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Improvement in Properties of Ni-Cr-Mo-V Steel through Process Control

Arnab Majumdar, Sanjoy Sadhukhan

***Abstract*—**Although gun barrel steels are an important variety from defense view point, available literatures are very limited. In the present work, an IF grade Ni-Cr-Mo-V high strength low alloy steel is produced in Electric Earth Furnace-ESR Route. Ingot was hot forged to desired dimension with a reduction ratio of 70-75% followed by homogenization, hardening and tempering treatment. Sample chemistry, NMIR, macro and micro structural analyses were done. Mechanical properties which include tensile, impact, and fracture toughness were studied. Ultrasonic testing was done to identify internal flaws. The existing high strength low alloy Ni-Cr-Mo-V steel shows improved properties in modified processing route and heat treatment schedule in comparison to properties noted earlier for manufacturing of gun barrels. The improvement in properties seems to withstand higher explosive loads with the same amount of steel in gun barrel application.

***Keywords*—**Gun barrel steels, IF grade, physical properties, thermal and mechanical processing, mechanical properties, ultrasonic testing.

I. Introduction

IN India, heavy duty ordnance items with large cross section forgings for different applications are manufactured with Ni-Cr-Mo-V low alloy steels of different composition ranges. High strength, hardness, good toughness and low ductile-brittle transition temperature are prime requirements which often overlap. It has taken into account that the processing route is the same and the chemical compositions as well as mechanical properties of various types of ordnance products are overlapping or in the close proximity. This present system of production of overlapping grades of steels is associated with a numbers of difficulties as follows.

There is a huge production changeover while switching over from one grade to other system, which increases wastage of man hours, increase the number of heat treatments, delay in fulfillment of target and thus loss in customers' confidence and consequent loss of good will in the market which costs a lot. Always there is a chance of high inventory cost locked up by producing excess quantity of certain graded steel with a certain future target. Keeping a large stock of raw materials of different kinds also increases inventory cost which is highly undesirable; because, more space is required for items which has no immediate use. There are always various types of complexities; like mixing of products, dispatching problem, high transport cost, management problem, supply to demand failure, occurring due to large varieties. It has been seen from experience that there is change in demand of product at any time of year. From production point of view, it is a constraint to break the normal production planning based on earlier demands already placed, but still demands to be fulfilled in time as matter is concerned with national security. It is seen that quality control system is another great concern as more product variety means more inspection, more material testing, more testing time and more manpower requirement for quality control which increases quality cost. In case any time any product gets rejected due to say surface cracks, it cannot be converted to other product of lower dimension rather being rejected. More variety of materials means multitasking R & D which increases R & D cost and time also.

To minimize the constraints, it is tried here to present a single grade of steel to replace the closely related existing 17 grades by exploring in different directions. The main aims of this replacement were to get the advantages of better properties with cost reduction. Considering logical factors two melts as *Alloy-1* and *2* with little variation in compositions were prepared through EAF-LFVD-ESR processes followed by forging in two different ratios and due heat treatment applied. Both of the materials were characterized chemically, mechanically and metallographically and the results were correlated with the required properties range of the selected grades. Upon comparing the results, it has been significantly noticed that both *Alloy-1* and *2* are well capable to replace those seventeen selected grades with cost reduction and process advantages in different aspects partially or fully. It is also found that wall thickness of few gun tubes can be reduced to their maximum extent with retaining their required working properties which will reduce the material & transportation costs, increase mobility of heavy duty gun systems as well as increase their life cycles.

II. Literature Review

A. Development in Melting of Gun Barrel Materials

Up to 1970's Ni-Cr-Mo-V - low alloy steels were produced in electric arc furnace when the targeted strength level was ≤ ~ 800 MPa after heat treatment. However, increasing trend to higher operating stresses and the need to have reasonable safety margins necessitated the modification in the processing route as the earlier steels contain higher 'S' level besides poor cleanliness rating. These were found to be adversely affecting the low temperature toughness and fatigue life at high strength level [1]. Again, Ni-Cr-Mo-V steels are highly susceptible to hydrogen flaking, which increases with increasing hydrogen content in molten metal. It has been found to be a function of the chemical composition in low alloy steels.

Arnab Majumdar is with the Department of Metallurgical and Materials Engineering, National Institute of Technology, Durgapur, India (e-mail: xie.7802@gmail.com).

To lower hydrogen level and to obtain a clean steel the processing route was modified as melting in Electric Arc Furnace (EAF) followed by Ladle Furnace Vacuum Degassing (LF-VD) and Electro Slag Remelting (ESR) [1]. ESR offers the capability of producing the steel with improved cleanliness, soundness, better chemical homogeneity over the ingot volume, improved forgeablity and higher manufacturing yields [2]-[5]. The reduction in volume fraction of inclusions gives greatly improved mechanical properties, particularly the toughness in the transverse direction. It also brings down the sulfur level drastically. High 'S' impairs the impact toughness of these steels [6].

Vacuum degassing of the liquid steel before casting of the electrode for ESR shows a major improvement with respect to solidification defects. The ESR quality forgings produced from vacuum degassed and bottom poured electrodes showed none of the solidification defects after the normal end cropping considered characteristics of ESR. Vacuum treatment of liquid steels also accelerates the solid diffusion annealing (Anti Flaking) cycle resulting in a significant reduction in the manufacturing cycle time.

