and fracture behavior under ballistic impact loading conditions. Therefore the Research Study was carried out in order to maintain the Mechanical Properties of Q & T HSLA Steel weldments with the improvement in Ballistic performance as well. The described design methodology in the said Project is equally useful for the Mechanical as Well as Ballistic Properties of Q & T HSLA Steel Weldments. The HSLA Steel picked up AISI 4340 Steel due to its enormous utilization and availability in local market.

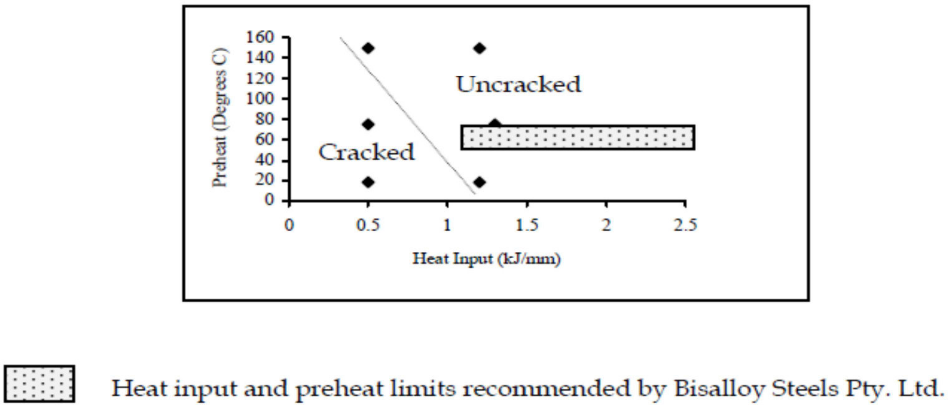



**Fig.1:** Combination of Pre Heat and Heat Input for Hydrogen Induced Cracking [10].

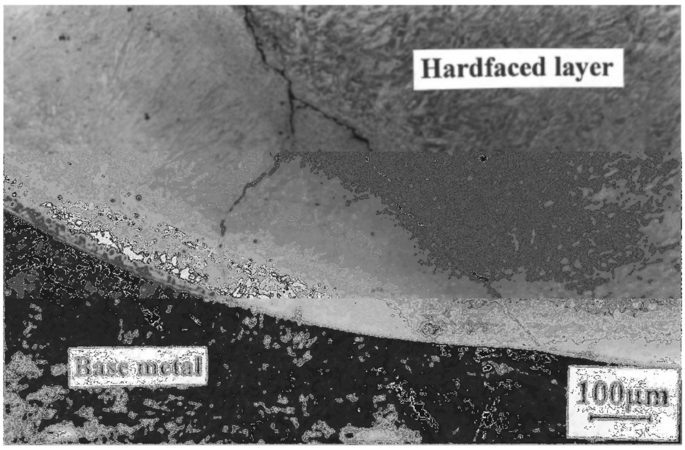



**Fig.2**: Cracks in the Interface of base Metal and Hard faced layer[13].

Austenitic Stainless Steel is employed for welding of these types of steels and one of the defects like Hydrogen Induced Cracking can be minimized but the softness of the ASS material does not allow the said welded structure to withstand the service conditions. To increase the Ballistic Performance of Soft welds usually the idea of the Hard facing is employed. Sandwiching of the Hard faced layer between soft Austenitic welds makes the welded structure unshattered due to high Hardness of Hard facing layer and High energy absorbing capacity of Austenitic stainless Steel. But this design philosophy leads to crack origination at the interface of the Base Metal and Hard faced layer [13].Very recently the idea of "Insertion of soft Buttering layer between the Base Metal and Hard facing layer" is introduced in the literature [3].As buttering is the technique to satisfy the Metallurgical considerations and remove the mismatch present between the Base Metal and Weldment Material if any. This technique not only lessens the Residual Stresses present at the interface of Base Metal and Weldment[14] but also provide the anchoring effect by keeping the joint integrity intact.

