

**IDENTIFICATION OF SIGMA PHASE IN SUPERALLOYS BY CORRELATION
WITH ELECTRONIC AND MAGNETIC PROPERTIES**

by

Uriah David Otting

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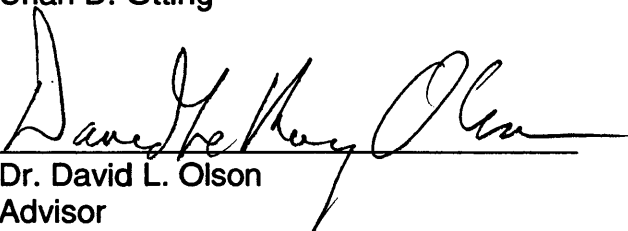
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Golden, Colorado


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ABSTRACT

Identification of Sigma phase in superalloys is only done through visual inspection. While the formation can be predicted using methods like PHACOMP and New PHACOMP, the sample must still be dissected to determine the amount of sigma formed. Since the formation of sigma phase is predicted with models that relate to electron vacancies in the d-band, it should also affect the electronic and magnetic properties of the material. By measuring the conductivity, Hall coefficient, Seebeck coefficient and the magneto-resistance of a specimen, it should be possible to determine the presence and amount of sigma phase in a non-destructive manner. This method could be used to gauge the age and potential lifetime of superalloys in field-testing, saving the cost of dismantling an expensive part.

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1.0 INTRODUCTION

Superalloys are used in applications that require high strength and low ductility at extended exposure to high temperatures. During use at high temperatures, embrittling phases can form. Many methods are used to predict the formation of these compounds. By measuring the electronic and magnetic properties of an alloy, it should be possible to predict the nature of its microstructure and measure the formation of intermetallic phases. This could be accomplished non-destructively to save money and time.

The first chapter of this document will review the concepts behind superalloys and intermetallic phases, especially sigma phase. Methods of predicting sigma phase are recounted and compared to the proposed model. The proposed method of measurement will then be outlined. The following chapter deals with the specifics of the proposed measurements and possible effects that sigma phase will have on them. Finally, the advantages and possible applications of the process will be reviewed as well as the work done so far on the project.

1.1 Superalloys

In the 1930's, it became necessary to find new materials for use in aircraft

engines. Thus began the development of superalloys in the United States [1]. They are used for a variety of purposes, for the most part they are used for applications that require high strength at elevated temperatures for long periods of time. They form components in turbine engines, nuclear reactors, steam power plants, and space vessels [2]. Many of the alloys actually gain strength as they age. Superalloys can be designed for specific applications and applied in different ways. The formulation of these alloys is a subject of much research with both corporations and institutions[3].

Superalloys are designed for different purposes and with different qualities. Some of the desirable qualities are high strength, low thermal expansion coefficient, creep resistance, density, corrosion resistance, oxidation resistance, and phase stability [1]. While in some ways an imprecise science, the design of superalloys is carried out in a methodical way. The effects of elemental additions are studied and evaluated [2,3]. Researchers use methods such as Phase Computation (PHACOMP) or New PHACOMP to determine the phase stability of the compounds. Because of the effect each alloying element has on another, the prediction and measurement of relationships becomes extraordinarily complex. In Figure 1, a portion of a three-phase diagram is presented, notice the large compositional region in which sigma phase is expected to form. There are over twenty different elements in some alloys, thus requiring a twenty dimensional figure to model, too complex for

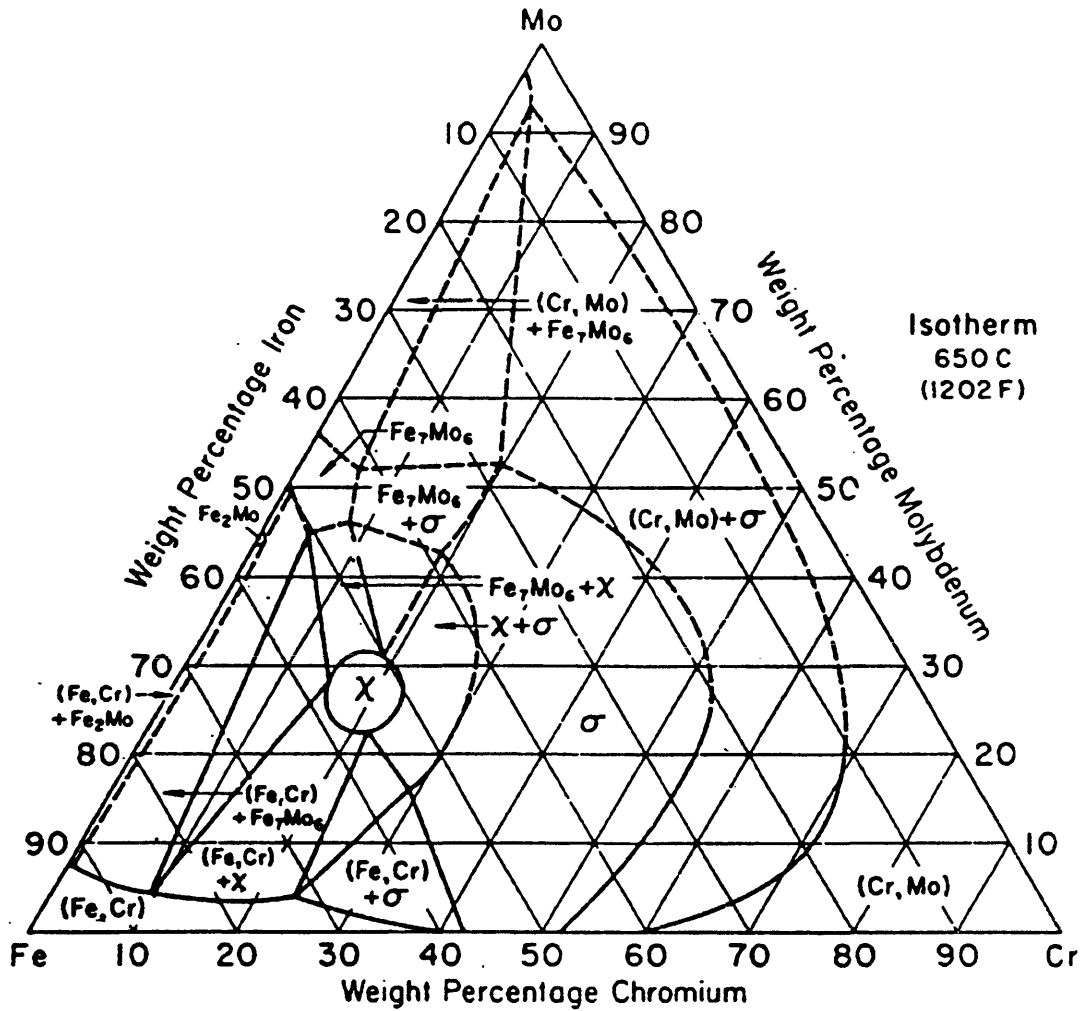


Figure 1. Section of the Iron-Molybdenum-Chromium ternary phase diagram at 923 K showing regions of sigma phase formation. From Metals Handbook [4].

casual reference and understanding. Nevertheless, with all the varying alloying compositional systems, they can be divided into a few main groups: nickel-, iron-, cobalt- and chromium-based alloys [1]. Each has its primary uses and deficiencies. Depending on the application, different elements are used to gain the required properties [1,2].

A sample composition for Haynes Hastealloy X is given in Table 1. The alloy has multiple elements used to push it to the edge of its performing range. Different companies will use different alloys but they all want to push the edges of the range, making the strongest, lightest and resistant alloys on the market.

Table 1. Composition of Haynes Hastealloy X, provided by manufacturer.

Element	Weight Percent
Al	0.15
B	0.002
C	0.07
Co	0.77
Cr	22.05
Fe	18.18
Mn	0.63
Mo	9.10
Ni	47.94
P	0.018
S	0.003
Si	0.42
V	0.05
W	0.43

The gamma phase is usually the region in which superalloys are designed

to function for the most severe time and temperature constraints in an air atmosphere. Some of the materials are designed for use in temperatures up to eighty percent of the melting temperature. They are usually strengthened by precipitating gamma prime phase from the matrix. Originally, this was in the form of small particulates. Eventually the alloys made use of a regular network of the gamma prime phase precipitate for strengthening. Gamma prime has the peculiar property of gaining strength as temperature increases. As gamma prime phase forms in the matrix it forms dislocations. These dislocations combine to strengthen the material [2].