B. Hot Working of Gun Barrel Materials

Often one heavy-duty forged ordnance product is made of all the output of one ESR slug. Even a single crack occurring anywhere along the length of the product results in rejection of the system. The forger therefore plays it safe and shapes of the material under optimum conditions of high plasticity. The production of heavy duty ordnance item involves a reduction by hot working of ~50%. In the past years, starting with a 600mm diameter ingot, forging was being completed in three to four heats, the average reduction in a hot working out to ~ 15%. The reheating temperatures maintained were also high, even though progressively decreasing heat treatment temperatures were used for successive heats. Due to small % deformation in any heat, the scope for dynamic or metadynamic recrystallization was rare [7], rather static recrystallization used to take place; moreover, relatively high reheating temperatures and little deformation strain results relatively larger recrystallized grain and likely grain growth. Towle and Gladman [8] have discussed for AISI 304 austenitic stainless steels where the final grain size at the end of forging is quite coarse.

When forgings are heat treated, there can be a problem of getting the recommended properties. The Limit of Proportionality (LOP) is subjected as a measure of strength. Considering as 1177 MPa (120 kg/mm^2) minimum specified; however, the governing specification shows relaxation of -30 MPa (3 kg/mm^2), with the result that LOP values higher than 1147 MPa (117 kg/ mm^2) are still considered acceptable. Even if values less than even 1147 MPa are below the acceptable limit, results as low as 1080 MPa seen in many cases [1].

Many specifications governing the Ni-Cr-Mo-V steels allow repeat heat treatment to reach the desired mechanical properties. However, should there be a failure even after third heat treatment, the forgings have to be rejected involving a great loss.

With many changes in the ordnances generated from this steel, there is entire reduction of ~50% is given in one heat, in typically three passes, but without resorting to any reheating in between resulting finer grain size. This is likely the reason of improved LOP values at present.

Low alloy fine austenite grains improve the strength of martensite [9]. The martensite laths are arranged in packets whose size is directly related to austenitic grain size.

Grange [10] has shown that AlSl 4340 Ni-Cr-Mo steel works under Hall – Patch type relationship between 0.2% Yield Strength and prior austenitic grain size in the hardened and tempered condition at 677K [Fig. 1]. However, the slope of the straight line decreases from quench hardened state [Fig. 2] to tempered state [Fig. 3] as shown in case of Fe-0.2%C steel [11].

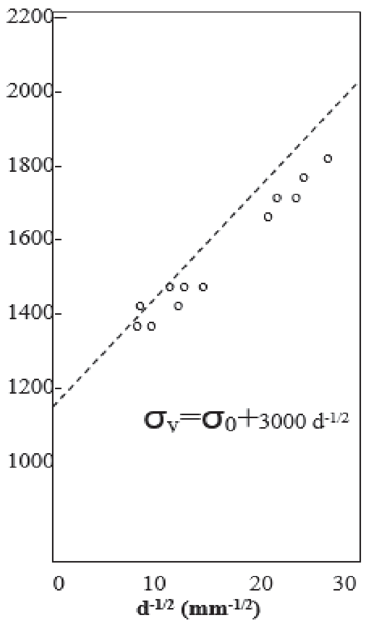

Fig. 1 Prior austenite grain size over Yield Strength of the commercial martensitic steel AISI 4340 [10]

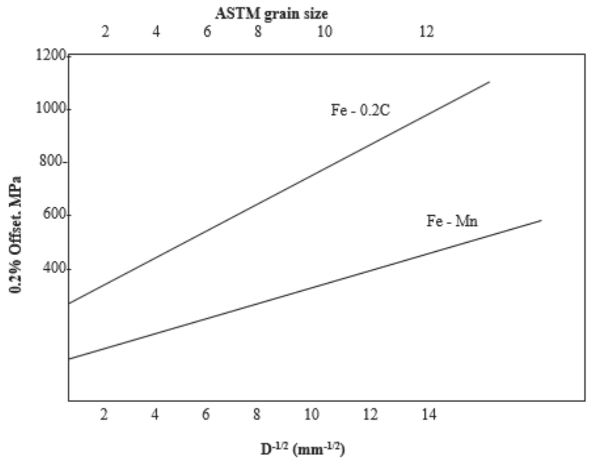

Fig. 2 0.2% offset yield strength vs $D^{-1/2}$ for Fe-0.2C and Fe-Mn as quenched Martensites. D is packet diameter [10]

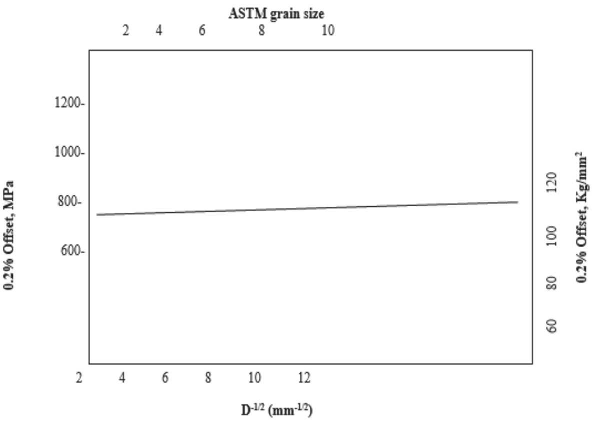

Fig. 3 0.2%offset yield Strength vs $D^{-1/2}$ for Fe-0.2 C Quench and Tempered lath Martensite. D is packet diameter. (Tempered in lead bath for1 min at 673 K) [11]

C. Heat Treatment of Gun Barrel Materials

Tensile strength along with yield point of low alloy steels decreases with increasing tempering temperature is a well-stated phenomenon. When the LOP values after hardening treatment falls short of specified minimum, one is inclined in adopting an approach involving lowering the tempering temperature to push up the LOP value.