## 2. Experimental

Base Metal employed in this research study was closely conforming to AISI 4340 specifications. The Chemical composition of the Base Metal and Consumables used in this investigation are presented in Table 1.The steel used in this investigation was Oil-Quenched from 900 Centigrade (With Soaking time 30 minutes and then Tempered at 250 Centigrade for 2 Hours).Hardness of the Base Metal achieved was 44 HRC.

| Element. | C (%) | Mn (%) | Si (%) | S (%) | W (%) | P (%) | Cr (%) | Ni (%) | Mo (%) | V (%) | Fe (%) | Co (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Base Meta(AISI 4340) | 0.38 | 0.70 | 0.28 | - | - | - | 0.82 | 1.72 | 0.02 | - | Balance. | 0.018 |
| ASS Electrode (AWS E-307-16) | 0.08 | 1.20 | 0.60 | 0.015 | - | 0.002 | 20.30 | 8.50 | 2.60 | - | Balance. | - |
| LHF Electrode( AWS E 11018-M) | 0.06 | 1.32 | 0.33 | 0.015 | - | 0.022 | 0.40 | 2.30 | 0.41 | 0.003 | Balance. | - |
| Hardfacing Stellite-6(AWS A5.13 ERCoCr-A) | 1.1 | - | <2 | - | 4-5 | - | 30 | <3 | <1 | 0.50 | <3 | Balance |

**Table.1:** Chemical Composition of Base Metal and Electrodes.

| Parameters | Unit | ASS | LHF | Buttering (ASS) | Hardfacing. |
|---|---|---|---|---|---|
| Filler Wire Diameter | mm | 4 (0.04 m) | 3.2 (0.0032 m) | 3.2 (0.0032) | 3.2 (0.0032 m) |
| Pre Heat Temperature | Centigrade | 150 | 150 | 150 | 150 |
| Welding Current | Amperes | 154 | 128 | 130 | 135 |
| Arc Voltage | Voltage | 28 | 24.5 | 12 | 27 |
| Heat Input | J / m | $1.55 \times 10^6$ | $0.61 \times 10^6$ | $0.3 \times 10^6$ | $1.41 \times 10^6$ |
| Travel Speed | mm / minutes | 166.5 | 304.8 | 304.8 | 154.2 |
| Travel Speed | m/s | $2.78 \times 10^{-3}$ | $5.08 \times 10^{-3}$ | $5.08 \times 10^{-3}$ | $2.57 \times 10^{-3}$ |

**Table.2**: Welding Process Parameters.

| Location | Hardness Rockwell (HRC). |
|---|---|
| Base Metal | 44 |
| ASS Root | 7 |
| ASS Buttering | 14-15 |
| LHF Capping | 34-35 |
| Hardfacing | 44 |
| Heat Affected Zone (HAZ) | 19 |

**Table.3**: Hardness at Different Locations.

Two plates of Base Metals were prepared in order to acquire samples for Mechanical and Ballistic Testing respectively. Double Vee joint was prepared .First of all Buttering of Beveled edges (Angle 60 Degrees) of the double Vee groove was buttered with the ASS electrodes with thickness 1.5 mm. Subsequent grinding operation was done in order to obtain finish surface of buttered layer. After applying Root pass of Austenitic Stainless Steel Hard facing layer of satellite-6 consumable was inserted. Although literature recommends AWS E FeCr-A7 consumable for Hard facing purpose [3]but it was employed due to instant availability and good Hard facing properties of Stellite-6 consumable. At the end capping pass of Low Hydrogen Ferritic (LHF) Steel was applied. Optimization value of Heat Input was selected so that proper melting of the Consumable Material to be welded was done without the “Lack of Fusion/Penetration” defect.