Decker notes that different factors affect the matrix properties. Aluminum, molybdenum, chromium and tungsten are all solid solution hardeners. Cobalt additions ease hot working at high aluminum and titanium concentrations. Lattice mismatch between the solution and precipitate can harden the solution. Boron and zirconium are added to retard diffusion and stabilize grain boundaries. Niobium is used slow gamma prime phase ripening. Carbides nucleated in the alloy can reduce ductility and strength, but the lack of carbon reduces those quantities further. Grain size is inversely proportional to strength. By modifying these parameters, the desired qualities can be formed in the alloy [2].

1.2 Intermetallic Compounds

Because of the many elements in their makeup, it is not easy to determine what chemical changes are actually occurring inside a superalloy. At the same time, certain trends have been noticed. For example, as the alloys age, their mechanical properties change [5,6,7]. The migration of elements within the matrix, while not altering the overall makeup of the alloy, can segregate sections so that the properties change [8]. This behavior can be both beneficial and detrimental to the alloy being studied depending on its use and the change in the alloy.

Many of the changes found in the alloy are caused by the formation of topologically close-packed (TCP) intermetallic phases [1]. These phases precipitate out of the matrix and alter the properties of the material. Intermetallic phases are stable mixtures of elements that form a coherent structure, rather than a mixture of other structures. These phases include sigma, chi, laves, R, mu and other phases [9]. In this work, the effect of sigma phase on the matrix will be the primary focus. The reason for this focus is that the sigma phase is usually one of the first phases to form and it borders the gamma phase [10], which is the usual phase of interest in the design of superalloys.

The formation of TCP phases in the matrix of the alloy is often planned. The literature contains many references to precipitation hardening [2,8,11,12]. These same phases are responsible for the embrittlement of the alloy. Most TCP phases form along grain boundaries and on impurities [13]. The conditions to

which the alloy is subjected are also important. It has been shown that stress can promote or subdue formation of intermetallic phases depending on the alloy used [14,15]. By altering the alloy composition, control over the formation of these phases can be achieved [2,3]. The lattice parameter and structure of the alloy is also a factor since many of the TCP phases require a compatible surface on which to form [6].

1.3 Sigma Phase

Sigma phase was first discovered in 1927 by Bain and Griffiths [16]. Sigma phase is the TCP phase most often associated with increased strength and embrittlement in alloys and consists of a tetragonal cell with a thirty-atom basis [8,17]. It forms lath and plate-like structures in the alloy (Figure 2) and promotes fracture while lowering ductility [18]. It is non-magnetic and has a high electronic resistance with a negative temperature resistivity coefficient [17]. Combining these factors, it is possible to design the component to actually improve over time. However, this result can make monitoring the quality of the part difficult since it may function well right before it fails.

Brewer identified sigma phase as an electronic compound phase. An electronic compound forms when the material has a certain electron concentration. If the properties of the material fall outside that range, the

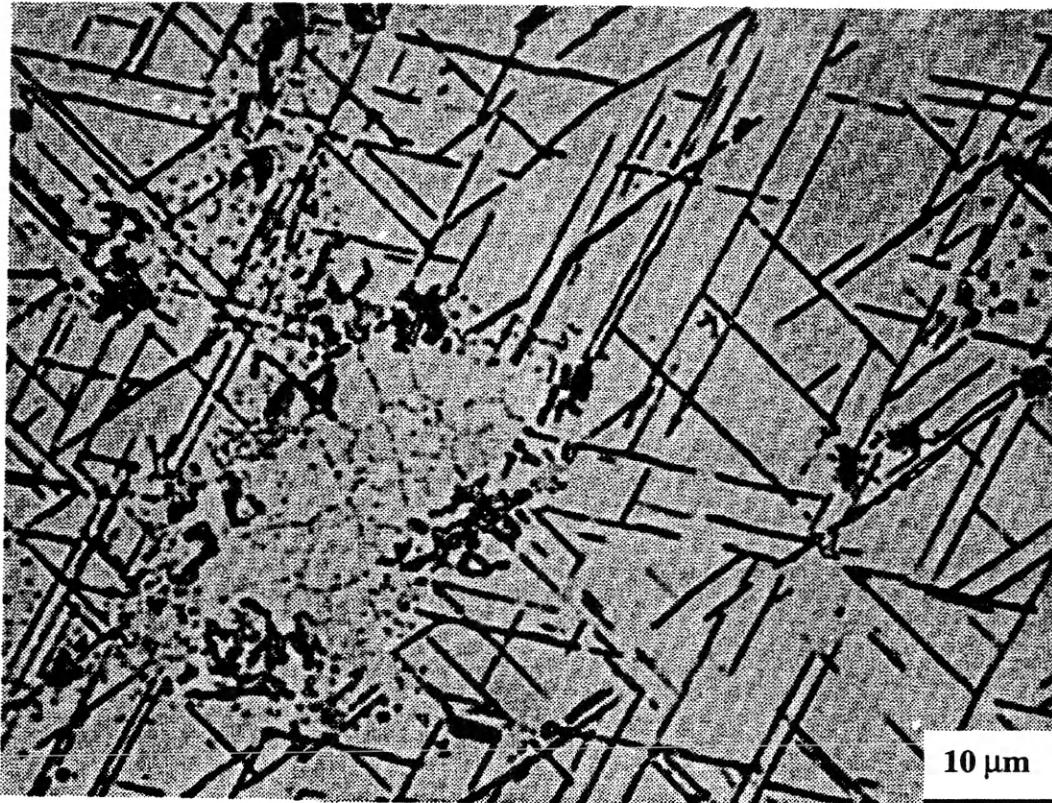


Figure 2. Optical micrograph showing growth of sigma phase in cast IN-100 superalloy after heat-treatment of 2500 hours at 1116 K [14].

compound will not form. The values for sigma phase formation are an electron to atom ratio of 5.6-7.7 with most lying between 6.0-7.1 and a strong peak at 6.6. Brewer determined that the determining factor in sigma formation is the s and p valence electron count which falls in the range of 1.2-1.9 for sigma phase [19,20]. When the levels of electrons in the superalloy reach these values, sigma formation is likely.

Sigma phase must have a suitable surface to nucleate on whether it be a grain boundary or impurity. Barcik found that the presence of $M_{23}C_6$ (M stands for a metal) in a superalloy promoted growth of sigma phase [13]. In ferrous alloys sigma phase grows preferentially in the ferritic regions of an alloy rather than the austenitic regions. The rate of consumption of the ferrite is proportional to the temperature at which the alloy is held. The rate at which sigma phase forms depends on the alloy composition, initial ferrite content (for ferrous alloys), temperature, cold working, annealing, manufacturing method, and recrystallization [7,11]. In many alloys, sigma phase has a specific temperature window in which it will form. In Figure 3, it can be seen that if the temperature rises above a certain level, the formation of sigma phase is reduced [14].

Sigma phase forms in a variety of systems. The most commonly studied form of sigma phase is in the iron-chromium phase diagram (Figure 4), represented by the composition FeCr [21]. Many alloys consist of multiple elements and phase fields for sigma phase can become quite complex (Figure 5).