Much of the heat treatments of the above mentioned steels have been done with tempering done at the range 623-673 K (350-400°C) for obtaining LOP values ≥ 1147 MPa. But, in Ni-Cr-Mo type low alloy steels, Tempered Martensite Embrittlement (TME) sets in when tempering is carried out in the temperature range 523-673 K (250-400 °C) [12].

Thomas [13] reported that TME is a result of decomposition of thin films of retained austenite present between laths of martensite and formation of cementite. Eliaz et al. [14] carried out analysis of failures arising out of TME in AISI 4340. The toughness remains at a relatively low level up to a tempering temperature of 673 K (400 °C). Only after tempering at ≥723 K (450 °C) good toughness value can be obtained. Several forged ordnance items made of Ni-Cr-Mo-V steels hardened followed by tempering in the temperature range 623-673 K, have also shown a brittle state with low resistance to crack propagation. Most likely TME resulted poor toughness in those products.

D. Evolution of Gun Tube Materials

For centuries, gun barrel designers have focused on the development and use of steels possessing high strength and toughness. Good mechanical properties being required to withstand the high interior ballistic loads where these pressure vessels are subjected to. Besides, the cannon bore is exposed to very high temperatures, where the propellant ignites and begins the evolution of hot gases to provide the propulsive force for the motion. With the use of more robust propellants, bore surface erosion has become increasingly problematic. This has forced barrel designers to implement various means that include coatings and alternate material liners to combat the phenomena [15].

One of the first major advances made to iron cannons was the development of a technique in the 1850's by Captain Thomas Jefferson Rodman [15] [16] casted cannon through core cooled with water over heated flask. This technique with slow cooling of iron increased tensile strength of metal. Still he failed to establish importance of pre-stress condition of cannon.

For late 20th century [16], improved chemical properties of Barrel Steel have introduced. These improvements for the higher grade have fewer defects. Latest development is ASTM A723 steel having higher yield strength than Rodman steel produced a century ago, being replaced by 4335-V modified steel used in World War II. For, A723 steel, it is being processed through either Vacuum Arc Remelts (VAR) or Electro-Slag-Remelt (ESR). Both processes significantly reduce the amount of sulfur and phosphorus and, combined with an increase in the nickel content, make A723 steel an excellent candidate for "modern" armament applications.

Fig. 4 The Rodman Cannon (ca. 1860 to 1900), Staple of Coastal Defense (Model 1861 15-inch Columbiad in 1860 at Fort Mason's Point, CA.) [15]

E. Stresses in Gun Tubes

Considering a gun only as a cylinder, we find that the two principal stresses Fig. 5 to which such a cylinder is subjected upon the explosion of a charge are [17] tangential stress and longitudinal stress.

The maximum stress in metal comes as tensile stress along with small amount of longitudinal stress, when both are taken into account; it's determined by Lame's Law. Thus, modern gun will fail to withstand pressure, when system is made of simple hollow cylinder, hence its construction will be such that it will able to withstand more internal pressure with simple cylindrical construction. But problem is to make the outer layers take a proper proportion of the stress. In one modern solution to the problem, the gun is constructed of layers of metal. The layers nearer the bore are held under an initial compression by the tension of the outer layers. Thus, when the gun is fired, the inner layers must first be expanded sufficiently removing the initial compression before they begin to experience a positive tension, while the expansion is continuously resisted by tension of the outer layers [Fig. 5].

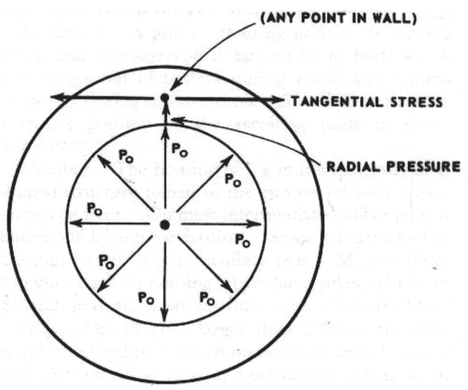

Fig. 5 Forces in Gun Barrel [17]

F. Properties of Gun Tube Steels

Gun steel is elastic within limits, when stress is applied so as to set up a strain not exceeding the elastic limit of strain of the steel, then the steel will return to its original shape and dimensions when the stress is removed. It is then said to have been worked within its elastic range. Reaching the elastic limit of strain, with increment in stress steel yield will suffer large strain with its production in semi-plastic range. The important point is that the steel has now received a permanent set though it will attempt to return to its former dimensions when the stress is removed resulting permanent elastic deformation that is permanent but elastic. These properties of gun steel are plotted in Fig. 6 [17], in which the ordinates measuring OY, represent the stresses applied to a test piece, and the abscissas along OX showing corresponding strains set up. Here the curve suggests that there occurs tension stress in steel, but its behavior will not differ under compressive stresses as well as compressive strains. The steel is shown by the curve OBDF. Important properties are: (1) it receives a permanent deformation and will resist a compression stress tending to compress it to its former dimensions. (2) It has changed its physical qualities in the application of a stress beyond its original limit, has given it a new elastic limit practically equal to the stress it has sustained.

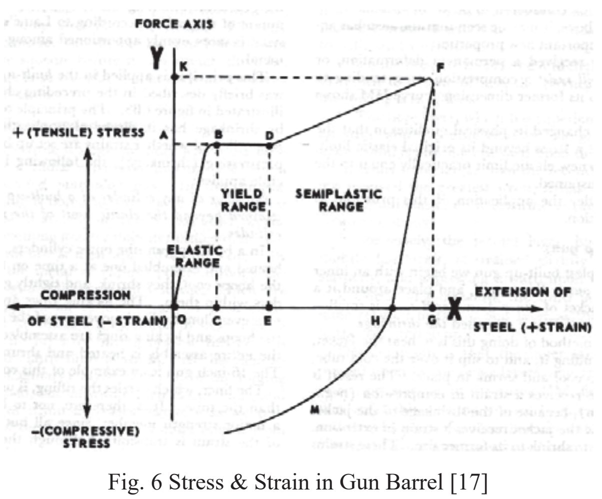

Fig. 6 Stress & Strain in Gun Barrel [17]

G.Autofrettage Operation for Gun Tube Strengthening

A widely accepted and experimentally proved process for increasing of the performances and life cycle of all gun calibers in addition to strengthening by due heat treatment is Autofrettage operation.

