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Clustering of GABA (A) Receptors

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Abstract

Targeting, clustering and immobilization of the neurotransmitter receptors is a complex process of molecular organization. At the postsynaptic level, anchoring protein model has been proposed for the mechanism of this organization. NMDA type of Glutamate receptors are anchored by the PSD 95 at the postsynaptic membrane. Gephyrin is essential for the anchoring of Glycine receptors and so Agrin for the Acetylcholine receptors at the post synaptic sites. In line with this, for GABA (A) receptors (GABA$_A$Rs), the similar concept has been expected but the heterogeneity and complexity of GABA$_A$Rs make their analysis extremely difficult. This paper will briefly discuss the current perspectives on the clustering of selected GABA$_A$R subtypes in terms of anchoring protein model.

Keywords: GABA (A) Receptors, neurotransmitter receptors, clustering

1. Introduction

Brain information processing depends on neural circuits, mediated by excitatory and inhibitory signals (Koch et al., 1983). These signals are generated by neurotransmitters like Glutamate, Acetylcholine, Glycine or GABA. When released from the pre-synaptic neuron, each neurotransmitter binds to its own receptor, leading to a change in its conformation and thus changing the receptors ionic permeability. It is this change in the ionic permeability that has the capability to alter the membrane potential of neurons which is approximately -70 mV at resting state. One of the factors important for this phenomenon is the clustering of neurotransmitter receptors targeted and immobilized in the special domains of the cell membrane. Targeting, clustering and immobilization of the neurotransmitter receptors is a complex process of molecular organization and at the postsynaptic level, anchoring protein model has been proposed for the clustering mechanism of neurotransmitter receptors like acetylcholine, glycine or NMDA receptors. For example NMDA type of Glutamate receptors are anchored by the PSD 95 at the postsynaptic membrane (Sheng and Pak, 1999; van Zundert, et al., 2004, Elias et al., 2008). Gephyrin is essential for the anchoring of Glycine receptors (Kirsch et al., 1993; Kirsch et al., 1995; Kneussel et al., 1999; Schrader et al., 2004; Feng, et al., 1998; Kimet al., 2006) and so Agrin for the Acetylcholine receptors (McMahan, et al., 1990;

Bezakova and Ruegg, 2003; Kummer et al., 2006) at the post synaptic sites. Similarly for GABA$_A$Rs (Gamma-aminobutyric acid type A receptors), the same mechanism has been expected but the heterogeneity and complexity of these receptors make their analysis very difficult. In this paper, I will discuss the current perspectives on the clustering of GABA$_A$Rs.

2. GABA$_A$Rs: The chloride channels

GABA$_A$Rs are GABA gated heteropentameric chloride channels and major sites of inhibitory neurotransmission in the mammalian brain. The subunits are encoded by 19 genes ($\alpha1-\alpha6$, $\beta1-\beta3$, $\gamma1-\gamma3$, δ, ϵ, θ,π, $\rho1-\rho3$) and subunit composition determines the receptor's distribution both in cellular and sub-cellular level (Fritschy and Mohler, 1995; Sieghart and Sperk 2002; Sun et al., 2004).

Until last year, the structure of GABA$_A$Rs was based on the homology modeling (Sine and Engel, 2006) but the crystallized structure of homomeric $\beta3$ subunit containing GABA$_A$Rs (GABA$_A$R-$\beta3$cryst) at 3Å resolution have finally revealed the receptor structure for the first time (Miller and Aricescu, 2014). The receptor, composed of five subunits and arranged around a central pore, has a cylindrical shape with a height of 110Å and with a diameter of 60 to 80Å. Each subunit has a long N- terminus and a short C terminus both located extracellularly, four transmembrane domains*(*TM1–TM4), a large

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intracellular loop between the third and fourth transmembrane domains. Each extracellular domain has an amino-terminal α-helix (α1) followed by ten β−strands.

The most abundant receptor subtype of GABA_ARs is the γ2αβ subunit combination (γ2−GABA_ARs) with a stoichiometry of 2 α, 2 β and 1 γ2 subunit (Benke et al., 1991; Tretter et al., 1997; Sieghart and Sperk, 2002). Clustered at the postysynaptic sites (Fujiyama, et al., 2000, 2002), besides to nonsynaptic regions, γ2−GABA_ARs are in the close proximity of GABA release from presynaptic neuron and quickly respond to GABA by allowing chloride influx to the cell and thus causing a strong hyperpolarization and mediating fast phasic inhibition (Farrant & Nusser, 2005). On the other hand, some GABA_AR subtypes are not located in the synapses. Electron microscopy studies clearly show that these receptors are non-synaptic (Nusser et al., 1998; Wei et al., 2003). So called extra-synaptic receptors, these receptors specifically contain δ subunit (Sommer et al., 1990) together with 2 α and 2 β subunits (Shivers et al., 1989; Jones et al., 1997, Patel et al., 2014), have higher affinity for GABA and mediate slow, tonic inhibition (Hausser and Clark, 1997; Farrant & Nusser, 2005). Another subset of GABA receptors containing α5, β and γ2 subunits are mostly extrasynaptic also (Kneussel, 2005; Loebrich et al., 2006). Therefore, different GABA_AR subtypes have different subcellular distribution, i.e., synaptic and/or extrasynaptic, or perisynaptic. However the factors underlying the mechanisms involved in the differential distribution of receptor subtypes are not well understood. In this study we will focus on the clustering of γ2 and δ subunit containing receptor subtypes since these subunits involved in different physiological functions (phasic and tonic), never co-assemble, and have different subcellular distribution.

3. Clustering of GABA_ARsubtypes: γ2−GABA_ARs and δ−GABA_ARs

GABA_ARs are assembled in the endoplasmic reticulum and microtubule-based transport mediates their mobility. Upon their arrival to the plasma membrane, the receptors diffuse laterally in the cell's surface but their interaction with specific adaptor proteins bound to scaffolding proteins with elements of cytoskeleton leads to the stabilization of neurotransmitter receptors at specific domains of plasma membrane (Tretter and Moss, 2008).Still, we cannot propose a mechanism for the membrane clustering for GABA_ARs in general but perhaps

mechanisms may be proposed for different receptor subtypes.

In this context, γ2−GABA_ARs correspond to one receptor subtype. γ2 subunit is specifically essential for the process of synaptic clustering (Essrich et al., 1998). Despite this, synaptic currents have been detected in neurons obtained fromγ2knock-out mice. It appears likeγ3subunit is a candidate for clustering GABA_ARs at synapses in the absence of theγ2subunit at least for certain neurons (Kerti-Szigeti et al., 2014). Another molecular factor that might be important in the clustering of γ2−GABA_ARs is the Gephyrin. Current literature suggests that the clustering of γ2−GABA_ARs in the postsynaptic membrane is facilitated by interaction of gephyrin with the cytoplasmic domain ofαsubunit (Tretter et al., 2008, 2012; Mukherjee et al., 2011).However gephyrin is required for clustering of γ2−GABA_ARs that contain theγ2 subunit together with theα2 or α3 subunit but not withα1 subunit (Essrich et al., 1998; Kneussel et al., 1999, 2001; Tretter et all., 2011). Yeast 2-hybrid studies and glutathione S-transferase pull down assays show that Gephyrin interacts with GABA_AR associated protein (GABARAP) (Kneussel et al., 2000; Kneussel and Loebrich, 2007). However, these two proteins are never co-localized in neurons and GABARAP is not found in the inhibitory synapses (Kneussel et al., 2000; Kittler, et al., 2001). Moreover studies of GABARAP deficient mice show that the number of GABA_ARs is not affected by the loss of GABARAP and immunostaining revealed no differences in the clustering of the γ2 subunit and the gephyrin (O'Sullivan et al., 2005).Conversely, GABARAP is not essential for the clustering γ2−GABA_ARs but gephyrin is the anchoring protein of at least certain combinations of γ2−GABA_ARs clustered synaptically. Other GABA_AR related proteins involve but not limited to some gephyrin interacting proteins like collybistin (Kins et al, 2000).

Although Gephyrin appears as a central protein for the postsynaptic clustering of some γ2−GABA_ARs, it is essentially dispensable for the clustering of extra-synaptic receptors (cited in Arslan et al., 2014). Extrasynaptic receptors are likely have their own assembly of proteins for their special arrangement in the extrasynaptic sites. For example radixin has been identified as anchoring protein for α5 containing GABA_ARs subtypes (Loebrich et al., 2006) which are extrasynaptic (Brünig et al., 2002). Is that the same case for the extrasynaptic δ−GABA_ARs? δ-GABA_ARs, are typically

composed of α6 and β subunits in the cerebellum (Jones et al, 1997); and composed of α4 and βsubunits in the forebrain (Peng et al., 2002; Jia et al., 2005; Chandra et al., 2006). Electron microscopy data show that they are located extra-synaptically or perisynaptically in these regions (Nusser et al., 1998; Wei et al., 2003). There is no any protein identified so far associated with the process of extrasynaptic clustering of δ-GABA$_A$Rs but α subunit and δ subunit might have an active role in this process. Studies show that when a gephyrin-binding site is introduced into the intracellular domain of α6 and δ subunits, δ-GABA$_A$Rs became closer to the synaptic sites (Wu, et al., 2012). Besides, targeting of δ-γ2 chimeric subunits to synaptic or extrasynaptic sites has been found to be dependent on the co-assembly with the α2 or α6 subunit. (Wu, et al., 2012) Therefore, the α subunit isoforms, together with the γ2 and δ subunits is likely play a significant role in synaptic or extrasynaptic targeting of GABA$_A$Rs, respectively. This view has been further supported for the δ subunit by the studies of recombinant δ-γ2 subunits expressed in primary cultures of neurons. By focusing on γ2-GABA$_A$Rs and δ- GABA$_A$Rs, Arslan et al. (2014) comparatively analyzed the differential clustering of synaptic and extra-synaptic GABA$_A$Rs in hippocampal neurons and suggested that extra-synaptic clustering of δ-GABA$_A$Rs is dependent on the cytoplasmic loop of δ subunit probably via an active process (Arslan et al., 2014). As a result, these studies make the δ subunit and especially its cytoplasmic domain as strong candidate influential in the process of extrasynaptic clustering of corresponding receptor subtypes. Thus, in order to identify any anchoring protein which may be involved in the extrasynaptic clustering δ–GABA$_A$Rs, δ subunit and its cytoplasmic domain should be further analyzed by proteomics and yeast 2-hybrid screens.

4. Conclusion

The heterogeneity and complexity of GABA$_A$Rs make the analysis of their differential clustering extremely difficult. Despite this, some progress has been achieved in understanding the process of synaptic and extrasynaptic GABA$_A$Rs clustering. In line with anchoring protein model, Gephyrin is essential for the anchoring of some subtypes γ2−GABA$_A$Rs that contain the γ2 subunit together with the α2 or α3 subunit (but not with α1). Regarding δ−GABA$_A$Rs, there is less information but the emerging data for the importance of δ subunit may better guide the design of new studies aiming to identify novel proteins involved in the

process. Thus, more progress is expected in the field to understand the molecular machinery involved in the process of differential clustering of GABA$_A$R subtypes.

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The Complexity of Mental Disorders

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Abstract

Upon completition of human genome project, there has been a huge effort to identify genes that have been associated to mental disorders like schizophrenia or depression. However, these investigations still remain at theoretical level. Thus, psychiatry does not seem to benefit from postgenomic era as desired. This paper will briefly discuss the reasons for this bottleneck in terms of the complexity of mental disorders.

Keywords: Genetic variation, gene-environment interactions, neuropsychiatric disorders

1.Introduction

Mental disorders are brain diseases that arise from the complex interplay of nature and nurture. In comparison to other complex disorders however, the effect of nature appears to be quite strong: the susceptibility for major psychiatric disorders show a strong degree of heritability (Moldin and Gottesman, 1997). Thus, following the completition of human genome project (HGP), there has been a huge effort to identify genes that have been associated to mental disorders like schizophrenia or depression. However, these investigations still remain at theoretical level.

This problem is already well reflected in the lack of validated drug targets. For example, a careful observation of scientific studies between the years of 1990-2001 will show the dramatic increase in the total number of research papers related to cognition and schizophrenia but, this progress was not translated to drug research as the clinical trials during the same period remained unchanged (Hyman and Fenton, 2003). Thus, considering the potential of new genetic approaches (see below), psychiatry does not seem to benefit from postgenomic era as desired. This paper will briefly discuss the reasons for this problem in terms of the complexity of mental disorders.