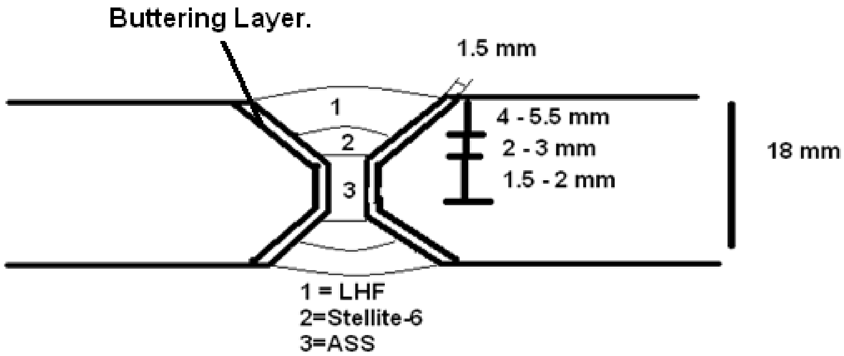



**Fig.3**: Weldment Configuration (Joint Angle = 60 Degrees).

The Weldment was produced by the Shielded Metal Arc Welding (SMAW). Different passes were inserted with different Welding parameters as shown in Table.2.

PWHT(Post Weld Heat Treatment) parameters were ,
Raising the temperature upto = 750 Centigrade (Rate = 180 *C/Hour)
Stress Relieving Temperature = 750 Centigrade
Soaking time = 60 minutes.
Then Cooling at 180 *C/ Hour.

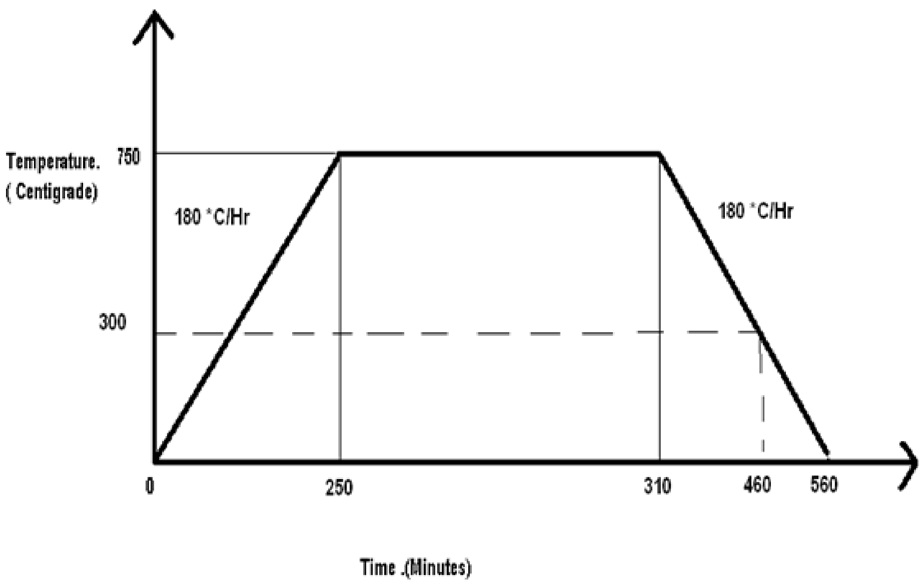



**Fig.4**: Post Weld Heat Treatment (PWHT) Graph.

The welded specimen was then chopped into number of samples using Plasma Arc Cutting technique(128 Ampere Current and 380 Voltage). Hardness survey was carried on different locations of the welded specimen. As well as the Metallographic characterization was done so that the complete information about the Metallic and Non-Metallic phases, Interface Microstructure & Grain morphology can be obtained.

Unnotched Tensile specimens were prepared to evaluate the Tensile properties of specimen using 200 KN Universal Testing Machine. Bending behavior was judged on the basis of Free Bend Test. Four Notched specimens were prepared according to the guidelines of ASTM(American Society for Testing Materials) for evaluation of Impact properties and Ductile to Brittle Transition Temperature as Well. Specimen for the Ballistic Test was prepared according to the dimensions given in Figure 5.

Theoretical Evaluation of the Ballistic performance was done on the basis of JSC(Modified Cour-Palis) Equation [15] as

For crater depth:

$$p = 5.24\, d^{\left(\frac{19}{18}\right)} (B\, H)^{-0.25} (\rho_p / \rho_t)^{(0.5)} (V_n / C)^{(2/3)} \qquad \text{Equation (1).}$$

Where,

$p$ = Crater depth on target (cm)
$t_b$= Target thickness for ballistic limit (cm)
$d$ = Projectile diameter (cm)
$\rho p$ = Projectile density (gm/$cm^3$)
$\rho t$ = Target density (gm/$cm^3$)
$BH$ = Brinel hardness for target.
Vn = Impact velocity (normal component of the projectile relative velocity) (km/s).
$C$ = speed of sound for target (km/s)

Now putting values in equation considering 8.5 Km/s(which is reliable figure in literature [3]) as Ballistic Limit.

