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Concurrent Development and Certification of SOFTCOMAG 49AA Alloy for Aeronautical Applications

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ABSTRACT

Softcomag 49AA alloy consisting of 49 wt per cent *Fe*, 49 wt. per cent *Co* and 2 wt per cent *V* is a soft magnetic alloy with a combination of very high saturation magnetisation and high magnetostriction and used for several aeronautical applications such as generators (stators and rotors), fixed iron moving armature units etc. Though this alloy is brittle in nature, it can be formed into hot rolled bars and cold rolled sheets by adopting suitable thermo mechanical treatments. In order to indigenise and subsequent type certification for aeronautical applications, the alloy was produced using 100 per cent virgin raw materials in a vacuum induction melting (VIM) furnace which not only ensures substantial reduction of inclusions, but also the production of homogeneous alloy as a result of induction stirring. The chemical composition was examined and hot working parameters of the alloy were so optimised that they would result in the best combination of magnetic, physical and mechanical properties for the end use, which forms the central theme behind the developmental activity that was simultaneously covered by a comprehensive certification process. The material thus produced is subjected to stringent quality control checks in accordance with stipulated airworthiness norms. The paper discusses in detail the indigenisation efforts and airworthiness certification of the alloy Softcomag 49AA and its comparison with equivalent grades, namely PERMENDUR 49 and VACOFLUX 50.

Keywords: Softcomag 49AA alloy, melting, processing, characterisation, testing, type certification

1. INTRODUCTION

Softcomag magnetic alloy 49AA, designated here as SOFTCOMAG 49AA, having 49 wt per cent *Co*, 49 wt per cent *Fe* and 2 wt per cent *V*, is an aeronautical grade alloy having high saturation flux density of 2.35 Tesla, high Curie point (950 ^{0}C) and high magnetostriction (+70 x 10^{-6}) and has been chosen for use in fighter aircraft[1-5]. A systems engineering design approach is utilised to translate the requirements of the user/customer. This calls for production technology to be fully evolved and standardised, i.e., the materials must be produced according to a fixed process specification and have been registered in accordance with an aerospace material specification. These standards contain material and process specification requirements consistent with conditions representative of the processing and manufacturing environment.

Many a commercial equivalents of Softcomag 49AA have been developed and produced. Notable among them include PERMANDUR 49[2,4], VACOFLUX 50[3] and CARPENTER[5]. The major constituents of most soft magnetic alloys are one or more of the common ferromagnetic element, namely *Fe, Ni* and *Co*. Most useful combination of these elements employ typically the substitutional solid solutioners. They contribute in terms of controlling the lattice crystalline structure to promote high permeability, low coercive force and low hysteresis loss.

The contents of a typical type certification standard for the production of Softcomag 49AA, that include the scope of the standards, reference to applicable documents, technical requirements, provisions for quality assured production and delivery. To ensure consistency in product quality, the test population must include ten batches of material from at least 3 to 5 production heats, casts, or melts for each product form. Since the production of aero grade Softcomag 49AA needs the fulfillment of certain physical, mechanical, magnetic and chemical property requirements of the alloy, the operational environment of the candidate alloy must be considered. Typically, these material property data exceed the scope of military specifications. Therefore, test data sufficient to statistically substantiate the alloy's behaviour in its operational environment must be developed. Material factors to consider are static-strength requirements, corrosion and embrittlement, environmental stability, magnetic properties, besides producibility, availability, costs, fabrication characteristics, inspectability, compatibility with other materials, thermal, and electrical characteristics. Furthermore, NDE techniques must be shown to be capable of detecting representative defects and the effect of defects on materials properties must be understood and characterised. Also the limitations of the NDE techniques being applied must be understood, along with the probability

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of detecting processing and manufacturing defects.

The present paper describes the above technological development effort for the production of aero grade Softcomag 49AA alloy with airworthiness certification, which is mandatory for the production of components for fighter aircraft.