2. The Human genome project and new opportunities

The completition of Human Genome Project (HGP) in 2001 has had big impact in the society both economically and medically. According to a study published by Battelle Technology Partnership Practice

(2011), $3.8 billion investment on the HGP by the US government has led to a drive of $796 billion in the U.S. economy between the years 1998-2003. Besides, medical diagnosis, treatment and disease prevention have been innovated. For instance, EGFR mutation in lung cancer, KRAS mutation in colon and lung cancers, BRAF mutation in colon cancer have led to the identification of molecular markers to be used for diagnosis (McLeod, 2013).

Although genomic approaches increasingly provide new answers in medical practice, much basic research remains to be done for an effective application of genomics especially for a translational psychiatric research. The HGP has led to the emergence of new approaches for the utilization of new genetic data. Among these approaches, analysis of genetic variations, i.e., single nucleotide polymorphisms (SNPs), analysis of gene expression and gene function have been especially powerful (Tang et al., 2009). As a result of these methodologies many candidate genes have been identified in relation to mental disorders like schizophrenia or depression but these investigations still remain at theoretical level (Ptacek et al., 2011). Why does not psychiatry seem to benefit from genomic revolution as desired ? This problem is likely a factor of complex nature of psychiatric diseases.

3. Genotype, phenotype and environment

Mental disorders are not caused by a single gene, rather by multiple genes (Arslan, 2015). The multiple genetic factors will not be discussed here in detail as it is rather a better known phenomenon. The genetic complexity of mental disorders is further increased by

gene×environment (G×E) interactions in between the genotype and phenotype (Caspi and Moffitt, 2006). Regarding this, a good example comes from a study of 2002 by Caspi et al. who published a research paper showing the role of the monoamine oxidase A gene (*MAOA*) in the development of antisocial behaviors. Utilizing the data from the Dunedin Multidisciplinary Health and Development Study (DMHDS), Caspi et al. showed the effect of G×E interactions between childhood maltreatment and the variations in the MAOA gene in the development of antisocial behaviors. Thus, the associations between childhood maltreatment and antisocial behavior have been found to be modified by the variations of MAOA gene. The gene encodes the Monoamine oxidase A (MAOA), an enyzme, which catalyzes the oxidative deamination of biogenic amines, including serotonin (5-HT), norepinephrine (NE), and dopamine (DA) and the neuromodulator phenyl ethylamine (PEA). There are several variations in the MAOA gene and these polymorphisms have already been shown to be associated with behavioral phenotypes such as aggression and substance abuse besides to affective disorders like bipolar disorder and panic disorder (reviewed in Shih and Thompson, 1999). Among these variations, a well-characterized upstream variable number tandem repeat (uVNTR) polymorphism in the promoter region of the MAOA gene that is known to affect gene expression causing high activity or low activity MAOA variants. Caspi et al (2002) found that the carriers of the low activity variant are more responsive to the effects of childhood maltreatment associated with the development of antisocial personality disorder than the carriers of high-activity variant. Since then, this paper has been well replicated Enoch et al., 2010 Prom et al., 2009Sjoberg 2007, Nilsson et al/. 2006 despite some negative results (Huang et al., 2004). Nevertheless the results were further supported by a study of meta-analysis (Taylor and Kim-Cohen, 2007). While the effect of the GxE is evident, it remains unclear how to incorporate this parameter in to genetic analysis as multiple genetic variations needs to be assessed in terms of environmental factors.

Besides to the complexity of genetic factors, and gene-environment interactions, a further complexity is the lack of biologically defined diagnostic criteria: psychiatric disorders are diagnosed on clinical grounds. According to the current version of the Diagnostic and Statistical Manual of Mental Disorders-V, (DSM-V), there are over 300 different types of mental disorders. One problem is the problem of objectivity: the main source of information about the symptoms come from the patients so they may not be objective. Still, many psychiatric illnesses can be diagnosed reliably according to the Diagnostic and Statistical Manual (DSM) and the International Classification of Diseases (ICD) the

standard diagnostic guidelines. But these guidelines often does not provide the objective tests to draw boundaries around a particular clinical state (Tandon 2012). Another problem is that sometimes patients may show a combination of such phenotypes (symptoms) that overlap across these disease boundaries defined by DSM (Arslan, 2015). Since the classical psychiatric genetic research has been directed to genetic effects on disease, it is likely that gene-discovery studies in psychiatric research still remains at the theoretical level, because disease diagnosis is not based on biological criteria so it interferes with the top-down research (Arslan, 2015).

4. Conclusion

Despite the opportunities of genomic revolution, there is a lack of genetic markers that reliably guide the diagnosis of psychiatric disorders (Hyman and Fenton, 2003). This problem seems to derive from the complex nature of psychiatric disorders. These complexities are multiple genetic factors, gene-environment interactions, subjective nature of psychiatric phenotypes and the lack of biologically defined diagnostic criteria that interferes with the top-down research. Recognition of these complexities however will lead to the emergence of new approaches. Among these approaches, integration of environmental factors into functional neuroimaging studies have good implications (Lederbogen, F., et al., 2011; Meyer-Lindenberg and Tost, 2012). Moreover, there is a growing literature addressing the complexity problem of psychiatric phenotypes by the use of intermediate phenotypes since 2000s (Bookheimer, et al., 2000). With the support of new statistical developments, a further progress will be the accumulation of data collected by multivariate, large-scale analysis of genetics and intermediate phenotypes that eventually leads to the analysis of psychiatric phenomenon in terms of neural activity, genetic variation, environmental context together.

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The Biological Revolution

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Abstract

Since the 1950s biological sciences are on the rise. Today the rise of biological sciences have become so drammatic that its role has evolved from a single discipline to completely new sets of disciplines which we call today as life sciences. Due to the advancements in genomic technologiesthe fields of life sciences like molecular biology, biotechnology, molecular medicine, nanobiotechnology and neuroscience have evolved rapidly. The positive impact of these developments are not only evident in science and technology but also in economic growth and development.

Keywords: genomics, biology, molecular biology, genetic engineering, biotechnology

The nineteenth century was the age of engineering which served as a fuel for industrial revolution in Europe and North America (Wengenroth, 2000). The twentieth century was the age of chemistry and physics, despite the fact that key discoveries in biological sciences begin to emerge during this period, too (Agar, 2012). New discoveries and foundationsin chemistry and physics like radioactivity, theories of atom, quantum and relativity, has revolutionized the science and technology.

The twenty first century is definitely the age of biology. Many discoveries and inventions like restriction enzymes, DNA sequencing and PCR, caused biology to become dramatically differentiated and this boosted the development of new disciplines collectively called life sciences. Especially young fields like molecular biology, modern biotechnology, molecular medicine, nanobiotechnology and neuroscience have developed rapidly. Thistrend can be easily tracked by a snapshot of Noble prizes given in the last decade. Interestingly, the majority of Noble Prizes in Chemistry have been awarded for thesubjects of biology since the beginning of 2000s. Table 1 lists the topics of biology (highlighted by blue color)awarded by Noble prizein the field of chemistry. Between the years of 2002 to 2015, nine Nobel prizes of chemistry out of fifteenwent to subjects of biology or subjects related to biology. Thus, the life sciences are on the rise.

The rise of the life sciences is very much dependent on the genomic research and associated technologies. The genome is defined as the total genetic information of a species. Today the genomic sequence of many species including *Homo sapiens* is publicly available already. This means that genomic sequence of human for example, is decoded, numbered, catalogued and stored in the publicly available databases –thanks to the power of Human Genome Project(Lander ES, Linton LM, Birren, et al., International Human Genome Sequencing Consortium, 2001). However, now, in this post-genomic era, we still do not know the exact meaning of this code which is composed of billions of nucleotides arranged in the form of forty six chromosomes in each somatic cells of our body. Even the number of genes in the human genome is not known precisely. So, the current challenge of the post-genomic era is to identify all of the genes found in the human genomeand to determine their functions and their interactionswith each other and with the environment.

Despite the need of further work to fully benefit from the post-genomic era, it is already visible that genomic technologies are becoming very significant for economic growth and development. For example, according to a report published by Battelle Technology Partnership Practice(Tripp and Grueber, 2011), the economic impact of genomic research is estimated as $796 billion between the years 1988 and 2010. In fact the return of investment has been calculated as 141:1 which implies that for every $1 invested by the U.S. government a $141 economic activity is generated. In addition, according to the same study, genomics generated at least 51,000 jobs, and indirectly supported at least 310,000 jobs leading to an increase of $20 billion in personal income and $67

billion contribution to the U.S. economy. These figures clearly indicate that developments in life sciences are not only crucial for further analysis of natural phenomena but also important for economic growth and development.

The strong economic impact of life sciences is not limited to recent impact of genomic research as explained above. The biotechnology companies like Genentech (acquired by Roche now) in the Silicon Valley has already been seeded in the 1970s when, for example, insulin is cloned in bacteria and produced as recombinant drug by the techniques of genetic engineering. Genetic engineering allows scientists to manipulate DNA for a specific purpose. Thus, it ispossible to inactivate, exchangeor

Table 1. Topics of Noble prizes in the field of chemistry since 2002. Rows highlighted by blue color show subjects of biology or subjects related to biology(source: nobelprize.org)

Year	Topic	Nominee
2002	biological macromolecules	John B. Fenn, Koichi Tanaka, Kurt Wüthrich
2003	channels in cell membranes	Peter Agre, Roderick MacKinnon
2004	protein degradation	Aaron Ciechanover, Avram Hershko Irwin Rose
2005	metathesis method in organic synthesis	Yves Chauvin, Robert H. Grubbs, Richard R. Schrock
2006	eukaryotic transcription	Roger D. Kornberg
2007	chemical processes on solid surfaces	Gerhard Ertl
2008	green fluorescent protein(GFP)	Osamu Shimomura, Martin Chalfie, Roger Y. Tsien
2009	structure and function of the ribosome	Venkatraman Ramakrishnan, Thomas A. Steitz, Ada E. Yonath
2010	palladium-catalyzed cross couplings in organic synthesis	Richard F. Heck, Ei-ichiNegishi, Akira Suzuki
2011	Quasicrystals	Dan Shechtman
2012	G-protein-coupled receptors	Robert J. Lefkowitz, Brian K. Kobilka
2013	multiscale models for complex chemical systems	Martin Karplus, Michael Levitt, Arieh Warshel
2014	super-resolved fluorescence microscopy	Eric Betzig, Stefan W. Hell, William E. Moerner
2015	DNA repair	Tomas Lindahl, Paul Modrich,
		Aziz Sancar

mutate a gene or genes of a given species. For example, when a gene is deleted or inactivated in the genome of a species it is called a knock-out (KO) organism (Tsien et al., 1996) and KO animals have provided the basis of many studies directed to understand the function of a selected gene during health and disease. Genetic techniques like cre/loxP systems help scientists manipulate genes in specific neuron types or tissues of brain (Tsien et al., 1996)Thus, ranging from knocking out genes to spatio-temporal control of gene activity, there are a wide variety of genetic engineering approaches to manipulate genomes. These methods and approaches are likely to increase in the future and thus more development in medicine, biotechnology, neuroscience, bio-nanotechnology and pharmacogenetics is expected in the future.

While the developments briefly described so far are revolutionary, there exists many associated problems. Among these problems is the lack of equal opportunity. The impact of the biological revolution is not equally felt across the globe. There is no enough stimulation in the developing countries and people in these countries continue to suffer from the diseases for which science will have found cures (WHO Report, 2006). Thus, we need to develop awareness to address the requirement for the equality of opportunity for the knowledge and benefits of biological revolution.

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A Review on Superalloys and IN718 Nickel-Based INCONEL Superalloy

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Abstract

In this study superalloys, their processing and application areas have been researched. The superalloys are widely used in the industrial production fields such as aircraft, nucleer, space industry and so on due to superior properties at high temperature and resistance to metallurgical and structural variations. The most important groups of the superalloys is Ni, Fe and Co-based superalloys. Also processing of the superalloys are investigated and another goal of the present paper is to investigate microstructure and mechanical properties of IN718 nickel-based inconel superalloy subjected to strengthening heat treatment.