$t_b$ = 1.8 cm
d = 0.762 cm
$\rho p$ = 7.5 g/cc
$\rho t$ =8.02 g/cc
*BH =264 BHN*
Vn = 8.5 Km/s
C =4.8 Km/s
P = 1.38 cm (0.0138 m)

As the thickness of the specimen was 1.8 cm (0.018 m) therefore velocity 8.5 Km/s can be considered as the Ballistic Limit of the specimen.

The Weldments were then characterized on the basis of some Non Destructive Evaluation techniques i.e. Radiographic Testing (RT), Ultrasonic Testing(UT) and Dye Penetrant Testing(DPT).Both RT and UT satisfied the prepared welded specimen while the DPT was done during the welding process followed by Back-Gouging in order to remove the defects present if any according ASME(American Society of Testing Materials) Section 9 guidelines as shown in Fig.6.

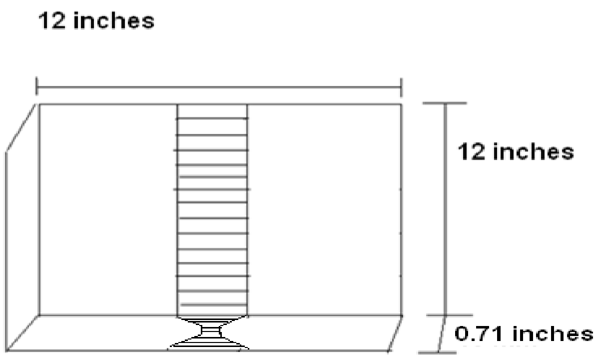



**Fig.5**: Specimen for Ballistic Testing.

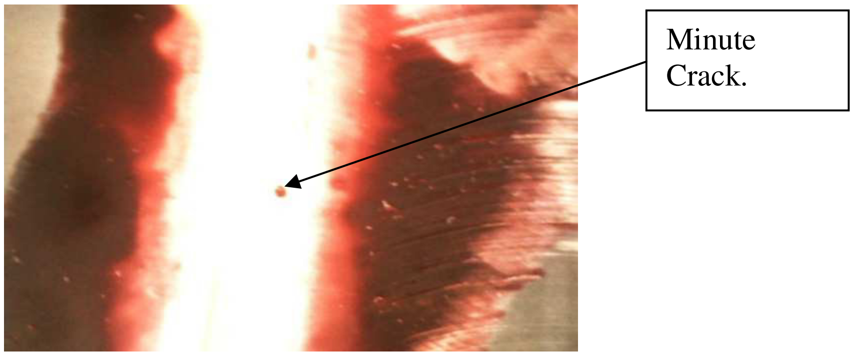



**Fig.6** Crack appeared after Dye Penetrant Test.

**3. Results and Discussion**

Hardness survey and the Metallographic analysis of the joint at different location as shown in Table.3 and Fig.7 clearly shows that the ASS Buttering layer has successfully provide the Anchoring effect between the Base Metal and the Hard faced layer. No cracks are present which are reported in literature as shown in Fig. 2. Microstructure of the welded joint at the location of the Buttering layer shows the Austenitic Matrix with skeletal delta ferrite network. While the base Metal clearly shows the acicular morphology of the martensitic structure. Whereas the acicular nature of the Low Hydogen Ferritic Capping indicates the good Mechanical Behavior of the joint due to the good potential of acicular Ferritic structure for High Strength and Toughness [16] .

Moreover this acicular type structure also explains that the Heat Input provided during welding process is perfectly suited for the formation of the acicular morphology otherwise the polygonal Ferrite structure would be obtained instead of this one. Therefore it can be said that the welding parameters adopted and presented in Table.2 are upto the level of optimization. The interface microstructures of ASS-Base Metal and ASS-Stellite-6 depicts that integrity between these types of phases is upto the mark and gives the indication of joint integrity.