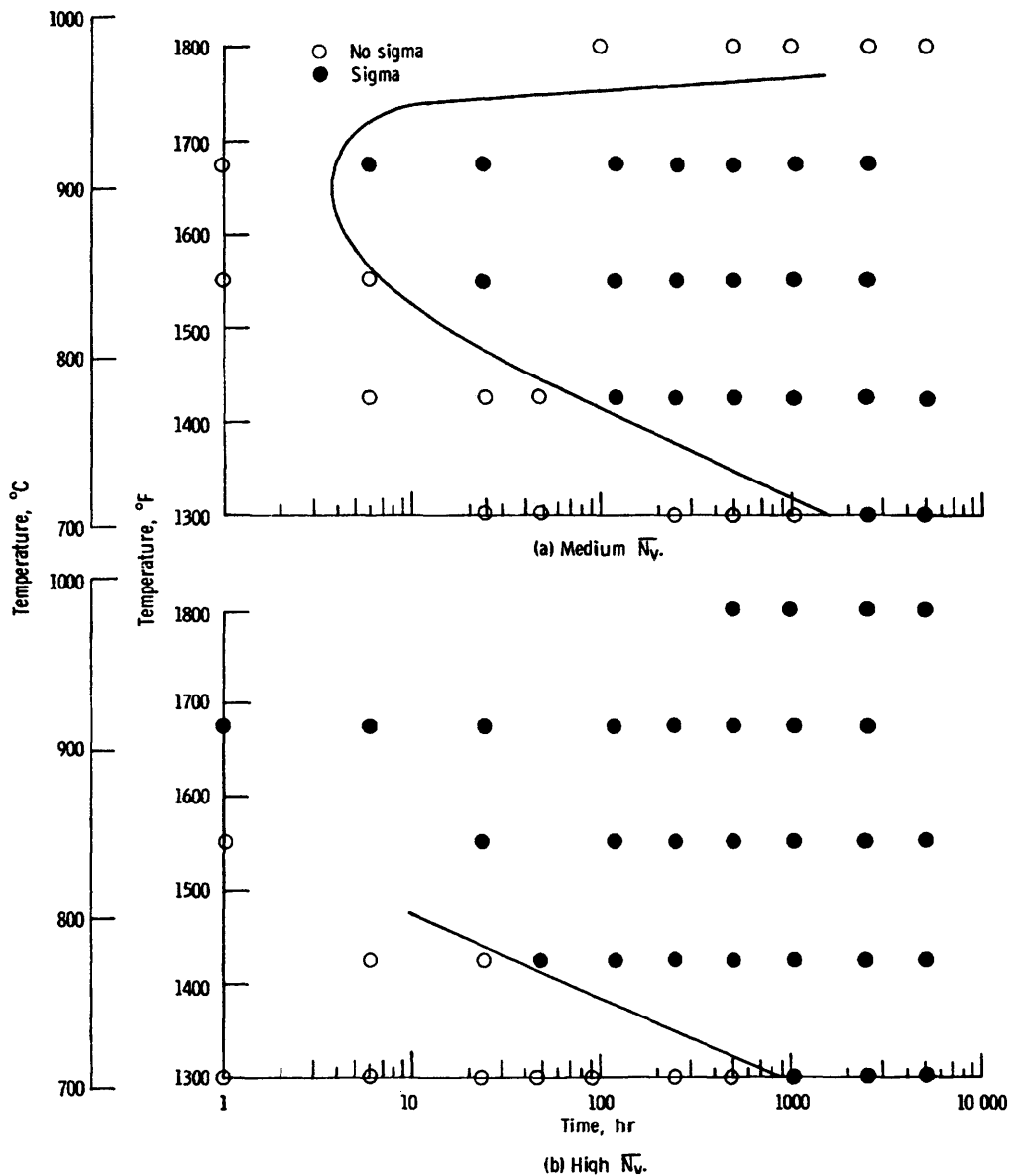


Figure 3. Temperature dependence of sigma phase formation in superalloy IN-100 as a function of temperature for a) partially sigma phase susceptible and b) highly sigma phase susceptible compositions [14].

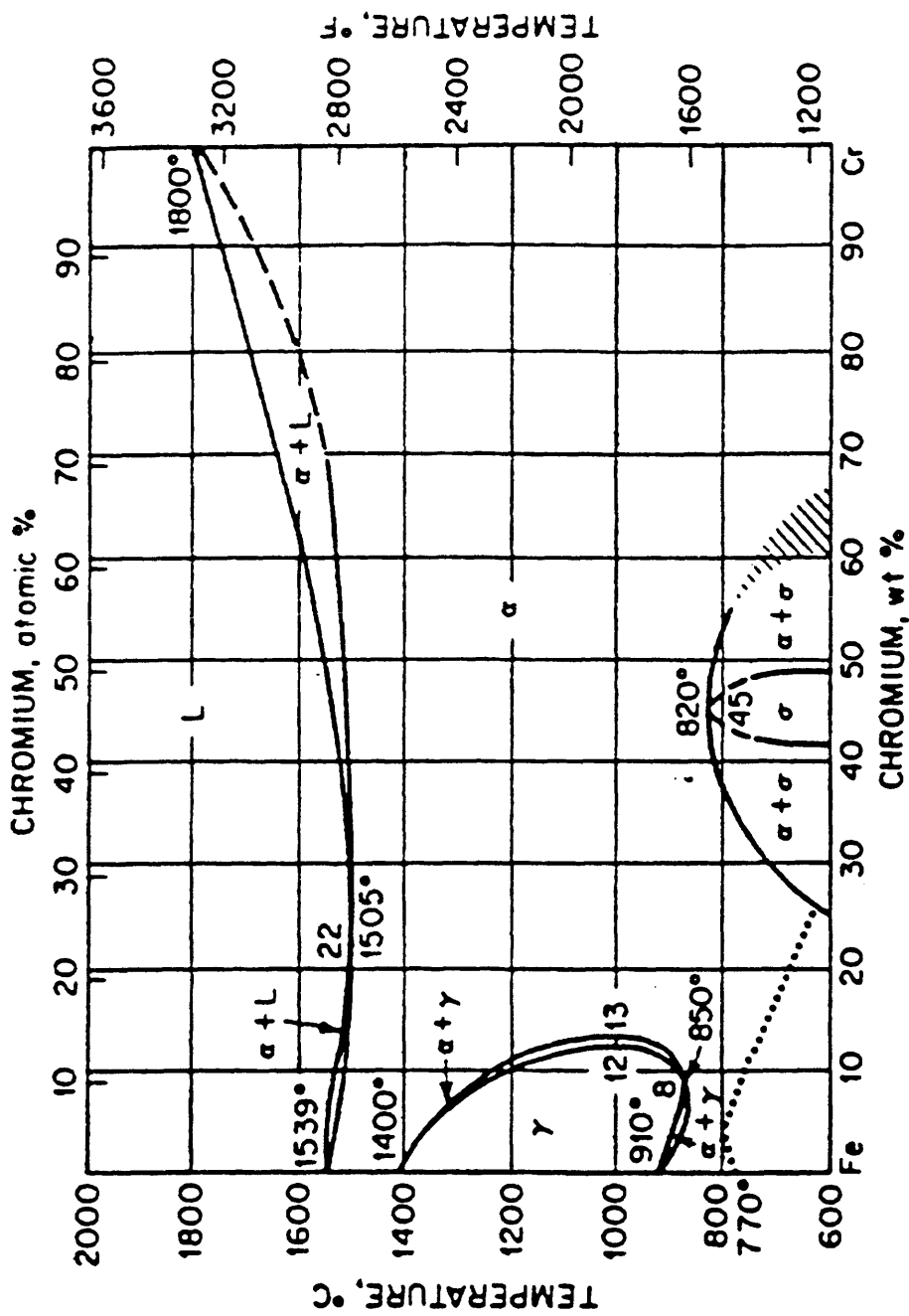


Figure 4. Iron-Chromium phase diagram showing region of sigma phase formation [22].

Depending on the alloy, some elements will promote sigma phase formation and some will hinder it [3]. Sigma phase forms more slowly in coarse-grained materials. The limiting rate in sigma phase formation is usually the diffusion of the atoms through the matrix [13].

Sigma phase has similar effects on most alloys. It decreases rupture life, tensile strength and ductility . In alloy IN-100, the room temperature yield strength could be increased with short heat treatments but longer treatments reduced yield strength to the original or lower values [14,15]. Sigma phase also increases hardness of the alloy (Figure 6) and lowers the coefficient of thermal expansion. One reason for this behavior is the compartmentalization of austenitic regions by sigma phase plates [11].

Stress has been shown in some alloys to reduce sigma phase formation to an extent. A possible explanation for this observation is that it creates a lattice mismatch, reducing suitable formation sites for sigma phase. If this behavior is the case, stress could also promote sigma phase formation in other alloys by changing their lattice parameters [14,15]. When sigma phase does form in the matrix it is often more compact than the lattice, introducing strain and causing micro-cracks to appear [23].