Keywords: *Superalloys, high temperature alloys, IN718 nickel-based superalloy.*

1   Introduction

The origin of the term "Superalloy" is rather obscure. Early works refer only to "Heat Resisting Alloys" or "High Temperature Alloys." The nomenclature "Superalloy" did not surface until the late '40s when the very popular fictional character, Superman, became a television hero. From that day forward, the word "Super" became a popular descriptor in the vocabulary. It is interesting to speculate that a fictional hero, Superman, had a role in the identification of the extremely important materials known as Superalloys. It will be likely never known who exactly is responsible for the term Superalloy. Instead of discussing the nomenclature of the term, the meaning of the term "Superalloy" will be focused on explaining it.

Many scientists who have attempted to describe Superalloys often employ esoteric and limiting technical terminology in the definition. These definitions are too specific and are difficult to use and understand in general. Ironically, some currently used definitions exclude many useful alloys of the past and are not acceptable for future alloys like the intermetallic. New definitions are needed in order to understand completely. Simplistically, Superalloys are alloys which:

o   are rich in at least one of the element nickel, cobalt and iron.
o   maintain structural, surface and property stability; at elevated temperatures, under high stress, and in severe environment.

This definition accurately describes essentially all existing Superalloys and provides flexibility required to include new materials such as the titanium and aluminum. Under this specification, rather simple chrome cast irons can be classified as Superalloys. For many years, the chrome cast irons were successfully used as furnace grate and shaker hearth materials. Certainly this application requires alloys with "Super" properties in order to survive at high temperature under stress in the severe corrosive environment of burning coal. Furthermore, various cast irons are used even today as diesel engine turbocharger casings and exhaust manifolds which operate at temperatures up to about 1400 °F (760 °C). By adoption of the proposed definition we find that Superalloys have a much longer history of service and that the door is opened wide for the alloys of the future.

Superalloys are heat-resisting alloys based on nickel, nickel-iron, or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation [1]. In fact, it is primarily used in gas turbines, coal conversion plants, and chemical process industries, and for other specialized applications requiring heat and/or corrosion resistance. A noteworthy feature of nickel-base alloys is their use in load-bearing applications at temperatures in excess of 80% of their incipient melting temperatures, a fraction that is higher than for any other class of engineering alloys.

This paper will also describe the investigations of a nanostructured (NS) state of nickel based INCONEL alloy 718 (IN718). This structure was generated in bulk semi products by severe plastic deformation (SPD) via multiple isothermal forging (MIF) of a coarse-grained alloy. The initial structure consisted of γ-phase grains with disperse precipitations of $\gamma^{\prime\prime}$ phase in the forms of discs, 50-75 nm in diameter and 20 nm in thickness.

2 Classification of Superalloys

Superalloys are classified into three based on the predominant metal present in the alloy. They are;
o   Nickel-based superalloys
o   Iron-based superalloys
o   Cobalt-based superalloys

2.1 Iron-based Superalloys

Irons-base superalloys evolved from austenitic stainless steels and are based on the principle of combining a closed-packed FCC matrix with (in most cases) both solid-solution hardening and precipitate-forming elements. The austenitic matrix is based on nickel and iron, with at least 25% Ni needed to stabilize the FCC phase. Other alloying elements, such as chromium, partition primarily to the austenite for solid-solution hardening [2].

The iron-based superalloys, which are less expensive than cobalt or nickel-based superalloys, are of three types: alloys that can be strengthened by a martensitic type of transformation, alloys that are austenitic and are strengthened by a sequence of hot and cold working (usually, forging at 2,000 to 2,100°F followed by finishing at 1,200 to 1,600°F), and austenitic alloys strengthened by precipitation hardening.Some metallurgists consider the last group only as superalloys, the others being categorized as high-temperature, high-strength alloys. In general, the martensitic types are used at temperatures below 1,000°F; the austenitic types, above 1,000°F.

The AISI 600 series of superalloys consists of six subclasses of iron-based alloys:

o   601 through 604: Martensitic low-alloy steels.
o   610 through 613: Martensitic secondary hardening steels.
o   614 through 619: Martensitic chromium steels.
o   630 through 635: Semi-austenitic and martensitic precipitation-hardening stainless steels.
o   650 through 653: Austenitic steels strengthened by hot/cold work.
o   660 through 665: Austenitic superalloys; all grades except alloy 661 are strengthened by second-phase precipitation.

Iron-based superalloys are characterized by high temperature as well as room-temperature strength and resistance to creep, oxidation, corrosion, and wear. Wear resistance increases with carbon content. Maximum wear resistance is obtained in alloys 611, 612, and 613, which are used in high-temperature aircraft bearings and machinery parts subjected to sliding contact. Oxidation resistance increases with chromium content. The martensitic chromium steels, particularly alloy 616, are used for steam-turbine blades.

The superalloys are available in all conventional mill forms; billet, bar, sheet, forgings, and special shapes are available for most alloys. In general, austenitic alloys are more difficult to machine than martensitic types, which machine best in the annealed condition. Austenitic alloys are usually "gummy" in the solution-treated condition and machine best after being partially aged or fully hardened.

Crack sensitivity makes most of the martensitic steels difficult to weld by conventional methods. These alloys should be annealed or tempered prior to welding; even then, pre-heating and post-heating are recommended. Welding drastically lowers the mechanical properties of alloys that depend on hot/cold work for strength. All of the martensitic low-alloy steels machine satisfactorily and are readily fabricated by hot working and cold working. The martensitic secondary-hardening and chromium alloys are all hot worked by pre-heating and hot forging. Austenitic alloys are more difficult to forge than the martensitic grades.

Alloy	Cr	Co	Mo	W	Ta	Re	Nb	Al	Ti	Hf	C	B	Y	Zr	Other
Conventionally Cast Alloys															
Mar-M246	8.3	10.0	0.7	10.0	3.0	—	—	5.5	1.0	1.50	0.14	0.02	—	0.05	—
Rene′ 80	14.0	9.5	4.0	4.0	—	—	—	3.0	5.0	—	0.17	0.02	—	0.03	—
IN-713LC	12.0	—	4.5	—	—	—	2.0	5.9	0.6	—	0.05	0.01	—	0.10	—
C1023	15.5	10.0	8.5	—	—	—	—	4.2	3.6	—	0.16	0.01	—	—	—
Directionally Solidified Alloys															
IN792	12.6	9.0	1.9	4.3	4.3	—	—	3.4	4.0	1.00	0.09	0.02	—	0.06	—
GTD111	14.0	9.5	1.5	3.8	2.8	—	—	3.0	4.9	—	0.10	0.01	—	—	—
First-Generation Single-Crystal Alloys															
PWA 1480	10.0	5.0	—	4.0	12.0	—	—	5.0	1.5	—	—	—	—	—	—
Rene′ N4	9.8	7.5	1.5	6.0	4.8	—	0.5	4.2	3.5	0.15	0.05	0.00	—	—	—
CMSX-3	8.0	5.0	0.6	8.0	6.0	—	—	5.6	1.0	0.10	—	—	—	—	—
Second-Generation Single-Crystal Alloys															
PWA 1484	5.0	10.0	2.0	6.0	9.0	3.0	—	5.6	—	0.10	—	—	—	—	—
Rene′ N5	7.0	7.5	1.5	5.0	6.5	3.0	—	6.2	—	0.15	0.05	0.00	0.01	—	—
CMSX-4	6.5	9.0	0.6	6.0	6.5	3.0	—	5.6	1.0	0.10	—	—	—	—	—
Third-Generation Single-Crystal Alloys															
Rene′ N6	4.2	12.5	1.4	6.0	7.2	5.4	—	5.8	—	0.15	0.05	0.00	0.01	—	—
CMSX-10	2.0	3.0	0.4	5.0	8.0	6.0	0.1	5.7	0.2	0.03	—	—	—	—	—
Wrought Superalloys															
IN 718	19.0	—	3.0	—	—	—	5.1	0.5	0.9	—	—	0.02	—	—	18.5Fe
Rene′ 41	19.0	11.0	10.0	—	—	—	—	1.5	3.1	—	0.09	0.005	—	—	—
Nimonic 80A	19.5	—	—	—	—	—	—	1.4	2.4	—	0.06	0.003	—	0.06	—
Waspaloy	19.5	13.5	4.3	—	—	—	—	1.3	3.0	—	0.08	0.006	—	—	—
Udimet 720	17.9	14.7	3.0	1.3	—	—	—	2.5	5.0	—	0.03	0.03	—	0.03	—
Powder-Processed Superalloys															
Rene′ 95	13.0	8.0	3.5	3.5	—	—	3.5	3.5	2.5	—	0.065	0.013	—	0.05	—
Rene′ 88 DT	16.0	13.0	4.0	4.0	—	—	0.7	2.1	3.7	—	0.03	0.015	—	—	—
N18	11.2	15.6	6.5	—	—	—	—	4.4	4.4	0.5	0.02	0.015	—	0.03	—
IN100	12.4	18.4	3.2	—	—	—	—	4.9	4.3	—	0.07	0.02		0.07	

Table 1: Compositions of commercial Ni-based superalloys (wt. %, bal. Ni).

2.2 Nickel-based Superalloys

Nickel-base superalloys are the most complex, the most widely used for the hottest parts, and, for many metallurgists, the most interesting of all superalloys [3]. They currently constitute over 50% of the weight of advanced aircraft engines. The principal characteristics of nickel as an alloy base are the high phase stability of FCC nickel matrix and the capability to be strengthened by a variety of direct and indirect means. Further, the surface stability of nickel is readily improved by alloying with chromium and/or aluminum [4].

The most prominent use is in the manufacture of gas turbines for use in commercial and military aircraft, power generation, and marine propulsion. Superalloys also find important applications in the oil and gas industry, space vehicles, submarines, nuclear reactors, military electric motors, chemical processing vessels, and heat exchanger tubing [5]. Several generations of superalloys have been developed, each generation tending to have higher temperature resistance [6]. The latest generations of superalloys incorporate expensive alloying metals such as rhenium and ruthenium to achieve the desired characteristics.

Because of this, the cost of some new super alloys can be five times more expensive than high-quality turbine steel. The outlook is for considerable growth in usage in these areas, in particular as the aircraft manufacturing and electrical power generation industries grow. However, the high cost of some of the alloying metals used along with nickel in superalloys may be a constraint to usage. For example, rhenium currently (March 2013) trades at about $4200 per kilogram and ruthenium at $65 to 85 per ounce.

A listing of some of nickel-based superalloys, with information on their composition and some of the uses is provided here:

o Inconel Alloy 600 (76Ni-15Cr-8Fe) is a standard material of construction for nuclear reactors, also used in the chemical industry in heaters, stills, evaporator tubes and condensers,

o Nimonic alloy 75 (80/20 nickel-chromium alloy with additions of titanium and carbon) used in gas turbine engineering, furnace components and heat-treatment equipment,

o Alloy 601. Lower nickel (61%) content with aluminium and silicon additions for improved oxidation and nitriding resistance chemical processing, pollution control, aerospace, and power generation,

o Alloy X750. Aluminium and titanium additions for age hardening. Used in gas turbines, rocket engines, nuclear reactors, pressure vessels, tooling, and aircraft structures,

o Alloy 718. (55Ni-21Cr-5Nb-3Mo). Niobium addition to overcome cracking problems during welding. Used in aircraft and land-based gas turbine engines and cryogenic tankage,

o Alloy X (48Ni-22Cr-18Fe-9Mo + W). High-temperature flat-rolled product for aerospace applications,

o Waspaloy (60Ni-19Cr-4Mo-3Ti-1.3Al). Proprietary alloy for jet engine applications,

o ATI 718Plus. A lower cost alloy which exceeds the operating temperature capability of standard 718 alloy by 100 Fº (55 Cº) allowing engine manufacturers to improve fuel efficiency,

o Nimonic 90. (Ni 54% min Cr 18-21% Co 15-21% Ti 2-3% Al 1-2%) used for turbine blades, discs, forgings, ring sections and hot-working tools,

o Rene' N6. (4Cr-12Co-1Mo-W6 -Ta7- Al5.8 - Hf 0.2 - Re5- BalNi) 3rd generation single crystal alloy used in jet engines,

o TMS 162 (3Cr- 6Co-4Mo-6W-6Ta-6Al-5Re-6Ru-balance Ni) 5th generation single crystal alloy for turbine blades.

2.3 Cobalt-based Superalloys

Nickel-based superalloys have limitations at very high temperatures, and so components in the combustion chamber, where the temperature may reach as high as 1100℃, are usually made of cobalt-based alloys.