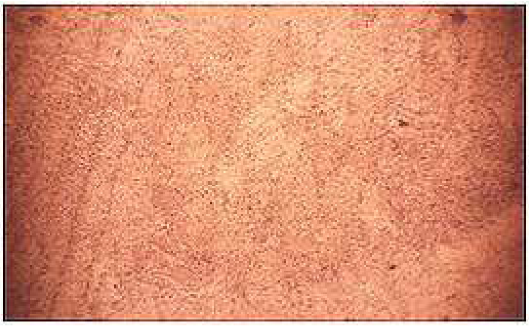
Tensile and Impact Strength ,shown in Fig.8 and Fig.9 ,in Study number 1 is of with Hard facing layer while the Experiment number 2-5 is without any Hard facing layer therefore despite of this Hard facing layer (reported in the Literature [13].Tensile and Impact strength of the standard sample is in agreement with the experimental data reported data in the literature.

ASS (Austenitic Stainless Steel).

Base Metal.

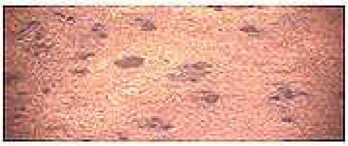
ASS-STELLITE-6 interface.

Base Metal – ASS Interface.



LHF (Low Hydrogen Ferritic) Capping.

Stellite 6 (Hardfacing Layer).



Defective Base Metal.

**Fig.7**: Practically Evaluated Microstructures(All are at 400 X ).

Weld metal chemistry of the ASS Buttering layer shows that it has approximately 9% Ni in it. Since Ni is Austenite stabilizer and it influences the Austenitic phase formation in the microstructure. The microstructure of LHF capping depicts the Ferritic morphology and therefore gives the optimum weld metal Strength and Toughness [16] .It can be inferred from the above discussion that adequate Tensile and Impact properties can be attributed towards the best combination of soft Austenitic phase and Acicular morphology of LHF in a compatible manner. This discussion justifies that High Carbon Equivalent Steel has given the defect free weldment with adequate Mechanical properties. Percentage elongation obtained by Free Bend Test was about 2.36 % whichinline with published value .

| Sample. | Ultimate Tensile Strength(UTS). (MPa) | Elongation in 203.2 mm Gauge Length. (%) | Joint efficiency. (%) =(UTS of Weld.) / (UTS of Plate.) |
|---|---|---|---|
| Average Values. | 611.5 | 6.65 | 47.4 |

**Table.4**: Tensile Properties.

| Serial #. | Temperature of specimen to be Tested. (Centigrade) | Impact Toughness(Joule). | Ductile to Brittle Transition Temperature Range. |
|---|---|---|---|
| 1. | -4 degree Centigrade. | 37.3 | 0-10 Degree Centigrade |
| 2. | Room Temperature (28 Centigrade). | 44 | |
| 3. | 100 degree Centigrade. | 53.1 | |

**Table.5**: Impact Properties.

Now the theoretically evaluated results of the Ballistic Test are compared with the already reported results in the literature then the satisfaction on the said welding methodology can be made as depicted in Fig.10.R.T.(Radiographic Testing) also verifies the unpresence of major defects in weldment. While DPT(Dye Penetrant Testing) shows the origination of minute cracks during welding process which were repaired at the spot.