Sigma phase makes alloy behavior difficult to predict. Under conditions known to precipitate sigma phase, models of strength and ductility often fail. One reason for this failure is that due to the complexity of a superalloy, even two

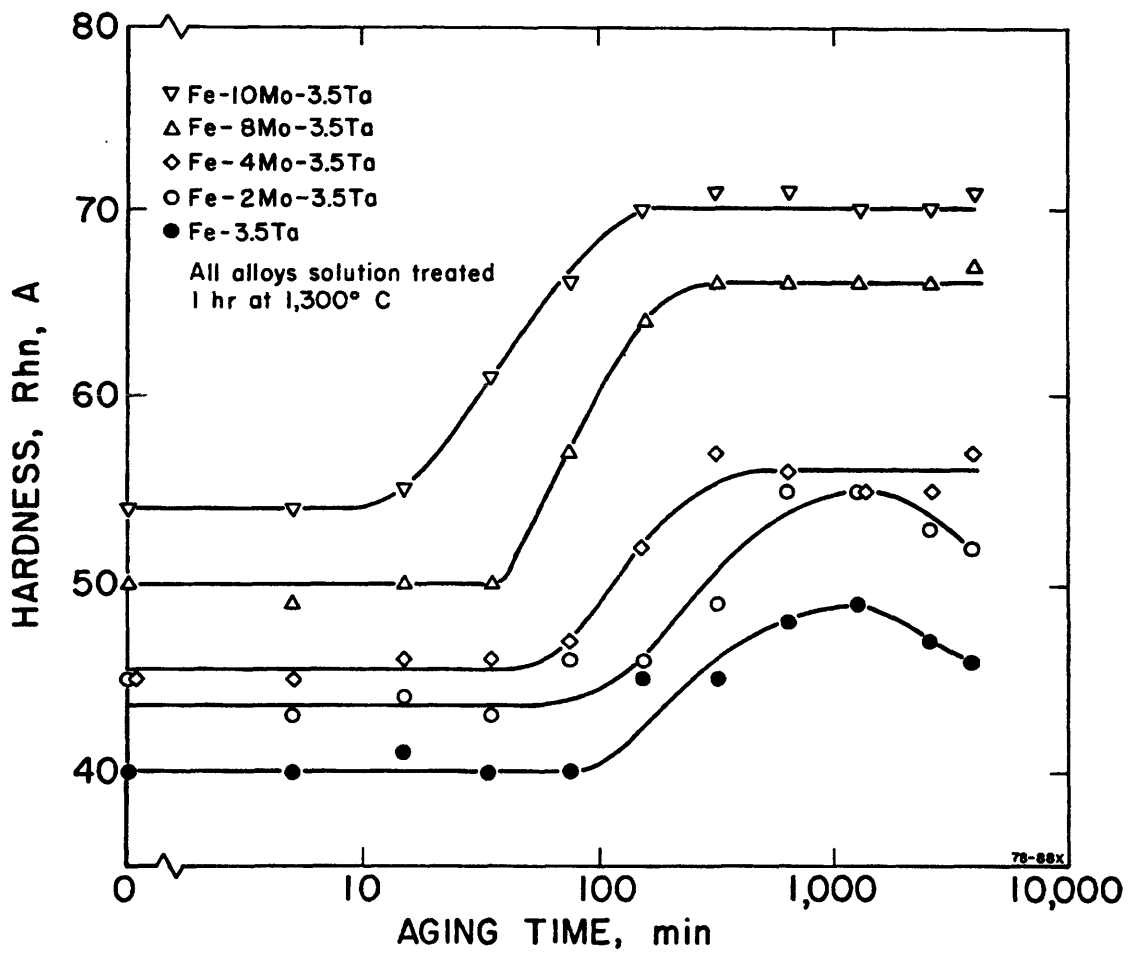


Figure 6. Precipitation hardening curves for a series of Iron-Tantalum-Molybdenum alloys aged at 923 K [12].

batches of the same alloy will not have exactly the same microstructure and properties. When taking data from one alloy, it is not often possible to immediately transfer that model to another alloy. It requires some modification. The Phase Computation (PHACOMP) method, discussed later in this work, has been successful in predicting sigma phase formation in many alloys. New PHACOMP modifies that model and appears to give even more accurate results.

Not everything about the sigma phase is a disadvantage. It is being investigated as a method of strengthening alloys without costly elemental additions. This practice works best when the alloy is a ternary or above, as sigma phase becomes brittle quickly in binary systems at room temperature [12]. It retains its strength and hardness at high temperature for long periods of time [11]. This result makes it ideal for strengthening high temperature components (Figure 7). It also lowers the coefficient of thermal expansion for a material, which allows a smaller tolerance when designing parts.

1.4 Sigma Phase Prediction

One of the first attempts at predicting sigma phase formation took the form of a simple ratio test:

$$\text{RatioFactor} = \frac{\text{wt}\% \text{Cr} - 16(\text{wt}\% \text{C})}{\text{wt}\% \text{Ni}}$$

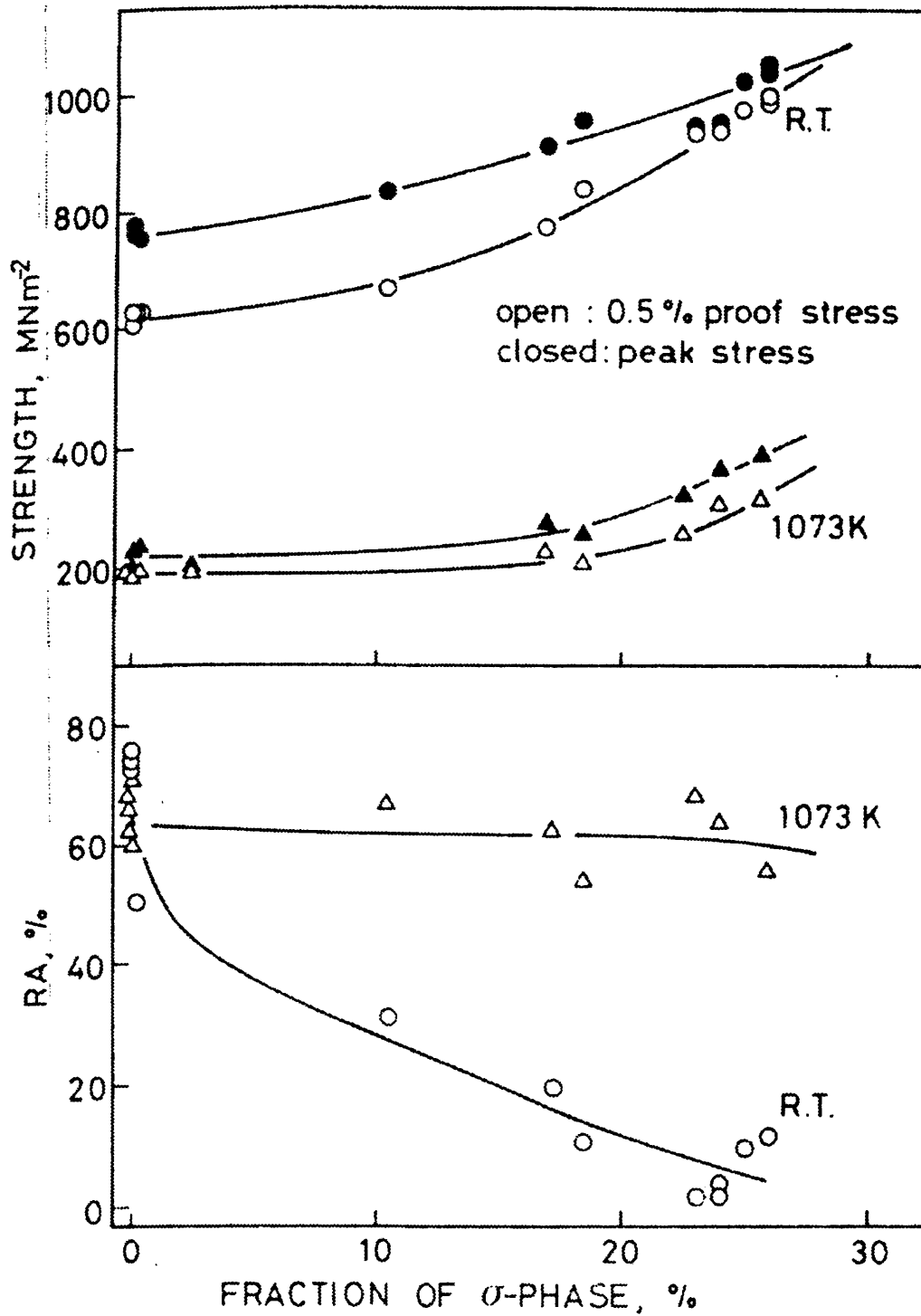


Figure 7. Variations of tensile properties at 300 and 1073 K with volume fraction of sigma phase; specimens solution treated at 1323 K and aged at 1073 K before deformation. [15]