The cobalt-based superalloys (Table 2) are not as strong as nickel-based superalloys, but they retain their strength up to higher temperatures. They derive their strength largely from a distribution of refractory metal carbides (combinations of carbon and metals such as Mo and W), which tend to collect at grain boundaries (Figure 1). This network of carbides strengthens grain boundaries and alloy becomes stable nearly up to the melting point. In addition to refractory metals and metal carbides, cobalt superalloys generally contain high levels of Cr to make them more resistant to corrosion that normally takes place in the presence of hot exhaust gases. The Cr atoms react with oxygen atoms to form a protective layer of Cr_2O_3 which protects the alloy from corrosive gases. Being not as hard as nickel-based superalloys cobalt superalloys are not so sensitive to cracking under thermal shocks as other superalloys. Co-based superalloys are

therefore more suitable for parts that need to be worked or welded, such as those in the intricate structures of the combustion chamber.

Alloy	C	Mn	Si	Cr	Ni	Mo	W	Fe	Co
X-45	0.25	.5	0.9	25	10	-	7.5	<2	Bal.
X-40	0.5	.5	0.9	25	10	-	7.5	<2	Bal.
FSX-414	0.35	.5	0.9	29.5	10	-	7.5	<2	Bal.
WI-52	0.45	.4	0.4	21	-	-	11	2	Bal.
Haynes -25	0.1	1.2	0.8	20	10	-	15	<3	Bal.
F-75	0.25	.5	0.8	28	<1	6	<.2	<0.75	Bal.
Haynes Ultimet	0.06	.8	0.3	25	9	5	2	3	Bal.
Co 6	1.1		0.8	29	<3	<1.5	5.5	<3	Bal.

Table 2: Chemical Composition of Some Cobalt-Based Superalloys.
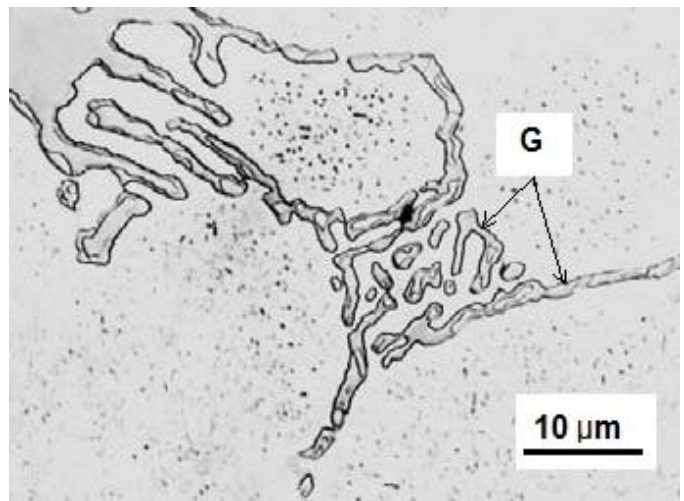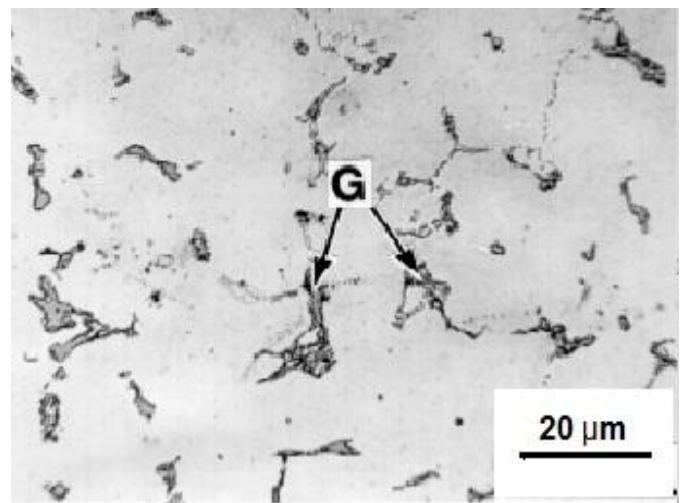

Figure 1: Optical micrograph of Haynes-25. G-mainly M6C carbides.

3 Application of Superalloys

The high-temperature applications of superalloys are extensive, including components for aircraft, chemical plant equipment, and petrochemical equipment [7,8].

Besides that superalloys are widely used in Aerospace and Marine industries, Nuclear reactors, heat

exchanger tubing, and industrial gas turbines. Figure 2 shows the F119 engine, which is the latest in a series of military engines to power high-performance aircraft. The gas temperatures in these engines in the hot sections (rear areas of the engine) may rise to levels far above 2000°F (1093℃). Cooling techniques reduce the actual component metal temperatures to lower levels, and superalloys that can operate at these temperatures are the major components of the hot sections of such engines [9].

The significance of superalloys in today's commerce is typified by the fact that, whereas in 1950 only about 10% of the total weight of an aircraft gas turbine engine was made of superalloys, by 1985 this figure had risen to about 50%. Table 3 lists some current applications of superalloys. It will be noted, however, that not all applications require elevated-temperature strength capability. Their high strength coupled with corrosion resistance has made certain superalloys standard materials for biomedical devices. Superalloys also find use in cryogenic applications.

Applications of superalloys are categorized below; the bulk of tonnage is used in gas turbines:

o *Aircraft gas turbines*: disks, combustion chambers, bolts, casings, shafts, exhaust systems, cases, blades, vanes, burner cans, afterburners, thrust reversers
o *Steam turbine power plants*: bolts, blades, stack gas re-heaters
o *Reciprocating engines*: turbochargers, exhaust valves, hot plugs, valve seat inserts
o *Metal processing*: hot-work tools and dies, casting dies
o *Medical applications*: dentistry uses, prosthetic devices
o *Space vehicles*: aerodynamically heated skins, rocket engine parts
o *Heat-treating equipment*: trays, fixtures, conveyor belts, baskets, fans, furnace mufflers
o *Nuclear power systems*: control rod drive mechanisms, valve stems, springs, ducting
o *Chemical and petrochemical industries*: bolts, fans, valves, reaction vessels, piping, pumps
o *Pollution control equipment*: scrubbers
o *Metals processing mills*: ovens, afterburners, exhaust fans
o *Coal gasification and liquefaction systems*: heat exchangers, re-heaters, piping.

3.1 Aero and land turbines

Cobalt superalloys are well-suited to high temperature creep and fatigue resistant non-rotating applications where stress levels are lower than for rotating components. For this reason, turbine vanes and other static non-rotating components are frequently designed in cobalt alloys [10]. A somewhat lower coefficient of thermal expansion and better thermal conductivity than the nickel superalloys make cobalt alloys good candidates for applications where thermal fatigue is a critical design issue. Due to long service life requirements, land based casting specifications are becoming progressively more stringent (more rigorous than for similar aero counterparts in some cases).

3.2 Surgical implants

The alloy under the proprietary name Vitallium has been known since the '30's of the last century. Today, this alloy is used for orthopaedic implants, most notably as artificial hips and knees. The alloy is generically referred to by its ASTM designation F-75 and contains 29% Cr and 6% Mo. While the ASTM specification limits carbon to 0.35%, implant manufacturers have opted for lower levels of carbon and an intentional alloying with nitrogen. This addition of nitrogen has allowed Co-Cr-Mo alloy to achieve high levels of strength with good ductility and without sacrificing corrosion resistance and bio-compatibility. Co-Cr-Mo implants may be produced by casting, forging or powder metallurgy technology.

3.3 Gas Turbine Engines

Superalloys are commonly used in gas turbine engines in those areas of the engine that are subject to high temperatures and which require high strength, excellent creep resistance, as well as corrosion and oxidation resistance. In turbine engines this is in the high pressure turbine where blades can face temperatures approaching if not beyond their melting temperature [11,5]. New jet engines are more efficient because of higher operating temperatures, requiring higher-performing components. The use of super alloys can allow the operating temperature to be increased from 1200°F to 1300°F. Besides increasing efficiency and power output, higher temperatures result in reduced emissions because the combustion cycle is more complete [12,13]. The diagram below shows the areas within a jet engine where nickel-based super alloys are used i.e. the hottest, highest pressure zones.
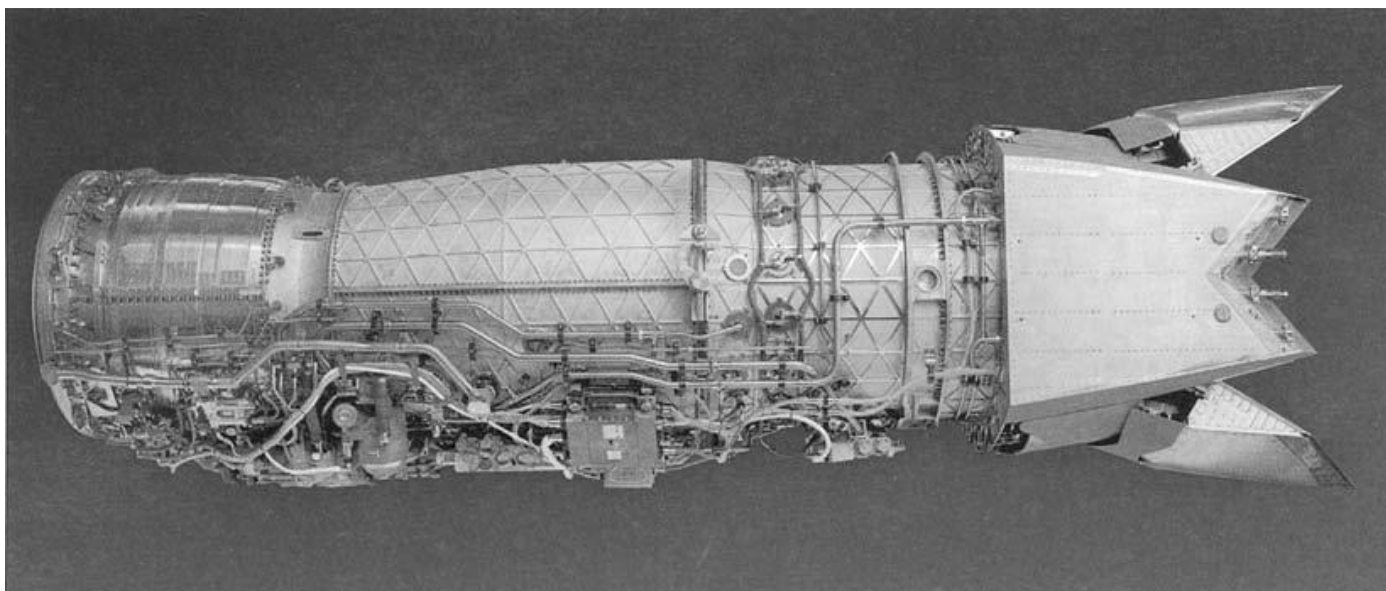
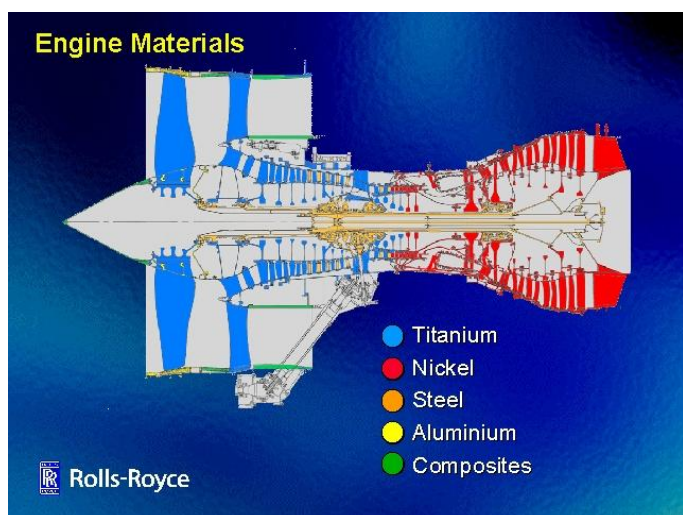*Figure 2: F119 gas turbine engine; a major user of superalloys.*

Figure 3:commonly used materials in gas turbine engine components.