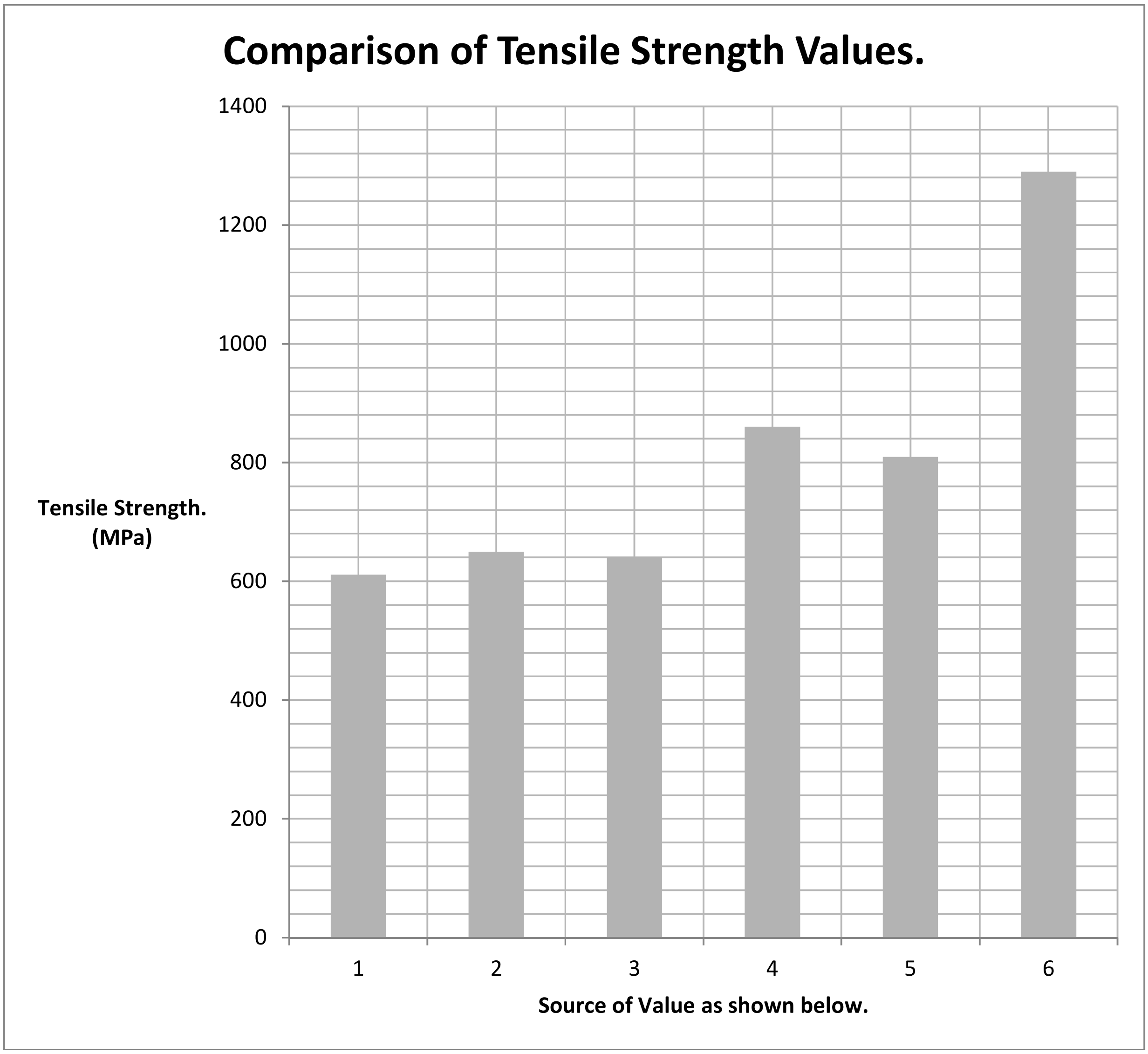



**Fig.8**: Comparison of Tensile Strength Values. Research Study # 1 = Tensile Strength of the said Research Study. Research Study # 2 [16] =Consumable used was AWS E 307-16 with SMAW Welding. Research Study # 3 [16] = Consumable used was AWS E 307-TI-1 with FCAW Welding. Research Study # 4 [16] = Consumable used was AWS E 11018-M with SMAW Welding. Research Study # 5 [16] = Consumable used was AWS E 110T5-K4-M with FCAW Welding. Research Study # 6[16] =Tensile Strength of Base Metal i.e. AISI 4340.