If this factor exceeded 1.7, then sigma phase was expected to form [22]. Another method was presented by Hull [3], who determined an equivalent chromium content of the alloy: (the elemental symbol represents the atomic percent of the element in the alloy)

$$\text{"Equivalent Cr."} = \text{Cr} + 0.31\text{Mn} + 1.76\text{Mo} + 0.97\text{W} + 2.02\text{V} + 1.58\text{Si} + \\ 2.44\text{Ti} + 1.70\text{Nb} + 1.22\text{Ta} - 0.226\text{Ni} - 0.177\text{Co}$$

However, other researchers determined that this equation was only useful for predicting one type of intermetallic and only valid for the type of steel he used [22,24].

In 1938, Linus Pauling compared the structure of the metallic bond to the covalent bond. Using the magnetic moment of a metal, he was able to predict the number of electrons participating in bond formation. He predicted values for the elements based on their magnetic moments and their position in the periodic table (Figure 8) [25].

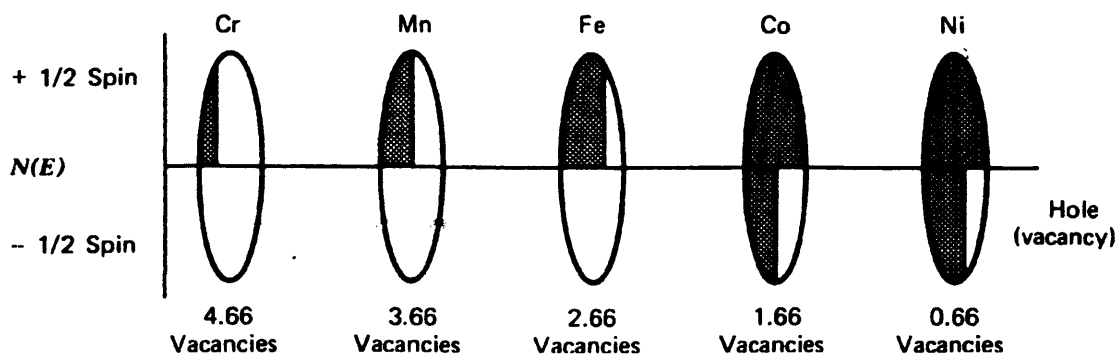


Figure 8. Pauling's predicted vacancies in the d-shell for five elements [25].

Pauling's theory of the number of electrons available for bonding is the start of the PHACOMP theory. Woddyatt et al. discuss the application of phase prediction in binary and ternary alloys to more complex superalloys. They use the average electron vacancy number (N_v) of the included elements to find an average N_v for the alloy. This number determines whether or not sigma phase will form. The number is determined from the residual austenite matrix left after precipitation of the carbides and γ' phase [26].

This residual matrix is calculated using the following PHACOMP process [1,26]. First, convert the composition of the alloy into atomic percent. Second, assume all the boron forms a compound of the following composition: $(\text{Mo}_{0.5} \text{Ti}_{0.5} \text{Cr}_{0.25} \text{Ni}_{0.10})_3 \text{B}_2$. Next, half of the carbon produces monocarbides in the following preference: TaC, CbC, ZrC, TiC, VC. The remaining carbon forms M_{23}C_6 ($\text{Cr}_{21}(\text{Mo}, \text{W})_2\text{C}_6$ or Cr_{23}C_6 if no molybdenum or tungsten is present) or M_6C ($\text{NiCo}_2\text{Mo}_3\text{C}$) if the Mo + W level is above six percent. Then the γ' precipitates out combining all the remaining aluminum, columbium, titanium, and one-tenth of the original amount of chromium with three times as much nickel. If the nickel is insufficient, then all the nickel is consumed to make a mixture of γ ($\text{Ni}_3(\text{Al}, \text{Ti}, \text{Cb}, \text{Cr})$) and β ($\text{Ni}(\text{Al}, \text{Ti}, \text{Cb}, \text{Cr})$). The remaining elements are scaled up to 100 percent and constitute the residual matrix.

The average electron vacancy number for the alloy is determined by the following expression:

$$Nv_{alloy} = \sum_i x_i Nv_i$$

The values of N_v are given in Table 2. The critical value of N_v , is approximately 2.52 [26] although values from 2.47-2.65 [10,27] have been advanced. This tool can be used in the design of new alloys to determine in advance whether they will be sigma phase prone.

There are a few problems with PHACOMP however. In multi component systems, other deleterious phases may form before sigma phase. The composition of the matrix also depends upon the temperature of the alloy [10]. The process for forming the austenitic matrix may not accurately represent the process happening inside the alloy. If the residual matrix is miscalculated, all the N_v values are incorrect. Murphy et al. [27] compared it to fitting a plane to four given points. It does not always fit and adjusting one parameter will only make another worse. PHACOMP also does not work well with cobalt based alloys.

Barrows and Newkirk [10] suggest a system to modify PHACOMP to include temperature dependence. Their theory predicts more accurately the gamma-sigma phase boundary. Their model has better success than the original but some alloys still are not accurately predicted.

The main reason for failure in PHACOMP is the assumption that all the elements in the same period of the periodic table have the same PHACOMP

Table 2. Elemental N_v and M_d values. From Morinaga et al. [28]

Element	N_v^i	M_d^i
Ti	6.66	2.271
V	5.66	1.543
Cr	4.66	1.142
Mn	3.66	0.957
Fe	2.66	0.858
Co	1.71	0.777
Ni	0.66	0.717
Zr	6.66	2.944
Nb	5.66	2.117
Mo	4.66	1.550
Ta	5.66	2.224
W	4.66	1.655
Al	7.66	1.900
Si	6.66	1.900

coefficients. The elements are known to have different chemical and physical behavior in going from the top of the column to the bottom. Thus different coefficients are required for the different elements. There is dispute about what the values of the coefficients should be for certain elements. The susceptibility to form sigma phase is also temperature dependent. Therefore, the critical value should be temperature dependent.

Morinaga, Yukawa, Adachi and Ezaki [28] propose a modification to the old system named New PHACOMP. The system uses the average energy level of the d-electrons (M_d) instead of N_v . It represents the formation of other phases better than PHACOMP and includes temperature dependence. The M_d levels correlate both the atomic radius and electro-negativity. The system is reduced to a residual matrix in the same fashion as with PHACOMP. The value for M_d is found in the same way as N_v :

$$Md_{alloy} = \sum_i x_i Md_i$$

With the M_d values given in Table 1. The critical value for $M_d=6.25 \times 10^{-5} T + 0.834$ (Figure 9). As seen in figure 10, their model correctly predicts the sigma phase forming status of 25 alloys some of which PHACOMP does not correctly identify. It also works well for cobalt-based alloys, another deficiency of PHACOMP.