3.4 Oil and Gas industry

Nickel-based superalloys are increasingly finding applications in the oil and gas sector. The environments encountered in oil and natural gas production are frequently corrosive and challenging. Often significant levels of hydrogen sulfide, carbon dioxide, chlorides, and free sulfur are present. In some of these environments high pressure and temperatures up to 450°F (232°C) can be encountered. Processing of oil and natural gas under these environmental conditions requires special materials. Nickel-base alloys 718, 725, and 925 are commonly used in oil and natural gas production. These alloys contain chrome and molybdenum which aid in resisting corrosion. Alloy 718 was initially developed for use in aerospace and gas turbines, but has become the preferred material for the manufacture of wellhead

components, auxiliary and down-hole tools, and sub-surface safety valves [14].

4 Processing of Superalloys

Superalloy processing begins with the fabrication of large ingots that are subsequently used for one of three major processing routes: 1) remelting and subsequent investment casting, 2) remelting followed by wrought processing, or 3) remelting to form superalloy powder that is subsequently consolidated and subjected to wrought processing operations [9]. Ingots are fabricated by vacuum induction melting (VIM) in a refractory crucible to consolidate elemental and/or revert materials to form a base alloy. Although selected alloys can potentially be melted in air/slag environments using electric arc furnaces, VIM melting of superalloys is much more effective in the removal of low-melting-point trace contaminants. Following the vaporization of the contaminants, the carbon boil reaction is used to deoxidize the melt before the addition of the reactive forming elements such as Ti, Al, and Hf. Once the desired alloy composition of the VIM ingot is attained, the solidified ingot is then subsequently subjected to additional melting or consolidation processes that are dependent upon the final application of the material. Charge weights of VIM ingots may range from ~2500 kg to in excess of 27,500 kg [15].

Considering the stringent requirements for minimizing defects in gas industry and turbines etc, a detailed understanding of structure evolution in each of these processing paths is essential. In the following sections, we briefly review the processing approaches

and aspects of superalloy structure that influence properties of superalloys [16].

4.1 Cast Superalloys

Investment casting is the primary casting process for fabrication of superalloy components with complex shapes, including blades and vanes. Ceramic molds containing alumina, silica, and/or zirconia are utilized in this process (Figure 4). The molds are fabricated by progressive buildup of ceramic layers around a wax pattern of the cast component. Ceramic cores can be embedded in the wax to obtain complex internal cooling structures. A thermal cycle removes the wax, and the mold is filled with remelted superalloy in a preheated vacuum chamber to obtain a shaped casting. The single-use mold is removed once the alloy has cooled to room temperature. Castings may be equiaxed, columnar grained, or single crystal. Equiaxed castings solidify fairly uniformly throughout their volume, whereas columnar and single-crystal castings are withdrawn from a hot zone in the furnace to a cold zone at a controlled rate. Following initial solidification, castings are subjected to a series of subsequent heat-treatment cycles that serve to reduce segregation, establish one or more size populations of γ' precipitates, modify the structure of grain boundary phases (particularly carbides), and/or assist in the application of coatings.
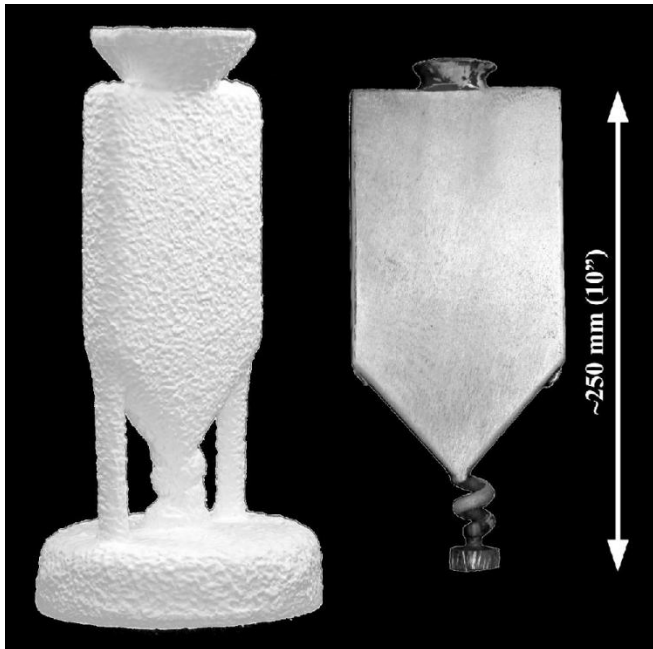

Figure 4: Ceramic investment casting mold with single-crystal starter at the bottom of the plate and single-crystal plate following directional solidification and removal of ceramic mold (courtesy of A. J. Elliott).

In all casting processes, the final structure (and therefore properties) of the material are sensitive to the thermal conditions present during solidification of the casting. Solidification is dendritic in character, and the primary and secondary dendrite arm spacings are dependent on cooling rate, $G*R$ (Figure 5). Associated with the dendritic solidification is segregation of the constituent alloying elements.
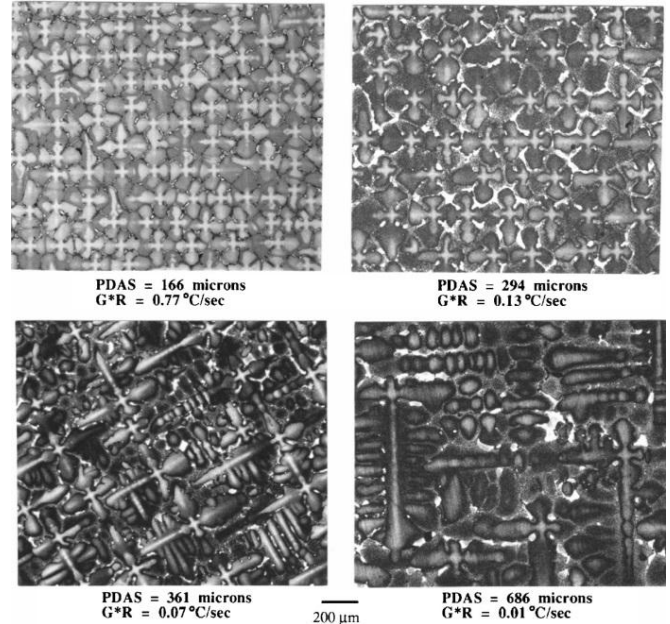

Figure 5: Variation in dendrite morphology and primary dendrite arm spacing (PDAS) with cooling rate (G*R) during solidification.

4.2 Wrought Superalloys

As mentioned previously, wrought alloys are typically fabricated by remelting of VIM ingots to form a secondary ingot or powder for subsequent deformation processing. A secondary melting process is necessary for wrought alloys because the high-temperature structural properties of Ni-based superalloys are very sensitive to microstructural variations, chemical in homogeneities, and inclusions. As ingot sizes increase, VIM melting often results in macro segregation or the formation of large shrinkage cavities during solidification. The formation of these solidification defects is caused by large-scale solute segregation associated with dendritic solidification under low thermal gradients. Because heat transfer during solidification of VIM ingots is limited by the low intrinsic thermal conductivity of the solidifying mass, large ingots are very prone to the formation of these features. Thus other secondary melting processes are utilized, including vacuum arc remelting (VAR), electro-slag remelting (ESR), and electron beam cold hearth refining (EBCHR) [17]. Here, only the more common VAR process is discussed in the context of avoiding property-reducing defects.
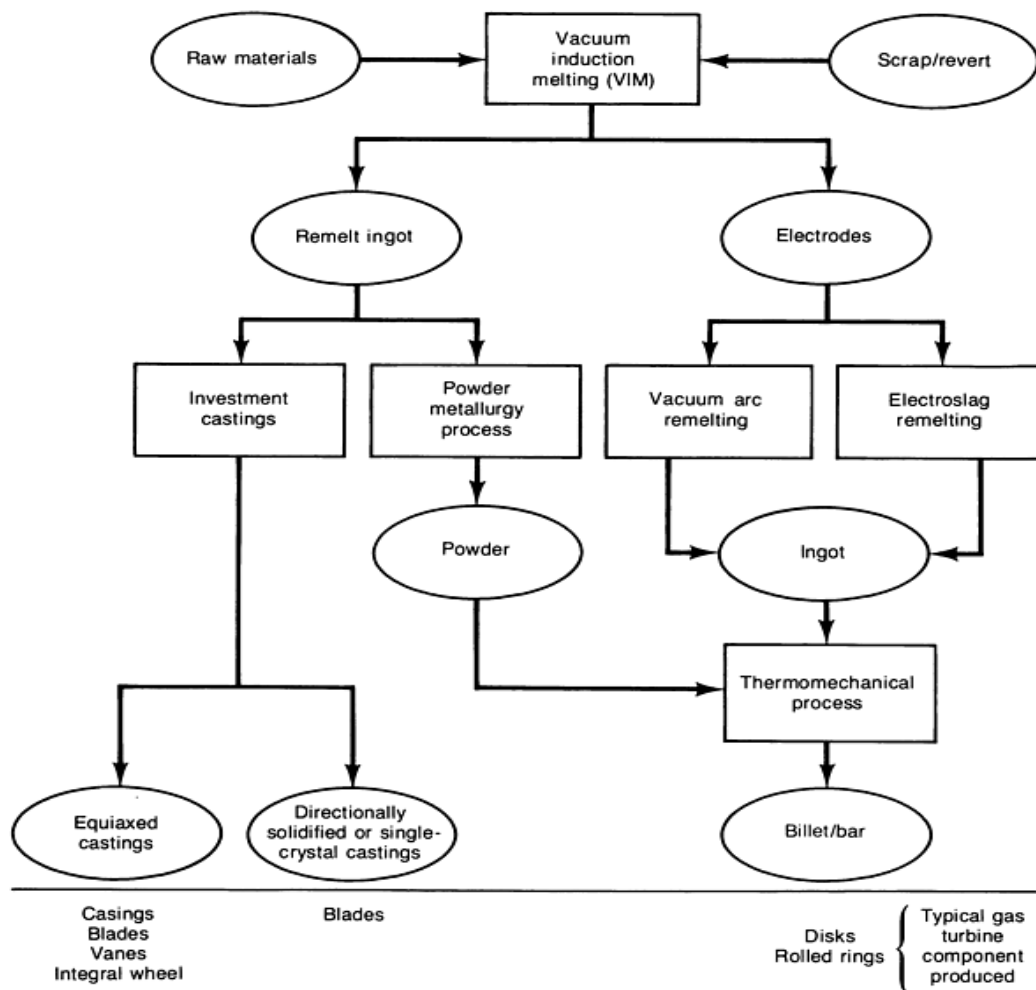
Figure 6: Flow diagram of processes widely used to produce superalloy component.

4.2.1 Melting and Consolidation of Wrought Alloys

Superalloy ingots must be melted and cast with due regard for the volatility and reactivity of the elements present. Vacuum melting processes are a necessity for many nickel- and iron-nickel-base alloys because of the presence of aluminum and titanium as solutes. Cobalt-base alloys, on the other hand, do not usually contain these elements and, therefore, may be melted in air.

4.2.2 Melt Processes

The traditional processes used to produce superalloy components are identified in Figure 6.

The VIM process produces liquid metal under vacuum in an induction-heated crucible. It is used as a primary melting step in the route to producing wrought and cast products, as well as near-net shape. Before being melted, the raw material can be refined and purified and its composition can be controlled. Vacuum induction melting has been widely used in the manufacture of superalloys, which must be melted under vacuum or in an inert gas atmosphere because of their reactivity with atmospheric oxygen and nitrogen.

The VAR process, a secondary melting technique, converts VIM-processed electrodes into ingots whose chemical and physical homogeneity have been significantly improved. In this process, a stub is welded to one end of an electrode, which is then suspended over a water-cooled copper crucible. Next, an arc is struck between the end of the electrode and the crucible bottom. Maintaining the arc generates the heat required to melt the electrode, which drips into the crucible and can subsequently be poured into molds. Many inclusions can be removed by flotation or a chemical and physical processes before the molten material solidifies.

The ESR process, another secondary melting technique, may appear to be similar to the VAR process, but there are a number of differences. Remelting does not occur by striking an arc under vacuum. Instead, an ingot is built up in a water cooled mold by melting a consumable electrode that is immersed in a slag, which is superheated by means of resistance heating. Rather than

operating in a vacuum, the process is conducted in air under the molten slag. During melting, metal droplets fall through the molten slag, and chemical reactions reduce sulfur and nonmetallic inclusions. Both ESR and VAR processes allow directional solidification of an ingot from bottom to top, yielding high density and homogeneity in its macrostructure, as well as an absence of segregation and shrinkage cavities.