Autofrettage [18] is an elastic-plastic technique used on thick walled metal tubes or pipes (cylinders) to improve the durability of the part by creating a compressive residual stress at the bore. In this technique, the cylinder is subjected to an internal pressure that is high enough to plastically deform the bore of the part but not so high that it bursts the part is applied to the inside of the tube. The result is that, after the pressure is removed, the elastic recovery of the outer wall puts the inner wall into compression, providing a residual compressive stress. The applications are typically heavy walled tubes that experience cyclic loading and are thus prone to fatigue. The main reason for using an autofrettage technique in cylinders is to increase its fatigue life. The analysis of residual stresses and deformation in an autofrettaged thick-walled cylinder has been taken place.

The stresses obtained by the loading during shooting inside the artillery barrel overlapping permanent stresses, thus, one obtains lower total stresses than in the case when these residual stresses are not present. Theoretically, the working pressure increases till the value of the autofrettage pressure without the appearance of other residual deformations in the material. Practically, the working pressure is established under the autofrettage pressure for safety reasons. Therefore, the working pressure in an autofrettaged barrel will be increased up to 150% [19] according to the geometry and to the change in plastic deformation being considered with normal plot. There can appear axial stresses in the hydrostatic method of elastic-plastic deformation having maximum values where the sealing with plugs installed at the end of the barrel. This procedure involves residual deformations for the final processing and its values depend on the desired degree of elastic-plastic deformation. Usually, the degree of deformation is 1-2%. [18] Under these conditions, the processing addition for the internal diameter (d) is about (0.019-0.02d). Some advantages of this method are: (1) with thickness of the barrel wall, the ability of differentiate autofrettage process on different sections, (2) the possibility of autofrettaging the gun barrels with a variable internal bore profile. Main problem is related to the high-pressure installation and to the sealing's accomplishment. [19]

H.Weight Reduction in Gun Tubes

Mobility of gun systems is highly desirable by army, as there is a frequent deployment of troops. So light weight gun tubes are always in high demand.

It is important to understand the significance that gun barrel mass plays in the overall system design. Weapon recoil force, F_r, can be expressed as:

$$F_r = \frac{1}{2} * \{I^2 / (m_r * L_r)\}$$

where, I is the impulse imparted by the cannon to the system, m_r is the mass of the recoiling parts, and L_r is the length of the recoil stroke. From this equation, it is clear that reducing the mass of the recoiling parts adversely increases the total force and imposes additional system burdens on the recoil mechanism. It includes various techniques to manage the recoil more effectively have resulted in renewed interest and emphasis on lightweight barrels utilizing advanced materials. Titanium alloys with refractory coating, Ceramic liners and hybrid composite materials are tried for it.

I. Improving Barrel Life

The US Armed Forces recently implemented chrome plating with large caliber, direct-fire weapon systems to protect the barrel's bore surface from harsh effects of propellant gases with mechanical wear of projectiles during firing. The electroplating process is used to deposit chromium onto these large caliber gun barrels. The process involves applying a chromium coat by passing electrolytic current contacting with the gun barrel. The essential components of the electroplating process include the barrel, an anode to complete the circuit, an electrolyte containing the chromium metal ions to be deposited, and a direct current power source. Here electrolysis takes place with barrel and anode in chromium electrolyte; where current being moved from nil, point is obtained when chromium deposition start, depositing a thicker layer of metal on surface of gun barrel having high resistance and less friction. Now advancement in ammunition technology marked chromium electroplating as insufficient in protecting the bores of large caliber gun barrels. Increasing muzzle velocity and range requirements have forced the development of advanced propellant formulations that causes the loss of chromium coated barrel resulting in degradation of life of barrel. The M1A1 Abrams tank main armament, 120 mm M256 cannon, has lost significant barrel life throughout the evolution of cartridges of dimensions 120 mm [Fig. 5]. Present formulations are based on 120 mm barrels, 50 of which will be fired. It requires improvements to increase the life of barrel from 260 rounds to 500 rounds life. But chromic acid required in this process forms carinogen with hexavalent chrome. Chromium electroplating can no longer support these advanced propellant formulations for a number of reasons. Most notable is the fact that as-deposited electroplated chromium experiences a significant amount of cracking during the plating process. These cracks are a result of volumetric changes in the chromium layer when electroplating process contaminants outgas. This volumetric change results in a severe tensile load that is only relieved by the formation of micro-cracks. As a result, the "compromised layer" spalls off revealing more unprotected steel and further propagating the erosion mechanism. Advanced materials and application technologies are one way to provide adequate bore protection, having melting temperature higher than chromium. Also it is required to have coating material maintaining elastic modulus that of steel. Refractory materials used here are tantalum, rhenium, and niobium. Due to cost and reactivity, tantalum has been the primary coating material of choice amongst these three.

J. Large Caliber Gun Tube Material Systems Design

Any materials system can be examined in terms of Processing, Manufacturing, Composition, Behavior and Performance. Cost comes after Manufacturing, where this part is related to high value. Cost plays a vital role where gun production must have comparable price with the existing system.