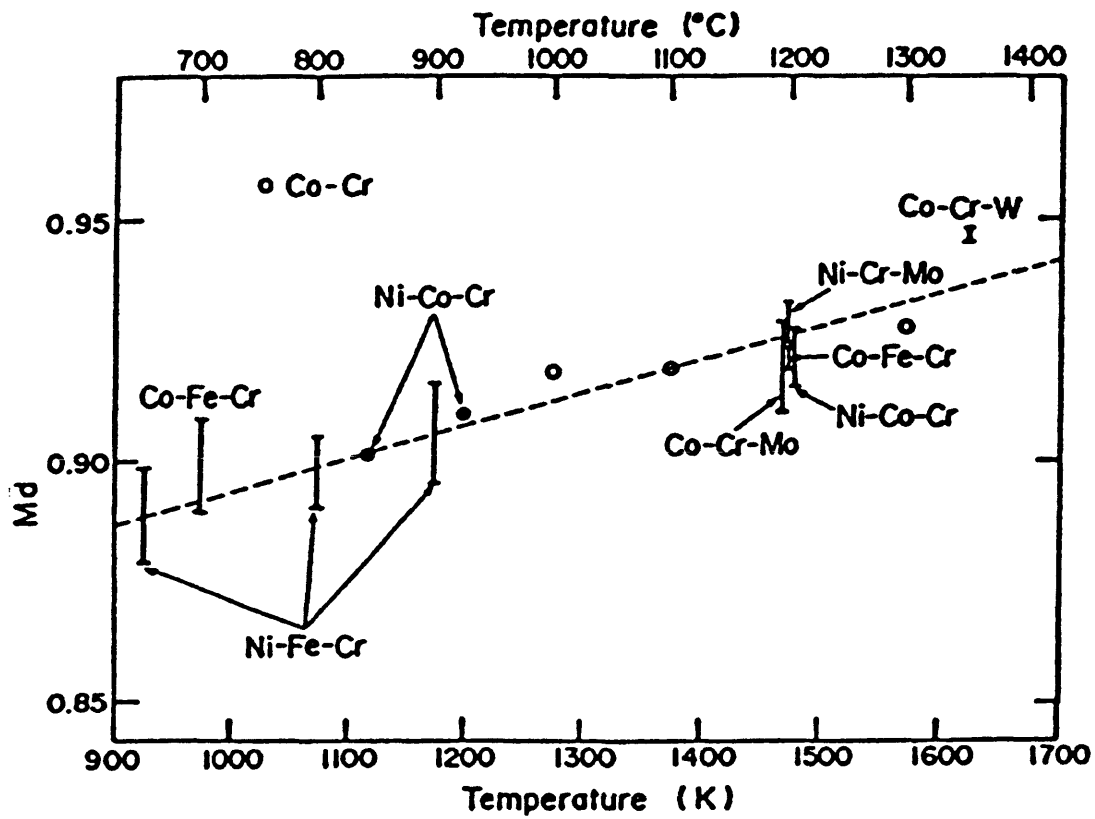


Figure 9. Temperature dependence of critical M_d value to which the alloys are tested to determine the susceptibility to sigma phase formation. [28]

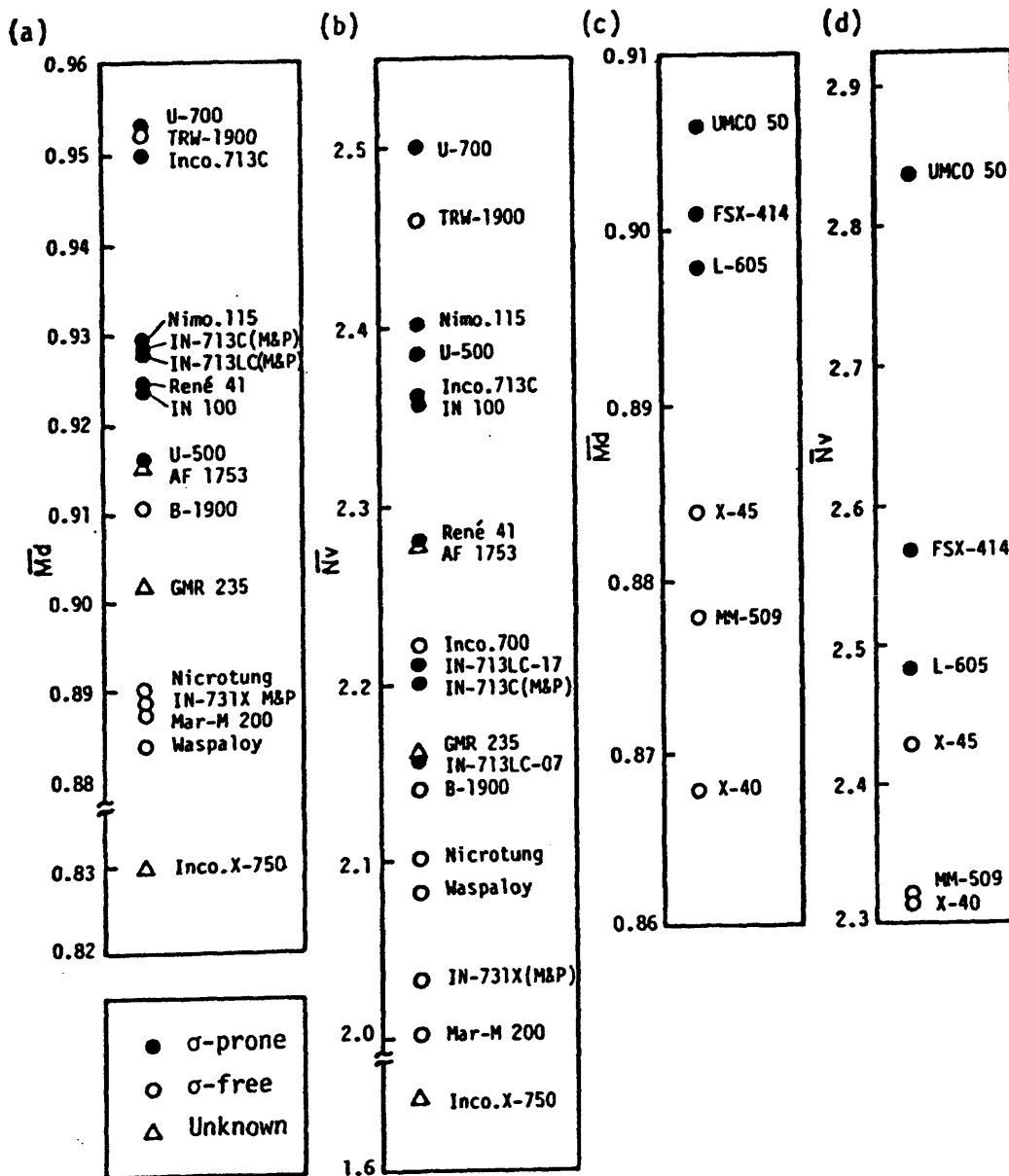


Figure 10. Estimation of the occurrence of sigma phase in (a,b) nickel-base superalloys and (c,d) cobalt-base superalloys. Comparison of PHACOMP and New PHACOMP values [28].

Another application of New PHACOMP is the prediction of terminal solidification. It cannot predict which phase will form but it predicts when it will. It also cannot be used if competing terminal solidification constituents are present [28]. New PHACOMP reduces some of the error in the old process but additional work is needed [29]. The residual matrix is still calculated in the same fashion, which is not always correct.

The PHACOMP and New PHACOMP use models to predict the structure and properties of the electron d-bands in the alloy. If the structure of those bands can be determined through direct measurement, the need for estimation would not exist. The models could be applied to the actual data.

2.0 PROPOSED METHOD

The formation of sigma phase in a superalloy has been found to affect the physical properties and characteristics of the alloy. It has also been related to a change in the electronic nature of the alloy. By extending this reasoning, it should be possible to use electronic and magnetic measurements to determine phase information about a superalloy.

As the physical properties and microstructure of an alloy change, the electronic properties do as well. Phases precipitate, leaving a different matrix behind, defects form and disappear and the electronic bonds shift from one compound to another. Currently, to examine any of these properties it is necessary to disassemble a component, cut it up and observe the phases present. Some of these components are expensive and such destruction is to be avoided if possible. Electronic measurements of an alloy are simple to acquire and can be performed almost anywhere. By relating these measurements to the phases present in the material, it will be possible to determine phase information non-destructively. These measurements could be used to perform spot checks on components to judge their remaining usefulness without taking them out of service

The proposed electronic measurements would determine phase, defect and magnetic moment of the metal. Conductivity is a measure of the defect structure in the alloy. The Seebeck and Hall coefficients can be used to determine the effective mass and the electron density of the alloy. The Seebeck (thermopower) coefficient indicates when the alloy content is promoting the filling of higher energy states and thus a phase transition. Measurements of the magnetic moment determine the number of bonding electrons in the alloy, the basis of both the new and old PHACOMP methods used to theoretically assess the susceptibility of the alloy to sigma phase formation. These measurements could then be used to create a three-dimensional model of the phase relationships in the material (Figure 11). This electro-magnetic space could be used as a map to locate the amount of sigma phase within a part and determine its remaining lifetime.