2. PRODUCTION TECHNOLOGY

Due to high criticality of application, integrity verification in each melt and consistent verification of 3 to 5 melts has been adopted for the certified production of Softcomag 49AA. A systematic process flow chart employed for the production of Softcomag 49AA is shown in Fig 1. In order to maintain the desired quality, rigorous quality assurance steps were adopted from raw material stage to finished product, at each successive stage of production as given at Table 1.

Extensive property evaluation has been conducted on these melts to adjudge the material capability. Optimisation of chemical composition, forging, rolling and heat treatment parameters has been done to obtain the best combination of properties for end use[6]. These are briefly described in the following sections.

2.1 Melting

Vacuum induction melting (VIM) using a 2.2 ton capacity furnace, was used for primary melting and 100 per cent virgin raw materials were used from approved aeronautical sources. The vacuum induction melting thus used was found to result in a Softcomag 49AA alloy that has low inclusion content and a homogeneous chemistry, principally due to induction stirring. It also reduced porosity levels and has resulted in uniform distribution of unavoidable impurities, enabling the production of ingots which are grossly improved in quality with considerable ease during forging.

2.2 Forging and Rolling

The ingots cast were forged using a reduction rate of 5-10 mm/min (which corresponds to a nominal strain rate of $1.6\text{-}3.2 \times 10^{-4}$ s^{1}), employing a start at 1100 ºC and the forging operation was continued till the forge stock has reached at 850 ^{0}C. Bogie hearth furnace was used for soaking and a 1500 ton press was used for forging. Ingots were thus reduced to various mill sizes by forging and they were further rolled by giving 10-12 per cent reduction to final section sizes that were specified by the user. To ensure a defect free structure and to avoid rejection at subsequent stages, ultrasonic testing was

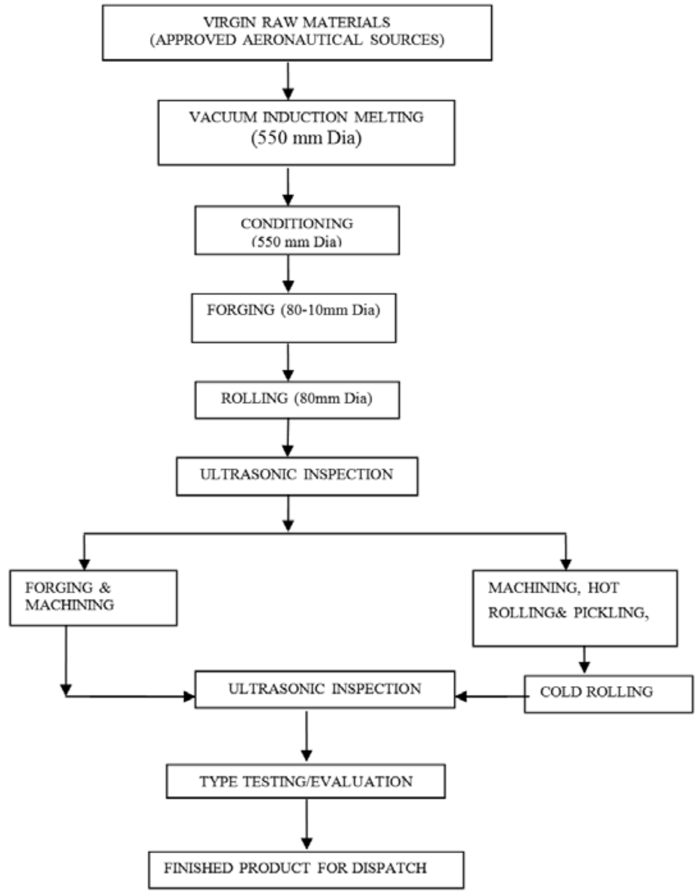


Figure 1. Process flow chart for manufacture of Softcomag 49AA.

