International Conference on Ideas, Impact and Innovation in Mechanical Engineering (ICIIIME 2017)
Volume: 5 Issue: 6

ISSN: 2321-8169
146 - 151

An Overview of Dimensional Stability of Invar 36 Material for Space Based Optical Mounting Applications

Romin A. Thakar[1], Snehal V. Trivedi[2]
[1]PG Student, Production Technology (Mechanical),Parul Institute of Technology
Parul University,rominthakar05@gmail.com
[2]Asst. Professor and head,Production Technology (Mechanical),Parul Institute of Technology
Parul University, snehal.trivedi@paruluniversity.ac.in

Abstract: All materials alter their shape and size in response to changes in applied and internal stresses and environmental conditions, including time and temperature serious consequences may occur for many applications, especially in the aerospace if material is instable. Control of dimensional instability is more complex for composite materials, components and structures because the response of each constituent is modified by all the others. Precision components like optics, telescope, satellite camera, needs high dimensional stability in the range of 1ppm to 1ppbbecause one micron change in telescope mirror mount could shift its focus to 10 micron. This will directly affect to the image quality and its resolution. The assessment of temperature and time dependent dimensional stability of Invar36 material is carried out for optical mounting application as higher dimensional stability is required.Factors affecting dimensional instability, Potential sources and types of dimensional instability is discussed here. Methods to improve the dimensional stability is also discussed.

Keywords— dimensional stability, temporal stability, invar36 material, space applications, qualification tests.

*****

1. INTRODUCTION

The stability of dimensions can be maintained actively and passively. In the first approach the actuators are used to restore the dimensions disturbed by stresses or environmental influences. The passive approach is to use the material that do not respond the influences of stresses and environment. The letter approach is less costly, less complicated hence is preferred.

For thermal effects we note that only few material can maintain dimensional stability about 10 ppm when heated from normal to 100 °C. Temporal stability also affect the dimensions of component significantly as some material changes its dimensions of 1-50ppm over months or years due to microstructure changes and internal stress relieving So need of very low thermal expansion and dimensionally stable materialin precision measurement systems like Laser Interferometer Gravitational Waves Observatory (LIGO) is very high.The wide range of aerospace material requirements has simulated their interest in dimensional stability behaviour of Composite material. For most aerospace applications only composite material can fulfil the requiring dimensional stability under variety of environmental conditions and otherrequirements like light weight, toughness, fatigue strength, low thermal expansion, durability, fabrication ability. The problemfor an engineer /designer to determine what the acceptable distortion limits are and choose the material accordingly. Current requirements for increasingly stable structures have motivated the precision measurements.[6]

1.1 Optical mirror mount

Optical Mirror Mounts are used to mount optical mirrors for integration into laser or optical systems. Optical Mirror Mounts are mounting components that hold optical mirrors in a stationary position for use and it is a mechanical structures which isolate an optical element from the mechanical and thermal effects of the structural support. Optical Mirror Mounts are designed to integrate with optomechanical products or optical posts to provide stability to the mounted component[10]. Generally, an optical mount should have the following specifications:

1. It must exert low stress on the optics to minimize optical surface distortion
2. It should have high stiffness to maintain the alignment of optics
3. It must maintain the specified tolerance in the operational temperature range
4. It must maintain the position of the optical element throughout its assigned life time.
5. The mount size and weight should be minimized Mounting fabrication and material should have minimum cost

1.2Material for opto-mechanical space applications

Generally, mount material should provide the required compliance within the length limitation as well as dimensional stability for repeated use throughout time. In space applications acceleration experienced during launch, relies of gravity effect as orbit is achieved, vibrations, vacuum, and thermal effects are the most affecting parameters while selecting mount material Stability is important because of continuous stress in mount material. Micro-yield strength (MYS) is a common figure of merit of dimensional stability of material. Although MYS is usually considered a safe limit, dimensional instability or room temperature, creep can happen in stresses less than MYS as well. Mount toughness determines its resistance to fracture or cracking. Most high-strength materials have low fracture toughness. Especial alloys alleviate this problem. To reduce thermal effects, a good match of coefficient of thermal expansion (CTE) of optics and mount material is helpful. However, thermal conductivity in most cases is not an important parameter[3].