4.3 Powder Metallurgy Superalloys

To increase the strength of polycrystalline Ni-based superalloys, levels of refractory alloying additions and γ'-forming elements have gradually increased to levels that make conventional processing routes deficient [18]. Elements such as W, Mo, Ti, Ta, and Nb effectively strengthen the alloy but also result in severe segregation within the ingot upon solidification. Additionally, the limited ductility of the high-strength alloys renders the ingot susceptible to cracking as thermally induced stresses evolve during cooling. Powder-processing routes have been developed to overcome the difficulties associated with melt-related defects and are viable for the production of advanced high-strength polycrystalline superalloy components. Listed in Table 1 are the compositions of some commercially available powder-processed Ni-based superalloys [19].

Powder processing begins with gas or vacuum atomization of a highly alloyed VIM ingot. Rapid solidification of the fine powders effectively suppresses macro segregation within the alloy. Because the low ductility associated with the corresponding high strength causes many of these advanced superalloys to be very sensitive to initial flaw sizes, the atomized powders are separated based on particle size. Standard 150 or 270 meshes are used to separate the powders into sizes$>100\mu$mand$>50\mu$m respectively. Powder sizes directly influence the initial potential crack size present in the finished component. Although finer powder sizes are desired to minimize initial defect sizes, costs increase substantially as yields are substantially reduced.

Once powders are collected into steel cans, the cans are evacuated under vacuum and sealed. The cans are then hot isostatically pressed (HIP) or extruded to consolidate the powder. The HIP process consists of heating the alloy to just below the γ'solvus temperature under a hydrostatic pressure of up to 310MPa. After 4 to 5 h, diffusion bonding and sintering of the powders under pressure yields a fully dense superalloy billet. Billet sizes are limited by the capacity of the HIP furnace; however, systems capable of forming billets up to 150 cm in

diameter and 300 cm in height are available. Consolidation under hot extrusion is often preferred over HIP because of the ability to produce fine-grained structures (ASTM 12) and reduce effects associated with prior particle boundaries. The evacuated can containing the superalloy powder is hot extruded through a set of dies that greatly reduces the diameter. During this thermomechanical process, the individual powder particles are subjected to deformation and any oxide films initially present on the surfaces of the powder are broken up. Because substantial plastic deformation and adiabatic heating occurs during this process, hot extrusion temperatures are selected such that temperatures are maintained below the γ' solvus temperature.
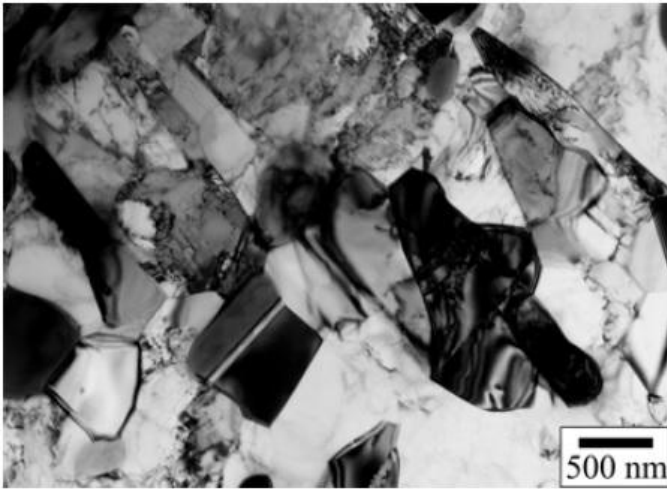
5 Investigation of IN718 Superalloy

Inconel 718 (IN718) is the most frequently used nickel based superalloys; hence this paper is also focused on an investigation into the microstructureand mechanical properties Inconel 718. Some of the applications of nickel based superalloys are in aircraft gas turbines (eg. disks, combustion chamber, casings, shafts, exhaust system, blades, vanes, burner, cans, stack gas reheaters), reciprocating engines (eg. turbochargers, exhaust valves hot plugs, valve seat inserts), metal processing (eg. hot work tools and dies), space vehicles (eg. Aerodynamically heated skins, rocket engine parts) heat treating equipments (eg. trays, fixtures, conveyor belts, baskets, fans, furnace mufflers), nuclear power plants, chemical and petrochemical industries and heat exchangers.

In nickel-iron superalloy Inconel 718, ultra-negrain and NS states allow the fabrication of components by superplastic deformation at higher strain. Components operating at elevated temperatures are subjected to heat treatment to have strengthening coherent disperse particles of second phase precipitated. Mechanical properties of NS Inconel 718 are reported elsewhere [20]. But the data on mechanical properties of NS Inconel 718 after heat treatment are missing, and that is why such results are important.

5.1 Initial Microstructure of IN718

Multiple isothermal forging (MIF) of bulk samples from investigated alloy carried out to various strains resulted in the formation of MC and NS states with mean grain sizes: 1 mm and 0.08 mm (figure7). The TEM and SEM [21] studies have shown that the duplex structure consists of g-phase and high temperature modification of

Ni3Nb - δ -phase. Plates of δ -phase with non-coherent boundaries are distributed uniformly. The NS state is characterized by higher dislocation density and non-equilibrium γ / γ boundaries [22]. Carbides with a mean size of 5 μ m are present.

(a)
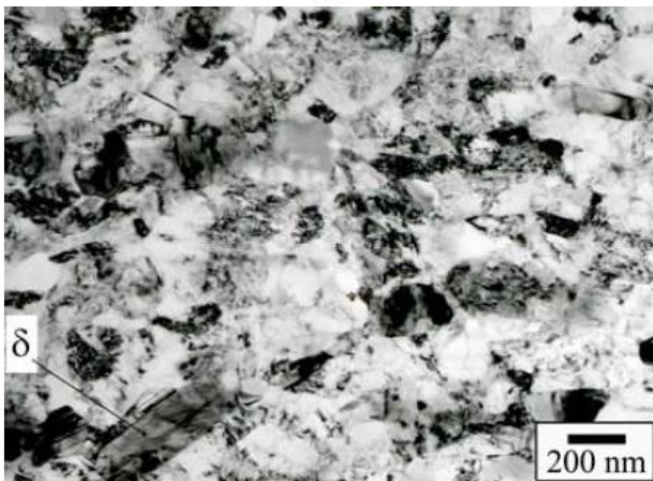
(b)

Figure 7: TEM image of Inconel 718 produced byMIF with mean grain size: (a)-1 μm; (b)- 0.08 μm.

5.2 Micrographs of Superalloys

IN718 nickel-based superalloy is investigated in using reflected light microscope with Nomarski filter, and the material is held for 20 minutes, 6 hours, and 72 hours at 850°C.In figure 8, the micrograph shows that no precipitation has occurred [23,24]. It can be seen that small y'' precipitates have precipitated out within the matrix [25]. In figure 9, the volume fraction of d is greater than when held for shorter periods of time. In figure 10, the long precipitates are seen to have become more spheroidal than after shorter periods.
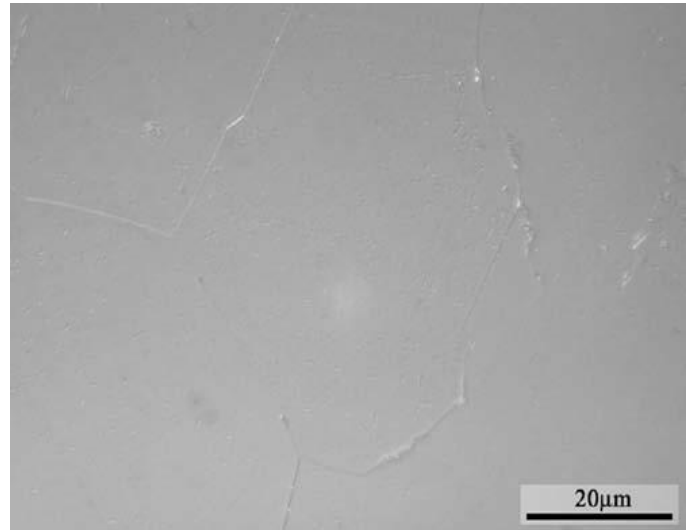

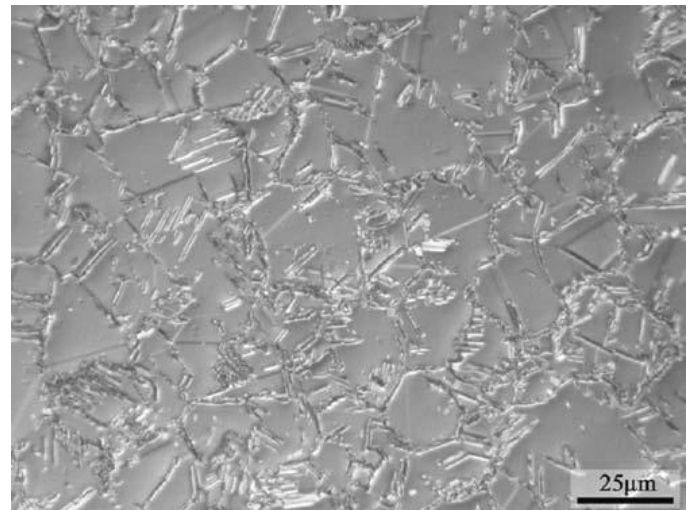*Figure 8: IN718 nickel-based superalloy held for 20 min at 850℃.*

Figure 9: IN718 nickel-based superalloy held for 6 h at 850℃.
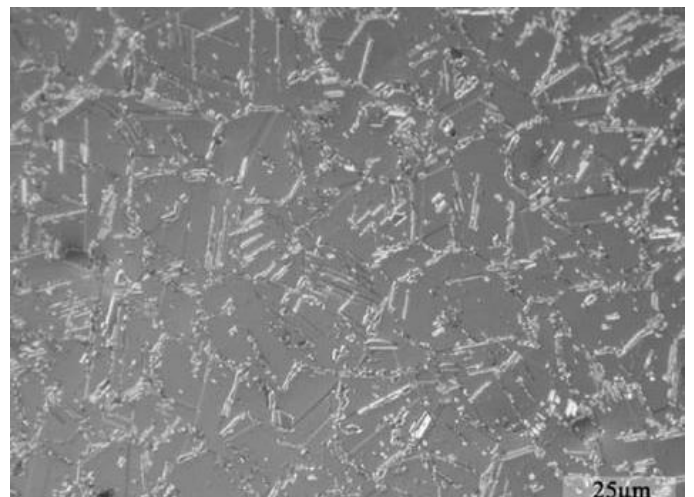

Figure 10:IN718 nickel-based superalloy held for 72 h at 850℃.

5.3 Mechanical properties of alloy after MIF at room temperature

According to the Hall-Petch relationship the strength of metals and alloys increases with decreasing grain size [26]. Tensile properties of Inconel 718 after MIF with various grain sizes are shown in table 3. The NS ($\gamma+\delta$) alloy exhibits very high room temperature strength, which is much higher than that of the ($\gamma+\gamma´´$) alloy subjected to the strengthening thermal treatment. At the same time, increase in strength of this alloy in a NS state is accompanied by some reduction of ductility.

Grain size (μm)	Phases	Ultimate strength (MPa)	Yield strength (MPa)	El (%)	RA (%)
-	$\gamma+\gamma´´$	≥1276[a]	≥1034	≥12	≥15
1[b]	$\gamma+\delta$	1184	920	21.9	22.2
0.3[b]	$\gamma+\delta$	1560	1300	5.1	11.0
0.08[b]	$\gamma+\delta$	1920	1845	4.8	6.1

*Table 3: Mechanical properties of alloys after MIF at room temperature.*

The data on mechanical properties of the heat treated alloy are presented in table 4. These data evidently correspond to the material specification requirements. It is obvious that the initial nanostructure leads to maximum strength for the alloy at room temperature.

## 5.4 Mechanical properties after heat treatment

The studies on microstructure after carrying out the standard heat treatment [27] of MC and NS alloys showed that it resulted in the generation of uniform structure, the average grain sizes of g-phase being 3.9 and 4.6 μm, accordingly. The difference of initial structural states is inherited after carrying out thermal treatment. From figure 11 it is evident that after heat treatment (HT) some quantity of globular δ-phase is present in grain boundaries, which retards grain growth during annealing. Volume fraction of δ-phase is 2.9% for MC state after heat treatment and 3.3% for NC state.