Breaking of gun tube occurs into three zones [20], namely coating, liner and jacket. A gun tube may have all three of these components made from the same material, it may have a continuous gradation of materials from the coating through the liner to the jacket. This is known as a functional gradient material, or FGM.

Currently, all fielded gun systems use tubes that are monobloc steel, except the 50 cal M2 machine gun, which has a Stellite insert. The steel is generally a low alloy medium carbon Ni-Cr-Mo steel tempered in Stage III, which can be used here possessing the required specific strength and resistant towards erosion and also fabricable and inexpensive too.

Before World War II, the service life of gun tubes was generally based on fatigue. With advancement of war, phenomenon of thermo-chemical erosion acts as the important factor in life. For the gun, the surface erosion increases by many folds through mechanical processing. Certainly when erosion exceeds its limit, then tubes are removed from its use. Finally, however, performance attributes that are degraded by erosion are dispersion and muzzle velocity [21], [22].

III. Experimental Works

A. Selection of Materials for Experimental Works

Here in this experiment, high strength low alloy steel is considered with range of chemical composition and mechanical properties in heat treated condition, used for manufacturing of different gun barrel tubes of varying sizes.

Replacing by a suitable single grade of low alloy steel, considering Alloy-1 with various composition range is designed with extensive analysis of data from conventional products. However, their compositions were designed to meet the necessary mechanical properties of the range of product along with cost efficiency.

The logical approaches and justifications towards selection of composition ranges of Alloy-1 have been enumerated in the later discussions respectively.

The Alloy-1 is prepared through same production route and after due forging and heat treatment, were gone through different testing and the obtained results were compared with the selected grade and then were compared with Alloy-1 themselves to determine the suitable one to propose.

B. Melts Preparation with Different Compositions

One of Ni-Cr-Mo-V low alloy steel melts of different chemical compositions as Alloy—1 is prepared as *15MT CAP. Electric Closed Arc Furnace ⇨ 20MT CAP. Laddle Furnace-*

Vacuum Degassing ⇨ 10MT CAP. Electro Slag Refining ⇨ 2650 MT Capacity Hot Forging Press ⇨ Annealing Cum Anti Flaking Cycle for H_2 Removal ⇨ Machining of Forgings ⇨ Heat Treatment in PIT Type Furnaces and their corresponding analysis of sample.

Preparation of Melt was done through the following path:

C. Steel Melting through 15T EAF-LF-VD

Furnace Repair→Addition of Lime & Coke/Carbon→First charge→Power on→1st charge melt- down→Lime→2nd charges→Lime at melt down→Oxygen lance or ore (Oxidation)→Spar, Fe-Mn, lime →Single/double slag off→ Lime, Spar, Coke, Fe-Si, Fe-Alloy (De-Oxidation)→Tapping at 1650℃ to lf→Temperature rise (1680℃) and composition adjustment→VD operation for 15 minutes→Addition of alloying elements and CaSi wire as per requirement→ Temperature measurement→Teeming of liquid steel in C.I. Moulds→ Stripping of ingots after solidification→Dispatch to ESR Section (10T ESR)

1. Forging Process

Pre heating of slug up to 1200°C in step wise → forging in steps and ratio as required→ transfer to Heat Treatment section

2. Heat Treatment

Heat treatment to be applied as per schedule required→ parting of Test Pieces→ transfer for Test Piece preparation

3. Material Testing

Test Piece preparation→ testing → Result & Analysis

The parameters and results obtained at each and every stage of manufacturing are noted down for analysis.

D. Preparation of 1ST Melt as "ALLOY- 1":

The Alloy-1 was wisely selected by intricate analysis of chemical composition and required mechanical properties ranges of selected grade. The grade-3 is found to be of higher strength, although its fracture toughness value is little lower than Gost B which may be neglected as it will be within the safety factor tolerance provided to Gost B, even it can be obtained by composition variation. All other grades are coming under this Metal 1. Hence composition of Alloy-1 is mainly concentrated within the composition range of Metal 1. The grades of lower mechanical properties requirements will have wide scope of increase in safety factors, thus increases in life cycle and can be operated with higher explosive power of ammunitions. There will also have a wide scope of wall thickness reduction and consequently reduction in cost which are to be analyzed quantitatively, such as:

- **C% -** 0.30-0.4 (higher value is more than some of the pre-existing grades by 0.05% and by 0.03% though tried to keep at higher side to reduce deviation)
- **Ni -** 3.0-3.30 (its lower value is coming within all other ranges except a few which is 0.7% more, even it is 0.4% more than higher value of Alloy-1, which can be adjusted by vanadium in alloy-1 Higher value of Gost B is less than of Alloy-1 by 0.20%. Hence it is tried Ni to be at lower side of the range for little deviation)
- **Cr -** 0.85-1.00 (it is tried Cr to be at higher side to balance the effect on incubation time due to less Mn % in some grades, which will be adjusted by Vanadium in Alloy-1)
- **Mo -** 0.50-0.60 (its lower value is 0.20% more than grades, which means increase in strength is an advantage and simultaneously reduction in ductility which can be adjusted by Mn. Hence it is tried Mo to be at lower side of the range for little deviation)
- **V -** 0.10-0.18 (with addition of little amount of vanadium, forms strong carbide and also acts as a grain refiner)
- **Mn** - 0.30-0.50 (it is tried Mn to be at higher side to increase ductility and increase incubation time, as in Alloy-1 ductility is an issue)
- **S** - 0.012 max (less S higher strength and clean steel)
- **P** - 0.012 max (less P is recommended always)
- **Si** - 0.25-0.45 (within the ranges of all grades)
- **Cu** - nil (but optional if required little may be added for enhancing corrosion resistance and ductility)
- **Trace elements -** to be within limit to protect from temper embrittlement effect of steel)

The Alloy-1 is prepared through same EAF-LFVD-ESR route has been mentioned earlier.