Table 1. Process steps for the quality assured production of Softcomag 49AA

Process Steps	Quality Assurance
1. Raw material and material control	• Approval of sources • Comparison with aeronautical specifications • Raw materials inspection certificate • Test certificate by suppliers
2. Process control	
(a) Primary melting (Vacuum induction melting)	Crucible condition, ultimate vacuum level, leak rate, melt chemistry, ingot surface, and soundness, etc.
(b) Forging	Furnace atmosphere, heating cycle, calibration of furnaces, finish temperature, dimensional check, ultrasonic testing, macro examination, surface quality check, etc.
(c) Rolling	Temperature control, visual inspection and removal of defects
(d) Heat treatment	Furnace atmosphere, heating cycle, calibration of thermocouples, and furnaces, etc.
3. Testing and evaluation	Dimensional check of test specimens, calibration of all equipment, and heat treatment furnaces. • Load cell calibration. • Metallurgical, physical, chemical, and magnetic property evaluation. • Verification of test results, and consistency in melt etc.

carried out at different stages of forging and rolling processes.

2.3 Heat Treatment

Suitable heat treating temperature for production of Softcomag 49AA alloy with specific properties is chosen so that best soft magnetic characteristics with optimised mechanical properties are obtained[7-9]. For this, a highest possible temperature, which results in highest soft magnetic properties, is selected and employed. The wrought products of the alloy produced by forging and rolling were then heat treated under the optimised conditions of 850 ^{0}C ± 10 ^{0}C/3 h in H_2 atmosphere followed by cooling to 300 ^{0}C using a controlled cooling rate of 60-180 ^{0}C/h, and then furnace cooled to room temperature.

3. CHARACTERISATION

Chemical analysis of the elements like *Mn, Si, Cr, Ni, Co, P*, and *V* was carried out using optical emission spectrometer as per ASTM E 354[10]. Carbon and Sulphur were analysed using Leco Carbon and Sulphur analyser as per ASTM standard E-1019[11]. Gases, particularly hydrogen, oxygen and nitrogen, were analysed using Leco Gas Analyser. Macrostructural evaluation was carried out in accordance with ASTM A-604[12]. Microstructural characteristics and grain size were determined in both annealed condition and in the final product forms as per ASTM E-112[13]. Non metallic inclusions were rated in accordance with method D of ASTM standard E-45[14]. Coefficient of thermal expansion was measured in accordance with ASTM standard E-228[15], using a dual push rod dilatometer. Magnetic properties of these materials were evaluated using DC in accordance with ASTM A-596[16] using ring shaped specimens. Mechanical properties, viz., Vicker's Hardness (ASTM E-92[17]), tensile properties at ambient temperature (ASTM E-8[18]) and elevated temperature tensile properties (ASTM E-21[19]) were evaluated and reported. Both ambient and elevated temperature tensile tests were done on specimens with gage length that is 4 times the gage diameter, in accordance with the ASTM E-8 and ASTM E-21. Young's modulus was determined in accordance with ASTM E-111[20]. Finally, the ultrasonic inspection was carried out in accordance with AMS 2630A using 2 mm flat bottom hole (FBH) as reference standard[21]. Sizes and tolerances were checked in accordance with AMS 2241[22].

4. RESULTS

4.1 Chemical Composition

The data in Table 2 provide the specified and average chemical composition obtained over five melts of the Softcomag 49AA alloy, evaluated in the fully annealed condition of the forged and rolled product of 80 mm diameter bars. These results show that the alloy's chemical composition is well within the permissible limits, specified by the AMS 2248[23]. The hydrogen, nitrogen and oxygen gases were also analysed and their levels were found to be 0.5, 10 and 53 ppm, respectively. Alloy produced by international manufacturers (Telcon, Permendur, and Vacuumschmelze) used for comparison with indigenised Softcomag 49AA alloy are having similar chemical composition.