State	Ultimate strength (MPa)	Yield strength (MPa)	El (%)	RA (%)	Grain sizes (μm)	Fatigue strength (MPa)	Fatigue strength (Cycles)
AMS 5662[a]	≥1276/1000[b]	≥1034/862	≥12/12	≥15/15	-	-	-
CG+HT[a]	1428/1176	1180/976	19/18	20/32	11-22	910	10[5 c]
MC+HT	1488/1169	1234/995	17/23	23/45	4.6	910	>1.6·10[
NS+HT	1520/1164	1252/993	19/21	35/42	3.9	910	>1.6·10[

Table 4: Mechanical properties of Inconel 718 after MIF and heat treatment.
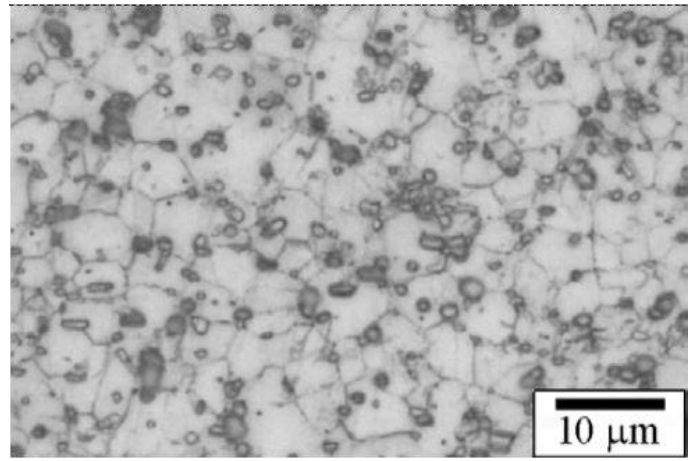
(a) _ MC+HT
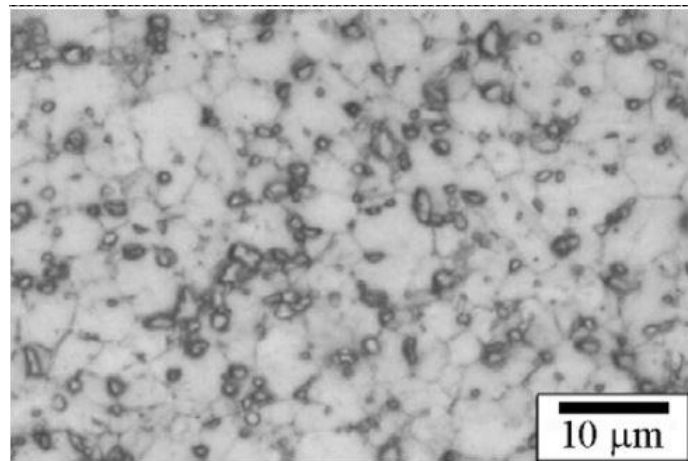
(b) _ NS+HT

Figure 11: Microstructure of Inconel 718 after MIF and heat treatment: (a), (b)

Comparative fatigue tests of the samples at room temperature have shown that the properties of NS alloy on the scale of 10^5 cycles are higher by the factor of 1.6 than those stipulated elsewhere [28]. Stress rupture data shown in table 5 indicate that with decreasing a mean grain size of γ-phase one observes the tendency towards decrease of stress rupture and increase of ductility. All presented conditions meet the material specification requirements.

State	Stress (MPa)	Time (hrs)	El (%)	RA (%)
AMS 5662	689	≥23	≥4	-
MC+HT	710	29.8	20.2	61.0
NS+HT		27.0	25.3	73.5

Table 5: Stress rupture data at 650°C of Inconel 718 after MIF and heat treatment.

The investigation results show that for increasing alloy's strength properties at operating temperaturesit are appropriate to have d-phase totally dissolved in order to increase the quantity of strengthening $\gamma´´$-phase precipitates during aging.

6   Conclusion

A superalloy is a metallic alloy which is developed to resist most of all high temperatures, usually in cases until 70 % of the absolute melting temperature. All of these alloys have an excellent creep, corrosion and oxidation resistance as well as a good surface stability and fatigue life.[29]

The main alloying elements are nickel, cobalt or nickel – iron, which can be found in the VIII. group of the periodic system of the elements. They are mostly used in aerospace and nuclear industry, e.g. engines. The development of these advanced alloys allows a better exploitation of engines, which work at high temperatures, because the Turbine Inlet Temperature (TIT) depends on the temperature capability of the material which forms the turbine blades. Nickel-based superalloys can be strengthened through solid-solution and precipitation hardening [30].

Nickel-based superalloys can be used for a higher fraction of melting temperature and are therefore more favorable than cobalt-based and iron-nickel-based superalloys at operating temperatures close to the melting temperature of the materials.

The newly investigated IN718 nickel-based superalloy which is the last version of Inconel 718 has been proceeding in the way to become a material that aerospace and defense industries never replace of any other material with combining its good mechanical properties, easy machinability and low cost.[31] With decreasing grain size to NS state of alloy 718 occurs a significant increase of strength properties at room temperature, in particular ultimate strength increased up to 1920 MPa. It is highly appropriate to employ NS Inconel 718 after heat treatment when it possesses high strength and sufficient ductility. For increasing service life of NS Inconel 718 components it is reasonable to develop a special heat treatment.

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Ultrasonic welding of dissimilar materials: A review

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Abstract

During the last few years ultrasonic welding has become significant attention regarding its suitable applications in comparison to traditional welding techniques. Bonding of dissimilar materials has always been a challenging task due to poor control on grain size and sensitive mechanical properties that could have been made by joining with traditional welding techniques. Moreover, joining dissimilar materials such as Aluminum/steel, metal/glass, Aluminum/copper had not been achieved without the usage of ultrasonic welding technique. This work presents a review of literature regarding the usage of ultrasonic welding technique in many applications. Additionally, this paper provides different examples and applications of ultrasonic welding technique and its application. Main advantages of this technique are, clean and undamaged exterior parts of weld, power savings, stable and strong bond, time efficiency

Keywords: ultrasonic welding (USW), dissimilar materials

1. Introduction

Ultrasonic welding is a joining process where high frequency vibrations are produced and converted into energy that is applied on work pieces that are held together under pressure. Energy produced as a product of vibrations is joining pieces of materials together but without melting. Ultrasonic welding provides high quality joint between similar and dissimilar materials. The joint is made in two ways either materials are deformed or diffused and deformed together in order to join them and produce high quality weld. Commonly, polymers are welded with ultrasonic technique, however, dissimilar materials are welded with this technique too. Main reason why nowadays similar and dissimilar materials are bonded ultrasonically is because it does not damage the base material. Bonding occurs with melting but the melting is not that high to cause breakage of materials. USW is suitable for non-ferrous soft metals and their alloys such as aluminum, copper, brass, silver and gold. [1] However, it is also suitable technique for joining metals such as titanium, nickel and their dissimilar combinations such as Aluminum/steel, metal/ceramic, metal/glass, Aluminum/copper. [2] This paper focuses mainly on the usage of the ultrasonic welding technique for joining disimilar materials and it applications regarding electronic, airspace, medical industry and automotive industry.

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2. Theoretical background

The ultrasonic welding process consists of five major components: power supply (providing electrical energy at high freuency), piezoelectric transducer (part that converts electrical energy into mechanical vibrations), wedge that amplifies mechanical work, sonotrode (enchances the amplitude of mechanical vibrations), and pneumatic cylinder that provides clamping pressure during welding. [3] In USW two system configurations are used wedge reed and lateral derive. Wedge reed system is more useful for joining of sheets with large thickness due to that anvil acts as vibrating part and resonates out of phase to the reed. Lateral derive system is simple and it gives good results for thin specimens due to its lower rigidity. Main parameters during USW process dependant on each other are vibration amplitude, clamping force, power, frequency, energy and time. Mostly euipment available for USW ranges from 15-75kHz. Nowadays, commonly used is 20 kHz since at this frequency very high strain rates (of order of 10^3-10^5s^{-1}) and strains can be developed in a fraction of a second during the shearing of micron-sized asperities between welded samples. [4]

3. Applications and usage of ultrasonic welding

3.1 Use of ultrasonic welding on $Cu_{54}Zr_{22}Ti_{18}Ni_6$ bulk metallic glass

A $Cu_{54}Zr_{22}Ti_{18}Ni_6$ bulk metallic glass has been produced by two proceses by arc melting and roll melthod that had to be further joined by ultrasonic wleding. A bulk metallic glass of dimension 15mm x 15 mm x 1mm was joined by the by sonotrode that exerts a normal pressure of 80 N with the vibration time from 0.3 s to 4.0 s under constant frequency of 20 kHz. Figure 1 shows the morphologies and microstrucure of work pieces with respect to different vibration times. The cross-section of the work piece of bulk metallic glass is described by upper plate morphology and interfacial morphology. The welded interface is discontinously welded after 0.3 s, thus, the optimum time for welding the bulk metallic glass is 1.0 s for vibration frequency of 20 kHz and exerted normal pressure of 80N. The thickness of upper bulk metallic glass significantly decreased after 1.0 s, and more after 4.0 s. The exerted force has been set constant to be 80 N for all pieces of bulk metallic glass. The morphological change occured due to the change in mechanical properties of the bulk metallic glass workpiece. Heat that was supplied and transferred during ultrasonic welding process increased the temperature and has been transfered to the bulk materials through conduction. Increase in the heat supplied with the respect to time came as a result in increasing the temperature in bulk metallic glass workpiece that lead to its crystalization temperature. The experiment has proven that by using normal pressure of 80N and time duration of vibration of 1 s and frequency of 20kHz has been welded 1 mm thich without any evidence of crystalization. The molecular strucuture
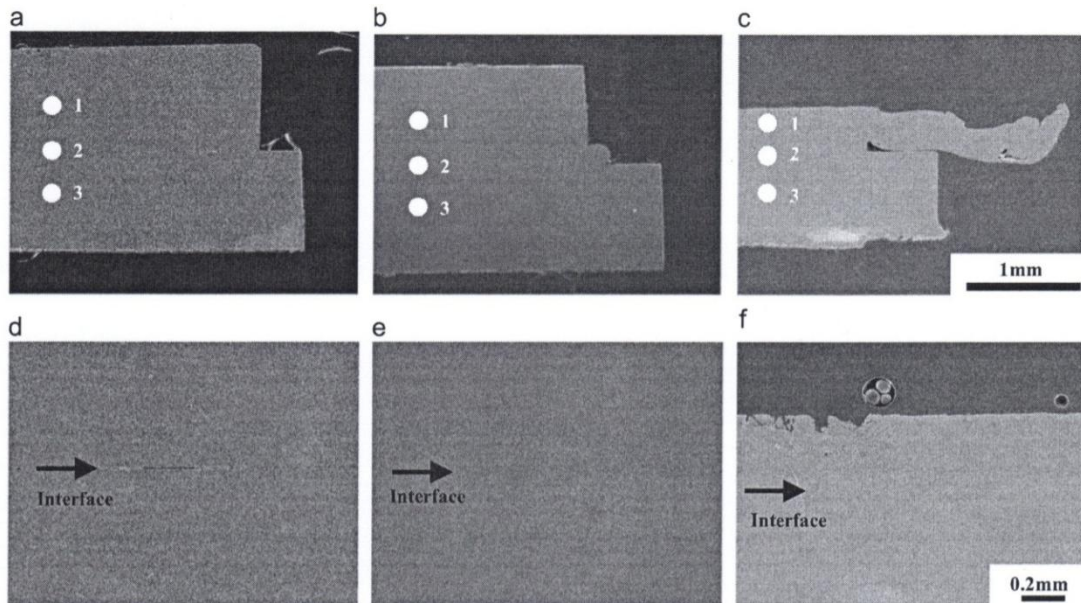
Figure 1: Cross-sectional morphologies and microstructures of joining workpieces with respect to time: (a) and (d) duration of vibration 0.3 s, (b) and (e) duration of vibration is 1.0 s, (c) and (f) is 4.0 s [6]

of the $Cu_{54}Zr_{22}Ti_{18}Ni_6$ bulk metallic glass has not been changed nor destroyed making it perfectly to be used in terms of developing further nanocomposites for electronic applications. [5]

3.1.1 Use of ultrasonic welding of 3003 Aluminium with 304 Stainless steel alloy

The ultrasonic welding process has been applied between two dissimilar materials 3003 Aluminium alloy of 300 m and Stainless steel alloy foil of 50 m with 2.4 kW ultrasonic device. The experiment included welding tip of 8x6 mm attached to sonotrode as shown in figure 2. The workpieces were cut in length paralle to dimension of 25 x 100 mm² and welded using 25 mm overlapping. Amplitude of vibration was 58 m. Power of the ultrasonic device was 2.4 kW and energy varied in range of 75 to 200J under different pressures. [7]
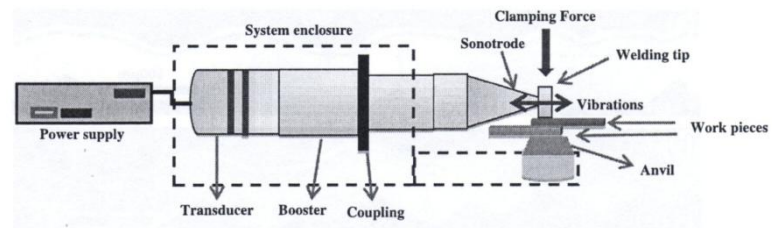

Figure 2: Schematic diagram for ultrasonic welding process device [8]

Figure 3(a) shows the microstructure of 3003 Aluminum. When the ultrasonic process is applied the external side of 3003 Aluminum experiences shear forces. In figure 3(b) the structure is similar to lower weld energy of 75 J. As the energy increased the recrystaliyation point emergend along the external surface of the 3003 Aluminum as shown in 3(c) and 3(d). The recrystalization apperead due to temperature differences.