E. Process Parameters Followed for Alloy-1

1. Melting Parameters:

Parameters for Melting are shown in Table I.

TABLE I
MELTING PARAMETERS FOR ALLOY-1

Tapping temp. (1630^0 – 1680 ^{0}C): 1654 ^{0}C
Mould Heating (80^0 – 100 ^{0}C): Hot
Teeming temp. (1540^0 – 1580 ^{0}C): 1560 ^{0}C
Ca-Si treatment (0.8-1.2Kg/ton): 15 Kg Lump
Teeming rate (0.8-1 MT/min): 9'10"
Al ingot addition (1.5-4 Kg/ton) :20 Kg at F/C & 20 mts at LF

2. Electro Slag Refining Parameters

ESR slag refining parameters are given under Table II.

(a) Melt Rate: 8.33Kg/Min
(b) Hot transfer temp. & duration: 650^{0}C & 85min
(c) Slag Composition (%): It is shown in Table II

TABLE II
ESR SLAG COMPOSITION FOR ALLOY-1

CaF_2 (38-44)	CaO (17–23)	Al_2O_3 (24–32)	MgO (2–6)	SiO_2 (5–9)	FeO (.2-.3)
45.97	18.94	24.87	5.94	6.10	Trace

3. Hot Forging Schedule

Schedule for heating is shown below.

- Forging start temp.: 1090 ^{0}C/1110 ^{0}C/1125 ^{0}C/1130 ^{0}C
- Forging finish temp.: 904 ^{0}C/917 ^{0}C/997 ^{0}C/915 ^{0}C
- Forging ratio applied: 70-75%

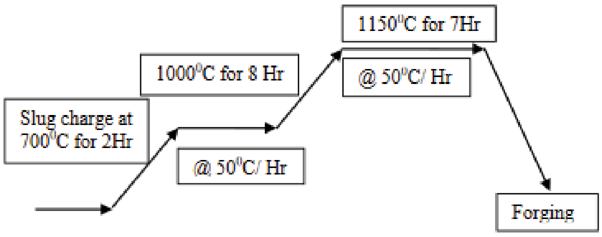

Fig. 7 Heating Schedule of Forging

4. Heat Treatment Schedule

- **Normalizing:** 900 ^{0}C X 5 Hrs followed by Air cooling
- **Hardening:** 860 ^{0}C X 5 Hrs then 870 ^{0}C X 1 Hr followed by Water Quench/Oil Quench
- **Tempering:** T-1(1st Tempering) at 530 ^{0}C X 6 Hrs followed by W/Q then pre-heating at 500 ^{0}C x 6 Hrs for straightening operation. T-2 (2nd Tempering) for 5 Hrs at 550 ^{0}C along with Air Cooling

F. Material Testing

Alloy-1 is tested for chemical analysis, UT, mechanical properties (tensile, impact, fracture toughness), NMIR, macro and microstructure analysis after due parting and preparation of test pieces.

IV. Experimental Results

The test report of test samples of Alloy-1 is appended below:

A. Material Test Reports of Alloy-1

1. Ultrasonic Test Report of Alloy-1

Result is normal and there is no sign of internal flaw.

2. Macro Examination Report of Alloy-1:

Specified range: The range taken for Plate-1 is *C2 R1 S1* accordance with *ASTM: E-381*.

TP Size: Here 20 mm thickness disk is considered which possesses Grind finish along with face polished for both of BE & ME Plates.

Result: It is shown in Table III.

TABLE III
Macro Result for Alloy-1

Conditions	BE	ME
Plate-I		
Central Segregation	*C1*	*C1*
Random Condition	*R1*	*R1*
Sub Surface Condition	*S1*	*S1*
Plate-II		
Flute Crack	*Absent*	*Absent*
Sponginess	*Absent*	*Absent*
Flakes	*Absent*	*Absent*
Any Other Defects	*Absent*	*Absent*

B. Non-Metallic Inclusion Rating Examination Report of Alloy-1

Specified Range: The sample taken of dimension 1.5 for thin series and 0.5 for thick series accordance to IS: 4163.

TP Size- Here sample of 20X10X10 mm^3 Grind finish and 20x10 mm² cross-sectional areas is taken with polished surface.

Result: It is shown in Table IV.

TABLE IV
NMIR Result for Alloy-1

Sulphide (A)		Alumina (B)		Silicate (C)		Oxide (D)	
Thick	Thin	Thick	Thin	Thick	Thin	Thick	Thin
Nil	*0.5*	*Nil*	*Nil*	*Nil*	*Nil*	*0.5*	*1.0*

C. Microstructure Analysis Report of Alloy-1

When the microstructure for both of the BE and ME are to be analyzed, it must be of 10X10X10 mm^3 dimension of Grind finish and 10x10 mm² cross-sectional area is taken with polished surface.

Result: Under optical microscope, microstructure of Tempered Martensite is shown below.