These measurements can be verified by comparing our results to predictions of susceptibility models such as PHACOMP and New PHACOMP. Optical inspection and experimentation on samples can also be used to calibrate them.

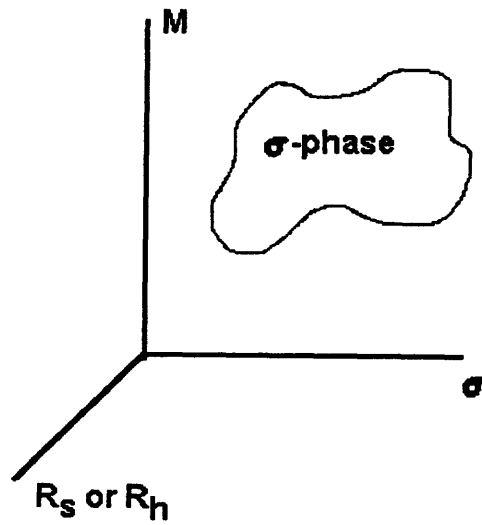


Figure 11. Simulated map of sigma phase susceptible region in electro-magnetic space, using the conductivity, Seebeck or Hall coefficient and magnetic measurements.

3.0 MEASUREMENTS

3.1 Conductivity

Conductivity measures the defect structure of the alloy. It is a fairly easy measurement to perform, and has been studied in many alloys. Other factors that can affect the conductivity are grain size and structure of the metal. These factors can be controlled and relationships found to calibrate the system.

Since sigma phase is a highly resistive compound the effects of its formation can be easily observed. The measurement will also depend on the grain structure of the material. Measurements have been performed on some alloys already. Using these results as a base, it will most likely be necessary to determine the conductivity of each alloy separately rather than applying a general rule [30]. Some of the results show decreasing conductivity with age while others show increasing conductivity (Figures 12 and 13) [17,31]. These different results could both be the result of sigma phase formation, since sigma phase formation could leave highly conductive channels, which increases the conductivity. On the other hand, if sigma phase compartmentalizes the alloy, the conductivity will decrease.

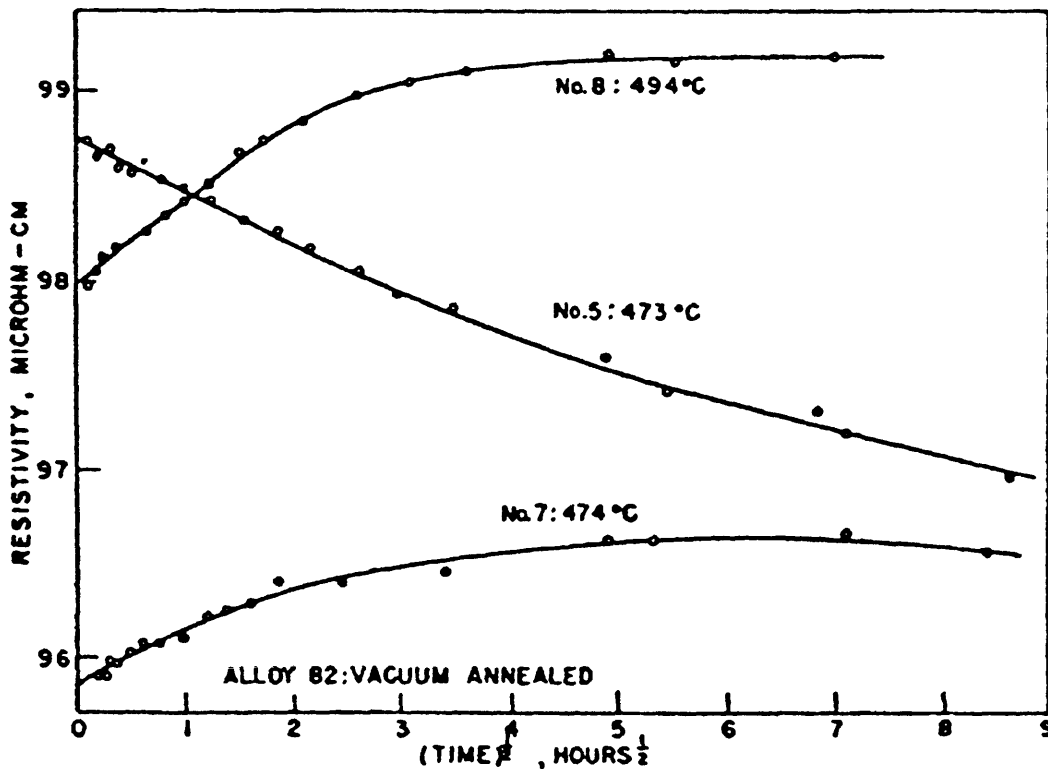


Figure 12. Time dependence of resistivity of a 30 weight-percent chromium-iron alloy after a temperature change of 25 K. [31]

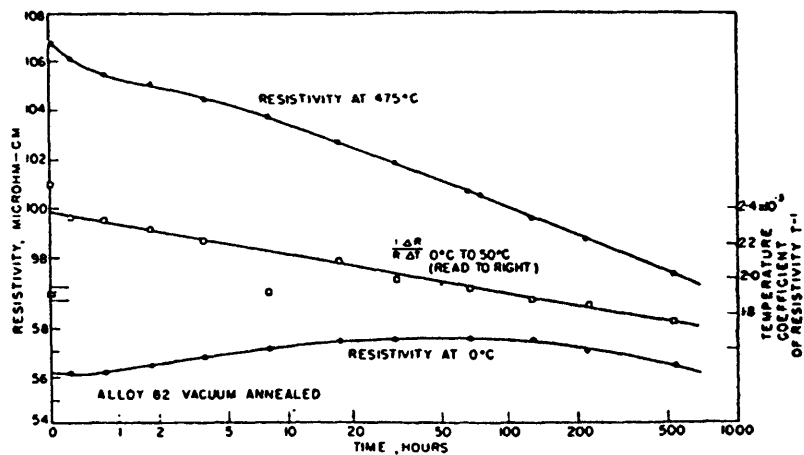


Figure 13. Changes in resistivity at 273 K and 748 K of a 30 – weight-percent chromium-iron alloy during aging at 748 K. [31]

Conductivity is measured by a four-probe method (Figure 14). A known current is placed across the outer probes and the voltage drop across the inner probes is measured. The conductivity is found according to:

$$\sigma = \frac{1}{\rho} = \frac{d \cdot I}{V \cdot A}$$

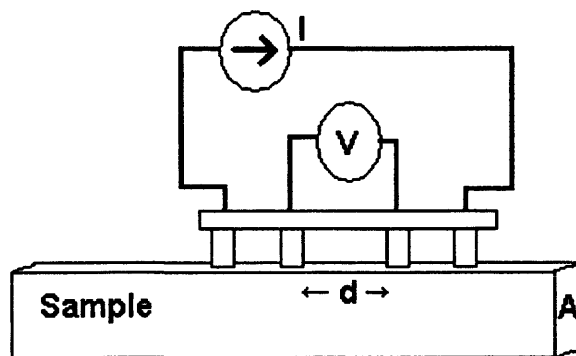


Figure 14. Setup for conductivity measurement.

Where I is the current, V is the measured voltage, A is the cross sectional area and d is the distance between the inner probes.

Conductivity measures all the defects in the system, not just sigma phase. Thermal defects, grain boundaries and sigma phase formation all contribute to the change in conductivity. To determine how much of this result is due to sigma phase formation, the measurement must be compared with others.

3.2 Seebeck Coefficient

The Seebeck (thermoelectric power) coefficient measures the density of electrons in the material. To take the measurement, a temperature gradient is established across the alloy. This thermal gradient causes the electrons at the high temperature end to speed up and propagate faster than the electrons at the low temperature end. As a result, more electrons move to the low temperature end, which establishes an electric field in the alloy. The strength of this field depends on the number of free electrons in the metal. Figure 15 shows a sample setup for taking Seebeck measurements.