To sum up, when the normal pressure of 30 psi was applied the strength of the bond was supplied with energy of 150 J. It has to be pointed out that as the
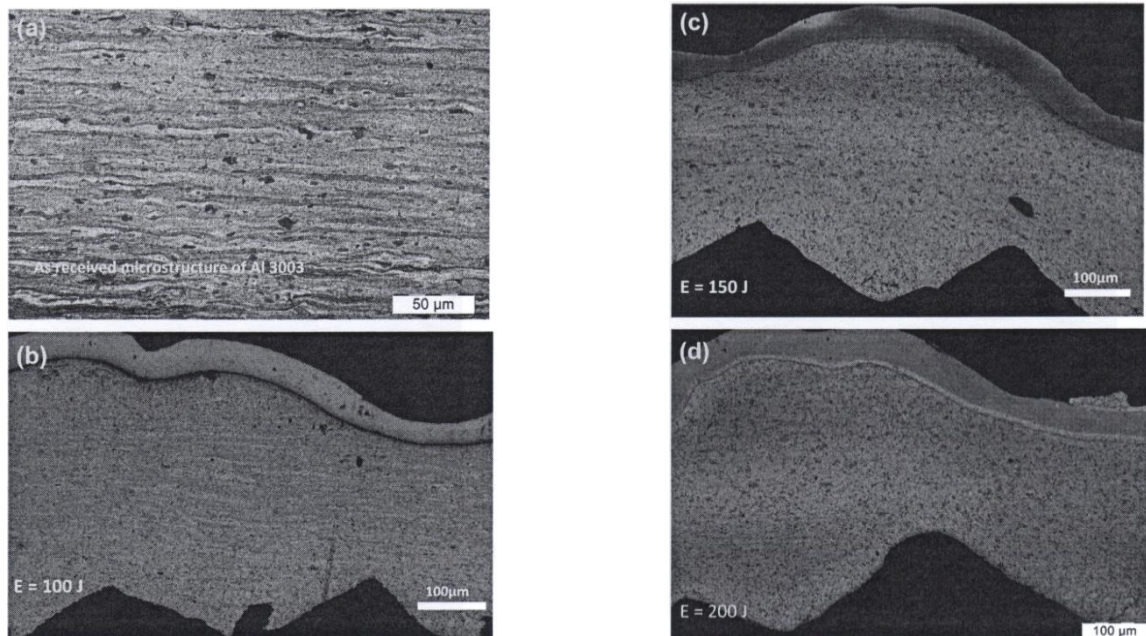
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Figure 3: Micrograph showing mictrostructure with different energies during ultrasonic welding [9]

normal pressure increases the strength of the weld can be sucessfully achieved at lower energy in shorter time period. Moreover, as the energy of welding increases thus the microstrucutre dissaperead and the weld recrystalized due to temperature differences. Additionally, the welding process performed with 125 J and 150 J energy shows the maximum tensile load and is characterized as a good weld as shown in. The good quality weld with maximum tensile strenght is achieved as a result of corresponding bond density is achieved. [10]

3.2 Ultrasonic welding of Al/Mg/Al tri layered clad sheets

Lightweighting has been regarded as a key strategy in the automotive and aerospace industries to improve fuel efficiency and reduce anthropogenic environment-damaging, climate-changing, human death-causing and costly emissions. [11-16] It has been reported that the fuel efficiency of passenger vehicles can be enhanced by 6–8% for each 10% reduction in weight [17]. Magnesium (Mg) alloy, as the lightest structural metallic material with a density of 30% less than aluminum and one fourth of steel, has been increasingly used in the transportation industry to reduce the weight of motor vehicles [11,12,18–22]. However, the concerns about poor corrosion resistance and low room-temperature formability of Mg alloys limit a widespread structural application in transportation industry [13–23]. Recently, roll cladding has been identified as a promising technique to improve the corrosion resistance and formability of Mg alloys [24–31]. In particular, Al-clad Mg alloy sheet can combine the corrosion resistance and formability of an Al alloy with the high strength-to-weight ratio of Mg substrate. Several studies have shown the successful cladding of Al on Mg alloy sheet using hot and cold rolling, which resulted in good surface corrosion resistance and improved formability [24,25,32].

Additionally, ultrasonic welding (USW) can be used to join Al/Mg/Al tri-layered clad sheets, in order to investigate weldability and identifying failure mode in relation to the welding energy. It was observed that the application of a low welding energy of 100 J was able to achieve the optimal welding condition during USW at a very short welding time of 0.1 s for the tri-layered clad sheets. The optimal lap shear failure load obtained was equivalent to that of the as-received Al/Mg/Al tri-layered clad sheets. With increasing welding energy, the lap shear failure load initially increased and then decreased after reaching a maximum value. At a welding energy of 25 J, failure occurred in the mode of interfacial failure along the center Al/Al weld interface due to insufficient bonding. At a welding energy of 50 J, 75 J and 100 J, failure was also characterized by the interfacial failure mode, but it occurred along the Al/Mg clad interface rather than the center Al/Al weld interface, suggesting stronger bonding of the Al/Al weld interface than that of the Al/Mg clad interface. The overall weld strength of the Al/Mg/Al tri-layered clad sheets was thus governed by the Al/Mg clad interface strength. At a welding energy of 125 J and 150 J, thinning of weld nugget and extensive deformation at the edge of welding tip caused failure at the edge of nugget region, leading to a lower lap shear failure load.

All in all, the resistance heat assisted ultrasonic welding technique (RUSW) were used. RUSW of 6061 aluminum to pure copper was investigated via comparison with the ultrasonic welding (USW) process when holding the welding parameters constant. The following conclusions were drawn:

1. Due to the synergistic effects of the ultrasonic energy and resistance heat, the peak power of ultrasonic vibration and the peak temperature of the weld interface are increased significantly in RUSW.

2. A thin, uniform, and continuous IMC layer was observed at the faying surface when the DC reached 1100 A. The IMC layer increases rapidly with increasing the DC values. As the DC increased to 1500 A, evidence of a solidified microstructure was observed at the weld interface. Both the EDS and XRD results confirm that the IMC layer is mainly composed of CuAl2.

3. The intermetallic reaction layer resulted in a good metallurgical bonding and increased the mechanical properties of the Al–Cu dissimilar joints. The lap shear load reached a maximum value of 550 N at the DC level of 1100 A, while for USW the maximum lap shear load was much lower (about 300 N) .

Copper and aluminum, with their high electrical and thermal conductivity, are preferred in the electronics industries and battery electric vehicles. Hence, a significant amount of Al–Cu joining is needed to transmit electricity. Unfortunately, joining of Al–Cu by conventional fusion welding methods is difficult due to poor weldability, high levels of distortion and rapid formation of bulk intermetallic compound (IMC). Therefore, solid-state welding methods, such as ultrasonic welding (USW) has

received much attention as alternative joining techniques for Al–Cu.[33]

3.3 Solid-state ultrasonic spot welding of SiCp/2009Al composite sheets

It has been challenging to join aluminum matrix composites (AMCs) using conventional fusion welding processes due to the occurrence of segregation and deleterious reactions between the reinforcement particles and liquid aluminum in the fusion zone. Development of robust welding processes to join AMCs thus holds the key in advanced lightweighting structural applications in the transportation sectors. The purpose of the study was to explore the weldability of AMCs via a solid-state welding technique – ultrasonic spot welding (USW). In this study 1.5 mm thick 17 vol.% SiCp/2009Al composite sheets in the annealing (O) and T6 conditions were subjected to USW, respectively, with the aim to demonstrate the welding feasibility of the composites. Microstructure, X-ray diffraction, microhardness and lap shear tensile tests were performed to evaluate the weld zone (WZ) characteristics in the USW joints. A characteristic band consisting of finer and denser crushed SiC particles that were uniformly embedded in the aluminum matrix was observed to occur in the WZ. The WZ of both types of joints had a much higher hardness than that of their respective base metal. The lap shear tensile fracture load increased with increasing welding energy and satisfied the requirement of AWS standard D17.2 for spot welding. [34]

To conclude, USW of 1.5-mm thick SiCp/2009Al–O and SiCp/2009Al–T6 composites was successfully achieved. Both types of welded joints exhibited higher volume fractions of SiC particles in WZ, creating a distinctive band-like structure consisting of crushed fine SiC particles uniformly embedded in the aluminum matrix. This was mainly attributed to the squeeze-out effect of softer Al during USW due to the severe shear strain rate caused by the high frequency vibration energy. The generation of h phase during the aging process of parent metal was re-confirmed by XRD. The peaks of XRD showed that volume fraction of h phase before and after welding remains same. The WZ of the joints had a much higher hardness than that of their respective base metal due to the presence of finer and denser crushed SiC particles. The 2000 J welded samples experienced higher hardness than that of 1000 J welded samples. This occurred because at higher welding energy, high frequency (20 kHz) ultrasonic vibration applies to the samples for longer period of time leads higher temperature, thus more Al being squeezed off in 2000 J energy input sample. The lap shear tensile fracture load increased as the welding energy increased, and the maximum lap shear tensile load of the USWed 2009Al–O/SiC and 2009Al–T6/SiC composites was obtained to be 3.1 and 4.5 kN, respectively, which fulfilled the requirements of AWS D17.2 standard.

4. Conclusion

All the studies have shown that USW technique satisfies criteria for joining

dissimilar materials with different thicknesses and composition strucutures. Moreover, the process ultrasonic welding is environmentally friendly since no flux material is required in order to join materials. In addition, energy used in ultrasonic welding is under 2000 watts and it is completed in less than a half second, meaning that it uses very little energy. This process does not change the internal structure of materials. Moreover, the duration of ultrasonic welding technique finishes very rapid and in short time intervals. It provides reliability in combining welding parameters. Joints produced by ultrasonic welding are stable, strong and the composition of disimilar materials is not damaged so the chemical structure stays constant throughtout. Moreover, energy consumption is low thus energy is saved.

Ultrasonic welding is extensively used in fileds of electronic, aerospace, automotive industry, medical industry since the chemical composition is not harmed nor changed and joints on microsclaes are able to be produced. For example, the most important thing in electronics industry is that the devices do not lose thermal and electrical conductivity. Thus, the USW technique ables the bonding of copper and aluminum and this technique does not damages these properties. Most commonly electronic part welded by USW technique are capacitors, electric motos, transformers, microcircuits, transistors, diodes.

With the usage of ultrasonic welding slightly the weight of aersospace and automotive devices can be reduced that leads to the fuel efficinecy and less environment pollution. Most improtant fact is that the joints between dissimilar materials have high economic and industrial advantage. Aluminum is a material that is slightly hard to weld due to its high thermal conducticity, and that is the reason why ultrasonic welding technique produces solid state weld that is achieveable. Since Aluminum is a light material and due to its softness it makes it suitable and commonly used material for aerospace engines.

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