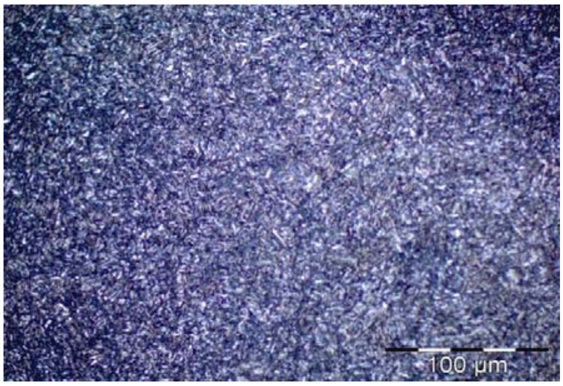

Fig. 8 Micro Structure of Alloy-1

D. Quantitative Analysis by Comparison of Results

The test results of physical and chemical properties and corresponding melting costs of Alloy-1 as obtained and tabulated has been compared with one of the selected range of selected grades as stated below in the tables of compared details of Gost: B and Alloy-1. It been used to analyze for two possible directions such as:

- Replacement with barrel wall thickness reduction by Alloy-1 in succession with cost reduction due to weight reduction by wall thickness reduction is also examined for both of the case.
- Replacement without reduction of barrel wall thickness by Alloy-1 in succession with increase in mechanical properties, increase in life cycle, and increase in capacity to be operated with higher explosive power of ammunitions, thus value addition to the material are examined for both the cases.

All the observational details obtained by the various physical mechanical and chemical experiments over the requisite element Gost: B and experimental sample Alloy-1 along with the comparison of the data obtained from the element Gost: B and the traditional Alloy-1, obtained as the quantitative analysis have been tabulated Tables V-VII.

E. Comparison of Physical and Chemical Properties (Gost: B vs Alloy-1)

Table V shows the comparison of the mechanical properties of the traditional Gost: B along with produced Alloy-1. Similarly, Table VI shows the comparison of the chemical properties of the conventional Gost: B element with Alloy 1 produced.

Through the mechanical comparison as stated in Table 5, it can be stated that Alloy-1 has the capacity to include all ranges of mechanical properties of all selected grades except its LOP is slightly less than of Gost:B although it is covering more than 80%.

More importantly, it is also noticed that the mechanical properties of Alloy-1 is much better than Gost: B, covering more than 80%, which means it will add value to the by increasing duration of their life cycles and safety of factors which are analyzed in the later part of discussions. There is also chance to reduce the thickness and weight along with lowering in cost of material and transport.

F. Comparison of Melting Cost (Gost: B vs Alloy-1)

Table VI makes the vivid comparison of the relative melting cost of the conventional Gost: B with Alloy-1 produced. From Table VII, it is observed that Alloy-1 has almost similar nature to that of selected low alloy steel. This produced Alloy-1 is found to be advantageous in terms of physical properties, increases production rate with reduction in time delay between demand and supply along with the effectiveness in management. Although there are certain grades which possesses relatively less melting and heat treatment cost than Alloy-1, but it will be overcome by other advantages such as increase in production rate over time loss, decreasing thickness and weight reduction ratio, optimization in the cost of balanced transportation etc.

The discussions in the change of the chemical properties along with cost affectivity for conventional Gost: B element with produced Alloy 1 has been considered as in Tables VI and VII.

TABLE V
PHYSICAL (MECHANICAL) PROPERTIES COMPARISON OF SELECTED GRADE OF GUN BARREL STEELS

Element	UTS in MPa	0.2%PS in MPa	LoP in MPa	% El (min)	%RoA (min)	Impact at +20 ^{0}C in J	Impact at T sub –zero(J)	FTT 20 ^{0}C (KIC min / MPa√m)
Gost:B 5192 -78,			*1176*		*20*	*34.3*	*29.4 at –50°C*	*120*
Gost:B after H.T.			*1201*		*51*	*45*	*46 at –50°C*	*128*
Alloy	*1464*	*1273*	*1247*	*14*	*49.1*	*59*	*49.5 at –50°C*	*125*
BE	*1464*	*1292*	*1260*	*14*	*51.4*	*78.48*	*51.1 at –50°C*	*129*
Alloy	*1400*	*1261*	*1234*	*13*	*43.7*	*57*	*49 at –50°C*	*123*
ME	*1400*	*1265*	*1234*	*13*	*41.9*	*74.56*	*58.8 at –50°C*	*131*

- *H.T.: Heat Treatment*

TABLE VI
CHEMICAL COMPOSITION COMPARISON OF SELECTED GRADE OF GUN BARREL STEELS

Grades	Chemical Composition range (wt. %)									
	C	Ni	Cr	Mo	V	Mn	Si	S	P	Al
Gost: B 5192-78, Grade-*OXH3MQA* (0-90) Modified	*0.33 to 0.40*	*3.00 to 3.50*	*0.85 to 1.20*	*0.50 to 0.70*	*0.10 to 0.18*	*0.25 to 0.50*	*0.17 to 0.37*	*0.012 max*	*0.012 max*	-
Metal: 1 after H.T.	*0.35*	*3.1*	*0.99*	*0.62*	*0.14*	*0.42*	*0.19*	*0.006*	*0.008*	-
Alloy 1	*0.38*	*3.15*	*0.99*	*0.57*	*0.14*	*0.34*	*0.27*	*0.001*	*0.008*	-

TABLE VII
MELTING COST COMPARISON OF SELECTED GRADE OF GUN BARREL STEEL

Grade	Direct Material Cost/ Heat	Labour Cost/ Heat	Variable Overhead Cost/ Heat	Fixed Overhead Cost/Heat	Total Cost/ Heat
Gost: B	*11,12,865*	*99,077.22*	*3,13,632*	*2,22,882*	*17,48,456 .22*
Alloy-1	**11,02,840.82**	**99,077.22**	**3,13,632**	**2,22,882**	**17,38,432.04**

V. DISCUSSIONS

Qualitative Advantages Due to the Replacement program

Besides above quantitatively analyzed advantages, following qualitative advantages of this replacement program should also be taken into consideration.

1st. Reducing Production Change over Time

With present production of gun barrel steels, there is a huge production changeover time during change. Proposing replacement by Alloy-1, the changes over time will be minimized to a great extent saves hour. For certain time, heat can be increased; resulting to reduction of total manufacturing cost, as well as good will of manufacturer will be protected by increasing confidence of customers.