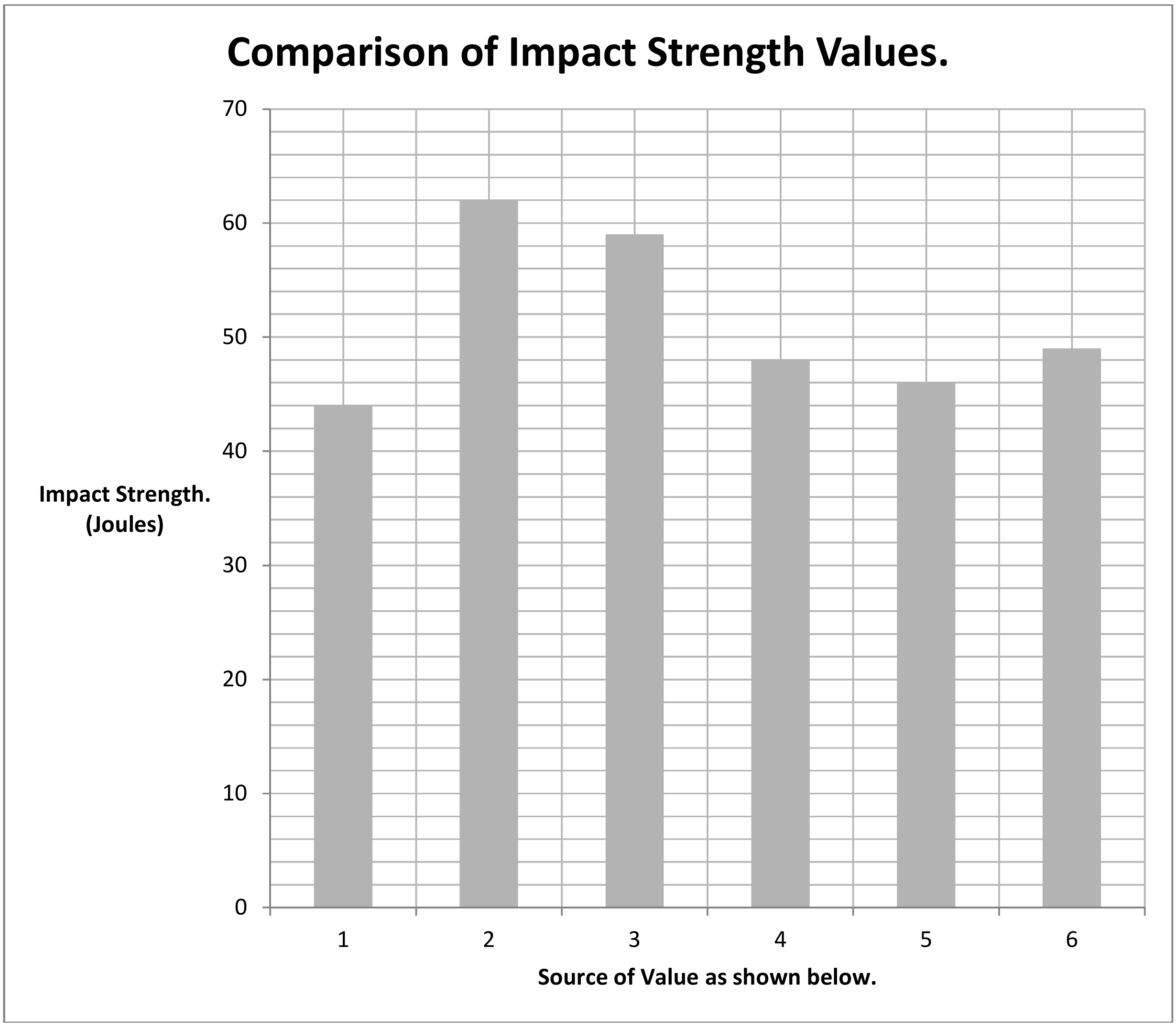



**Fig.9**: Comparison of Impact Strength Values. Research Study # 1 = Tensile Strength of the said Research Study. Research Study # 2 [16] =Consumable used was AWS E 307-16 with SMAW Welding. Research Study # 3 [16] = Consumable used was AWS E 307-TI-1 with FCAW Welding. Research Study # 4 [16] = Consumable used was AWS E 11018-M with SMAW Welding. Research Study # 5 [16] = Consumable used was AWS E 110T5-K4-M with FCAW Welding. Research Study # 6 [16] =Impact Strength (at Room Temperature)of Base Metal i.e. AISI 4340.