Table 2. Chemical composition of SOFTCOMAG 49AA forged and rolled bars of 80 mm diameter in the annealed condition

Element (weight per cent)	Specified value	Obtained value
C	0.025 max	0.0086
Mn	0.15 max	0.04
Si	0.15 max	0.02
P	0.015 max	<0.005
S	0.010 max	<0.005
Cr	0.15 max	0.10
Ni	0.25 max	0.05
Co	47.50-49.50	49.5
V	1.75-2.10	2.10
Fe	balance	balance

4.2 Microstructure

Macrostructural evaluation was conducted on specimens, obtained from top, middle, and bottom of the ingots. Such an examination has revealed that the ingot was free from shrinkage, cracks, pipe, porosity, blow holes, etc. The optical micrograph, shown in Fig. 2, clearly indicates ferrite morphology with grain size of ASTM number 4 to 6. This is slightly higher than the size of the grains of the imported Softcomag 49AA alloy, obtained and evaluated for comparison purpose. The imported alloy showed a grain size that in the range of ASTM number 5 to 6. The imported and indigenously produced alloys have marginal difference in their grain size. This has resulted in similar properties in the two alloys. The non metallic inclusions in both imported and indigenously developed products were found to be within the specified limits.

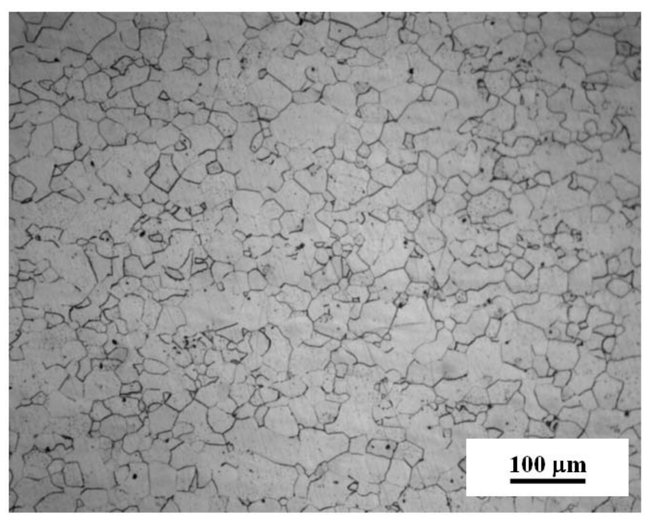


Figure 2. Microstructure showing ferrite morphology in annealed condition.

4.3 Physical Properties

Density of the Softcomag 49AA alloy produced in the present development was found to be in the narrow range of 8.11 - 8.12 g/cc, which is slightly lower than the typical value of 8.15 g/cc. Coefficient of thermal expansion (α) was measured in the temperature range RT-500 °C using a dual pushrod dilatometer. The α values thus determined are given in Table 3. Specific heat too was measured and it ranged from 0.401 kcal/kg °C to 0.434 kcal/kg °C against the typical value of 0.1 kcal/kg °C specified. Thermal conductivity values obtained were in the range 40 to 50 W/m-k, against the typical value of 30 W/m-k.

Table 3. Coefficient of thermal expansion (α) of the SOFTCOMAG 49AA alloy

Temperature range	Co-efficient thermal expansion (α), $10^{-6}/^0C$	
	Obtained	Typical
20-100	8.57	9.2
20-200	9.52	9.5
20-300	9.9	9.8
20-400	10.36	10.1
20-500	10.58	10.4

4.4 Magnetic Properties

Magnetic properties of the product have been evaluated and obtained properties (average of material from 5 different heats) are compared with specified properties (Table 4). The variation of flux density (B) and permeability (μ) with magnetic field strength (H) in the present Softcomag 49AA alloy is shown in Fig 3. The guaranteed flux density of 20000 Gauss was achieved below the specified 10 Oe Max. The remanence measured from a flux density of 21400 Gauss was 12600 Gauss.

Table 4. Magnetic properties of Softcomag 49AA alloy in the annealed condition of the forged and rolled bars.

Properties	Obtained value	Specified value
Saturation induction at 12.5 Oe (T)	2.135	>1.95
Residual induction (T)	1.26	1.0 minimum
Coercive filed strength (Oe)	0.46	2.00 maximum
Maximum magnetic permeability (μ)	11400	7000 typical