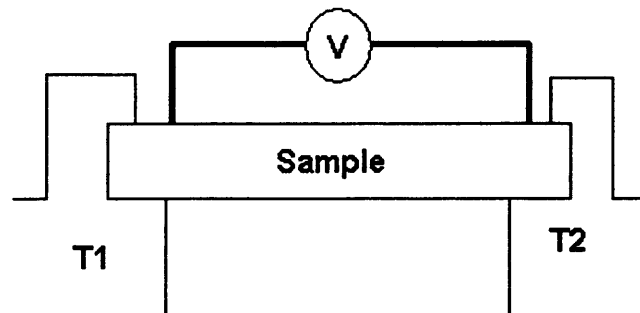


Figure 15. Apparatus for measuring Seebeck Coefficient

In a metal, the structure of the metal determines the number of electrons free to move around. Many of the superalloys are designed to have a FCC structure. Sigma phase fits in the domain of the BCC and HCP lattices [19].

With the formation of sigma phase, the number of conducting electrons drops as they are bound in the sigma phase. This measurement would also need to be done on an alloy by alloy basis since the base measurements of the different alloys would vary.

The Seebeck (thermoelectric power) coefficient gives information about the composition and electronic structure of the alloy. The difficulty in separating the information makes it necessary to relate the measurement to others.

Seebeck coefficient measurements also take a lot of time to set up and perform.

3.3 Hall Coefficient

The Hall coefficient (R_H) can give the same information as the Seebeck coefficient about the density of electron states. The apparatus for determining this is shown in figure 16. The Hall coefficient is determined by passing a current

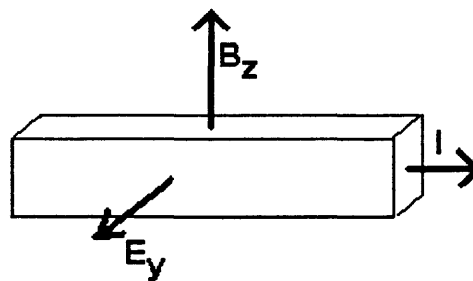


Figure 16. Diagram of established field for Hall coefficient.

(I) through a sample, perpendicular to a magnetic field (B_z). The magnetic field causes the electrons to deflect to one side of the sample, establishing an electric field (E_y) that exactly counteracts the effects of the magnetic field. R_h is determined by:

$$R_h = -\frac{E_y A}{B_z I}$$

where A is the cross sectional area [32].

The Hall coefficient is difficult to measure in metals due to their high conductivity. The advantage is that the measurement just gives information on the carrier concentration in the alloy, neglecting composition. Either the Seebeck or Hall coefficient can be used to garner this knowledge but since the results are so similar, only one will be used for this procedure.

3.4 Magnetic measurements

The critical calculation in the PHACOMP model is the average number of vacant d-orbitals that participate in the bonding of the superalloy. Direct measurement of the magnetic nature of the alloy should yield this information. The number of unpaired d-orbitals gives rise to the magnetic moment of the material. Using measurements of the magneto resistance or magnetic susceptibility of the

material, this number can be obtained exactly. When a magnetic field is applied to a metal, the metal generates a magnetic field. The strength of this field depends on the magnetic moment of the metal. The formation of sigma phase can also be monitored using these measurements. Sigma phase is non-magnetic and would lower the overall magnetic moment of the material [17]. In figure 17, the magnetic saturation of an alloy is given compared to aging time and temperature. This shows that with aging and microstructural change comes a shift in magnetic properties.

While the Colorado School of Mines does not possess the apparatus necessary to conduct magnetic measurements, the National Institute of Standards and Technology at Boulder does. Measurements of magneto-resistivity and magnetic moment can be performed there.

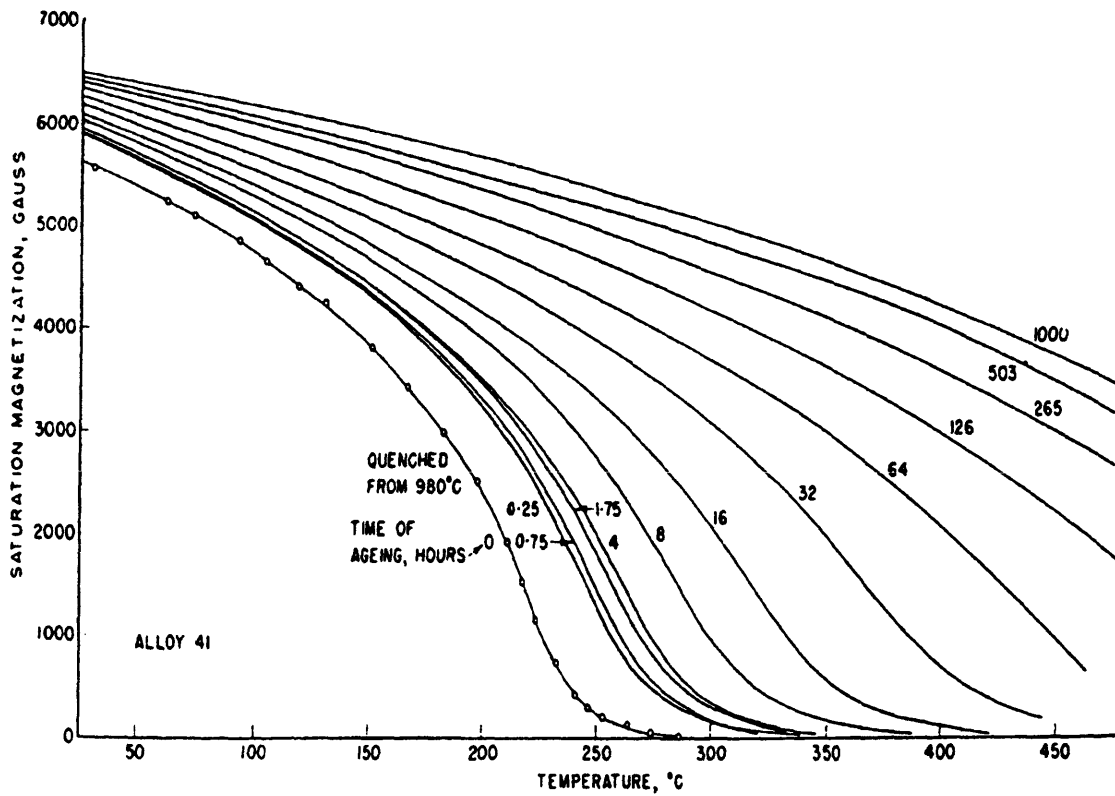


Figure 17. Magnetization/Temperature curves for a 53 weight-percent chromium-iron alloy aged at 748 K for a range of aging times. [31]

4.0 CONCLUSION

By acquiring and analyzing the electronic and magnetic properties of a superalloy, it should be possible to determine information about its phases and structure. This information can then be used to determine the lifetime and capabilities of materials. Due to the relative ease of performing these measurements, they may be used to perform field tests on superalloy components, without destroying them. This method will avoid the expense of producing large or specialized parts that would otherwise be destroyed for testing. It will also save time as the tests can be performed either simultaneously or sequentially on separate sections of the sample. This proposed procedure will make the testing of superalloys for the formation of sigma phase much simpler.

To test this theory, three samples of superalloys were acquired. Using New PHACOMP, the average energy level was calculated and compared to the critical value of M_d . The samples will be subjected to multiple heat treatments and the proposed electrical quantities measured. The results will be related to the phase data by optical inspection of the samples. With this information, it should be possible to construct a model of the phases in electro-magnetic space.

This method will be a viable alternative to destructive testing of superalloy components. By performing the measurements, with electronic devices, there is

no need to manufacture extra components that will just be disassembled for testing. In addition, the electrical test devices could be contained in a portable unit, available to test components outside the lab. This capability would allow greater versatility in the testing of parts for imminent failure. By measuring the electron structure, imprecise theoretical methods are bypassed and a more accurate picture of the superalloy can be formed.

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