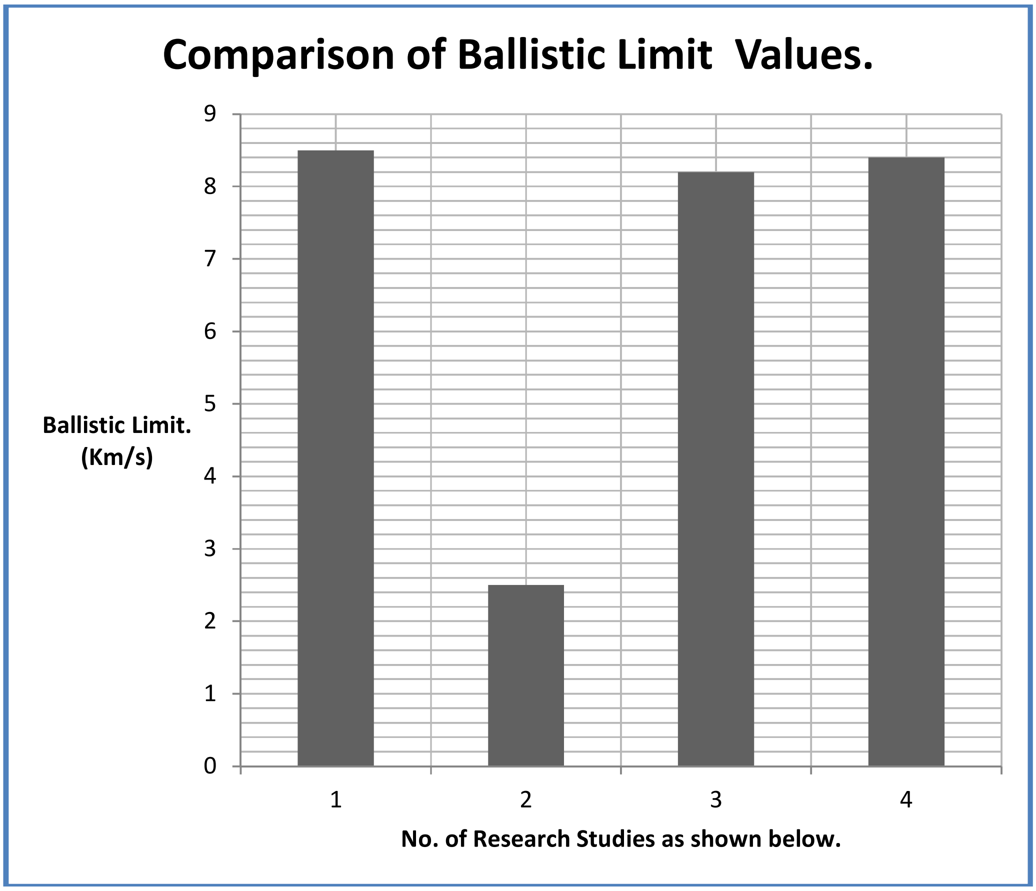



**Fig.10**: Comparison of Ballistic Limit Values. Research Study # 1 = Ballistic Limit of the said Research Study. Research Study # 2 [9] =Ballistic Limit obtained by the Study of Heat Input Effect on Ballistic Performance of Q & T HSLA Steel Weldments. Research Study # 3 [13] =Ballistic Limit obtained by Study of Hardfacing effect on Ballistic capabilities of Soft Welds. Research Study # 4 [17] =Ballistic Limit evaluated by study of PTA (Plasma Transferred Arc) Hard facing Effect on Q & T HSLA Steel Weldments.

## 4. Conclusions.

It has been concluded from the present research that Quenched and Tempered AISI 4340 can be welded without defects by the proposed welding strategy employed and with the use of newly recommended Low Hydrogen Ferritic steel consumable.

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