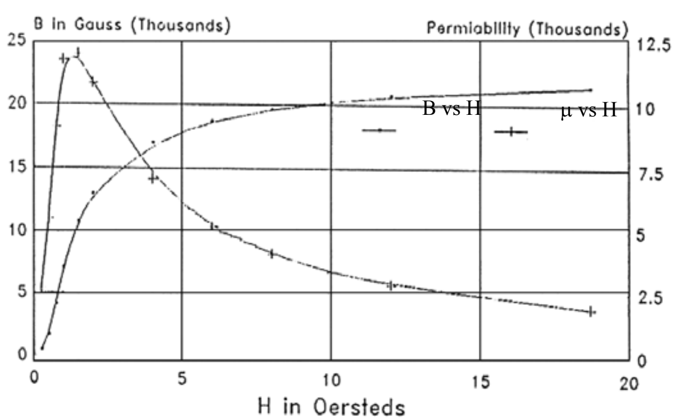


Figure 3. DC magnetisation curve, obtained from Softcomag 49AA alloy.

Magnetic properties of this alloy are found to be comparable as shown in Table 5 with equivalent alloys having the similar chemistry of other reputed international manufacturers. While most of the alloying elements lower the magnetic properties, Cobalt improves magnetic saturation induction[5].

4.5 Mechanical Properties

Hardness: Hardness in annealed condition ranged from 183 to 189 HV against specified 250 HV maximum and the same in as-forged and machined condition is in the range of 253-268 HV against 270 HV maximum specified.

Young's modulus: Young's modulus in annealed condition is between 229 and 248 GPa against 200 GPa minimum specified and the same in as-forged and machined condition is found to be from 188 to 247 GPa against 200 GPa minimum specified.

Tensile properties: Average values from tensile properties obtained from specimens of 5 different heats, tested at room temperature, 200 °C and -70 °C in forged and annealed conditions are given in Fig. 4. The data in Fig. 4 also show the specified values at RT for comparison. The RT tensile test data in Fig. 4 show that the Softcomag 49AA alloy exhibited tensile properties that are far superior to the specified values. The strength values are lower and elongation is higher than the specified value of the annealed alloy. Further, the alloy in the as-forged and machined condition too exhibited higher strength and elongation values as compared to the specified property levels. The strengths in this condition are more than 30 per cent higher and the elongation is more than 150 per cent higher.

The mechanical properties (hardness, modulus and tensile) of the presently developed Softcomag 49AA alloy, are much higher than the specified values. The physical and functional (magnetic properties, in this case) too are comparable or even superior to the specified values or those obtained from the same alloy of reputed international sources.

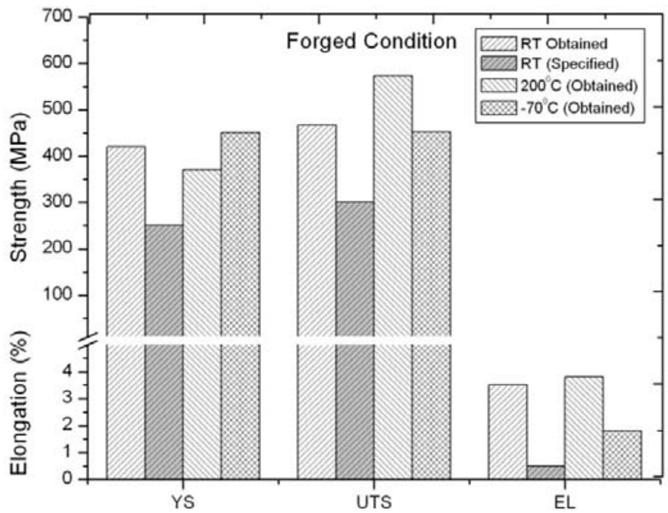
5. DISCUSSION

The Softcomag 49AA alloy is normally an intrinsically brittle material and virtually near impossible to process. Any additives to improve workability of the alloy would affect the magnetic properties. Since, the alloy is required in the form of 30-80 mm diameter bar and 0.2 mm thick strips, working of this alloy is inevitable. This challenge has been overcome by the optimisation of the chemistry and processing parameters briefly described below:

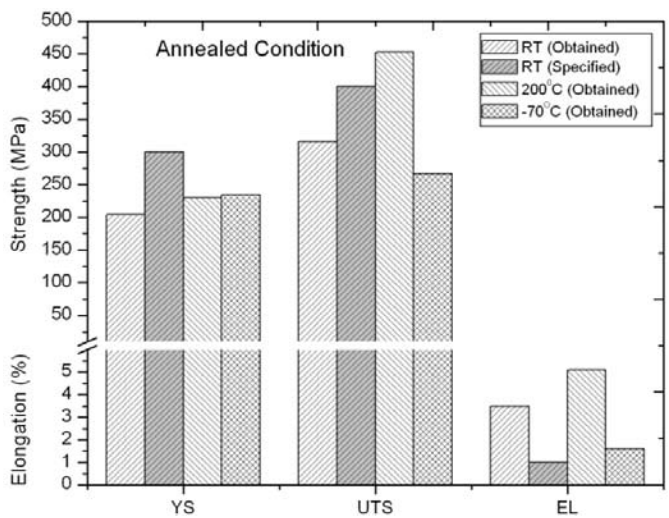
- Primarily, optimisation of alloy chemistry is vital to achieve the required high level of magnetic properties. This has been achieved in the present technological development by balancing the cobalt and iron contents within the specified ranges, by employing the Cobalt levels that are close to the maximum value in the specified range and restricting the iron to the minimum of the specified range.
- Secondarily, workability has been imparted to the alloy by controlled addition of 2 per cent Vanadium and 0.15 per cent rare earth mixture during melting. Vanadium and the rare earth mixture help in retarding long range ordering thus avoiding brittle structure; thus, improving the processing capability[5]. Hence, this is the only modification that can be

Table 5. Comparison of the magnetic properties of the indigenised Softcomag 49AA alloy with similar alloys manufactured by other international agencies

Properties	Specified	Softcomag 49AA alloy	Telcon Permendur 49	Vaccumschmelze Vacoflux 50
Flux density, Tesla at 10 Oe	1.95 min.	2.135	1.96	2.0
Coercive force	2.0 max.	0.46	1.2	1.4
Maximum permeability	7000 min.	11400	7000	8000
Curie temperature	925	940	940	950



(a)



(b)

Figure 4. Tensile properties of Softcomag 49AA alloy as a function of test temperature for (a) forged and (b) annealed conditions.

done to achieve the short range ordering resulting in ductile structure. After suitable thermo mechanical treatments, 90 per cent cold reduction could be given to the alloy in this condition without intermediate annealing. Intermediate annealing is to be avoided since it is found to result in an ordered structure, which will reintroduce the brittleness.

However, neither the cold rolled strip nor the components manufactured from the strip possess the required magnetic properties. To impart the same, suitable heat treatment with a constrained cooling rate has been designed and employed. Low annealing temperatures resulted in a structure which is magnetically not soft enough to give the desired properties. On the other hand, higher temperatures result in lower than desired mechanical properties. Heat treating for the best magnetic properties should ensure that the temperature does not exceed 900 °C. These conflicting requirements were balanced and a suitable heat treatment was arrived at. Such an optimised heat treatment condition is found to be: soaking at 850 °C followed by controlled cooling at a rate of 60-100 °C/h to obtain the desired coarse grain structure. The atmosphere used was non-oxidising and non-carburising, which should be either hydrogen or vacuum. This again was found to result in excellent magnetic properties. Such data comparison reveals that the present alloy development programme is successful and the Softcomag 49AA alloy thus produced can be used in Indian aeronautical and aerospace application with confidence.

6. CONCLUSIONS

The present programme of development with airworthiness qualification of Softcomag 49AA alloy has been satisfactorily completed and material supplied for end use was found to be highly satisfactory during performance.

The alloy has been successfully developed, commercially produced and type certified for Indian strategic satellite, missile and aeronautical applications. The production costs too were found to compare favourably with international prices, being lower by eight to ten per cent.

Indigenisation and supply of this strategic alloy has helped self reliance in several Indian aeronautical and aerospace programmes.

Consistency among melts and integrity within each melt have been the principal achievements of the present technological development and the Softcomag 49AA alloy, thus produced, was found to possess properties that are comparable or even superior to those specified values or those obtained from imported alloy from reputed international agencies.

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