2nd. Reducing Inventory Cost & Promoting Lean Manufacturing Concept

In industries, about 60% capital catches inventory cost. In case of present state of manufacturing, there is always a chance of high inventory cost locked up by production of excess quantity of certain graded steel in anticipation of target for a certain kind of barrel, by holding a large stock of raw materials of different kinds in anticipation of target for different barrels.

It is observed one heat capacity of the furnace is 15 T. Barrel needs 4.5 T for its complete manufacture; hence 1.5 T becomes unutilized for the time being until another more two heats are produced. Thus in different way inventory cost goes up which is highly undesirable. Thus lean manufacturing is applied and this is a step towards the supply chain management.

3rd. Standardization

As this is a process of variety reduction or simplification of products, leads to standardization which renders different advantages in manifolds, such as: avoid mix up of raw materials, easy identification, reducing dependency on human skill, easy product management, easy material handlings, reduces space holding by undesirable items, easy dispatch of materials etc.

4th. Effective Supply & Demand Management

It has been seen from experience that many times army floats demand for certain kind of gun barrels with short quantity in intermediate period of the year. By production, it is a constraint to break the normal production planning based on earlier demands already placed, demanding fulfillment in time as matter is concerned with national security. Hence the proposed replacement by a single grade steel is a significant solution to cope up with supply & demand at any time leaving time delay.

5th. Improving of Quality Control

As it is a step towards standardization, quality of product can be controlled at any stage with effectively and at lower quality cost. Extra material testing for various grades of steels can be reduced and thus testing time & cost will be definitely reduced. If any product is being rejected for surface cracks, it's converted to lower dimension product reducing rejection.

6th. Product Safety and Improvement in Properties

By going for replacement without wall thickness reduction, safety factor of barrels will be increased to their maximum extent as quantitatively discussed here. In terms of the Mechanical properties, they must be improved especially in condition of replacement without wall thickness reduction. It is also found in case of replacement with wall thickness reduction, toughness can be improved. Even in this case their tensile property can be developed by autofrettage operation.

7th. Improvement on Mobility

In defense it is observed that there is a frequent troop's deployment with time. So transportation or mobility of large numbers of bulky gun systems is a tedious job and involves huge cost. Hence army always needs higher mobility of their equipments to be deployed with troops. Replacing by a single grade with suitable thickness cum weight reduction can be adapted to gun tubes; it will definitely enhance their mobility as well as reduce transportation cost and so customer delighters.

8th. Costs as Consequence of Replacement by Single Grade

Cost due to replacement by the proposed single grade can be explored in different directions such as:

- It reduces material cost along with reduction of thickness and metal weight.
- It will reduce transportation costs, tubes being lighter by reduction of wall thickness with metal weight.
- Manufacturing cost will be reduced by reducing change over time with less man hour.
- Quality cost will be reduced by promoting less numbers testing and less rejection.
- It will increase goodwill of manufacturer by timely supply of product of higher quality, bearing high value in market which can be quantified later.
- Total cost being estimated for mass production over a long production period, cost reduction will be significant and attractive from commercial point of view.

However, from Table VII, it is found that few of selected grades are costing little less than Alloy-1 respectively, where single grade will minimize the excess melting cost.

VI. Recommendation

From the above stated analysis and calculations, Alloy-1 with certain chemical composition range can replace the existing grade over various advantages. Proposal for the chemical composition range of Alloy-1 is given below:

TABLE VIII
Proposed Chemical Composition of Alloy-1

%C	%Mn	%Si	%Cr	%Ni	%Mo	%V	%S	%P
0.30-0.40	0.30-0.50	0.25-0.45	0.85-1.00	3.00-3.30	0.50-0.60	0.10-0.18	0.012 max	0.012 max

VII. Conclusion

From the optimization numerical and experimental results, the following conclusions can be derived:

(1) From comparison Tables V-VII, it is clear that Alloy-1 can replace Gost: B, with wide advantages of cost reduction and performance improvement.
(2) The values as mentioned in Tables V and VI are proved useful as comparing the experimental data with the numerical results.
(3) The cost shown here are in approximate values which may bear less error. That will be surpassed within the cost reduction.
(4) The theory of autofrettage operation and coating application are not fully exploited here, improving strength of tubes with reduction their weight as well as cost.

VIII. Suggestions for Further Studies

(1) Effect of autofrettage operation for Alloy-1 may be studied and quantitatively analyzed for further improvement in mechanical properties and scope of wall thickness reduction and cost reduction.
(2) Effect of applied coat in Alloy-1 may be studied and quantitatively analyzed for further improvement in mechanical properties.
(3) Application of any suitable composite material which can replace all selected grade with more cost effective and

higher mechanical properties than by Alloy-1 may be studied and quantitatively analyzed.

(4) All expected advantages due to replacement by Alloy-1 need quantification determining the exact cost effectiveness of the proposed replacement program.

(5) Cost reduction by replacement program may be studied for mass production for a whole production year to have net savings in cost.

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Arnab Majumdar, student of National Institute of Technology, Durgapur, pursuing B.Tech course in Metallurgical and Materials Engineering for the session of 2014-2018. He has his schooling from Narendrapur Ramakrishna Mission Vidyalaya with a state rank of 20 in +2 level (WBCHSE). He also has three published paper publications in IEEE on Secured Routing Protocols in October, 2015. He is guided by Prof. Sanjoy Sadhukhan, Associate professor of Indian Institute of Engineering Science and Technology, Shibpur, guided him in this project and provided various details to complete the paper.