The real need of material for opto–mechanical space applications is Low thermal expansion and dimensionally stable materials. Most solid materials expands when their temperature is increased. This expansion is attributed to the thermal vibration of individual atoms associated with the temperature rise. As each atom vibration with increased amplitude, it occupies additional space. Actual value of CTE related to the strength of atomic bonds, which influence both the elastic module and melting point.In orbiting telescope subjected to alternating periods of sunlight and darkness, temp. Changes and temp. Gradients would occur in telescope mirror supporting structure. This could cause shifts in both axis and spacing of the secondary mirror relative to primary mirror, thereby impairing the quality of image. To minimize this problem, methods could be devised to hold the entire telescope assembly within narrow limits of the temperature [11]

Choice of Materials Design for dimensional stability usually starts with materials which already possess stability during temperature excursions. Exceptional dimensional tolerances required for both on ground based test beds and in space. Near zero CTE materials can be found in all major material categories, namely metals, plastics, ceramics. Advanced materials such as composites of nickel, carbon fibre and zerodur are more suitable, meet several requirements simultaneously and come in a variety of shapes and sizes.Composites of carbon fibre and zerodur are low expansion and dimensionally stable materials though we can’t use them in Laser Sintering (3D printing) method because of their composition requirements and different melting points of their composites so Here we choose INVAR material for study which is alloy of iron and nickel which are having almost same grain size and same melting point so we can easily fuse them together by laser.

1.3What is invar?

Invar, also known generically as FeNi36 (64FeNi in the US), is a Nickel steel alloy notable for its uniquely low coefficient of thermal expansion (CTE or α). It was invented in 1896 by Swiss scientist Charles Guillaume. He received the Nobel Prize in Physics in 1920 for this discovery, which shows the importance of this alloy in scientific instruments.Invar is a metal used in applications in which a high degree of dimensional stability under changing temperatures is desired. It is used in precision mechanical systems in many different industries and is not limited to opto-mechanical engineering applications. Invar alloys achieve near zero thermal expansion coefficient by virtue of their ferromagnetic behaviour near the room temperature. As the temperature raised, the ferromagnetic nature of the material diminished in intensity, reaching zero at Curie temperature[14].

The most valuable property of Invar is its low coefficient of thermal expansion (CTE). At room temperature it is approximately 1-2 ppm/K, however like most mechanical properties, CTE varies with temperature. Invar’s CTE is the lowest of any metal.

2. DIMENSIONAL INSTABILITY

Dimensional instability means the time/temperature dependent dimensional change in response to internal or external influences. Dimensional instability is an unacceptable change in dimensions or shape in an environment where such changes would not normally be expected. All materials are unstable to some degree and certain types of instabilities should be expected in most real applications. The problem is really narrow down to keeping the instabilities within acceptable limits. The problem at hand is that we want to control the dimensional change, a distortion or strain of the component of interest. If we require stability on the order of machining tolerances, strain of approximately 0.001, there is no serious problem but if part must maintain dimensional tolerance to parts per million, e.g. Microns/meter, then care and consideration must be given to materials selection and processing steps. In preparing to design and fabricate dimensionally stable components. It is important to realize that this implies controlling the sources of dimensional instabilities to a level such that any dimensional changes that occur are kept within specified tolerances. Because dimensional tolerances of products become smaller due to the demand of accuracy and reliability of dimensional instabilities becomes more and more a matter of concern. [1]

2.1 Demand of dimensional stability

Long term dimensional stability is required for support structures in many instruments having optical components like mirror mounts. For example, imaging systems on future space flights such as the Saturn-bound Cassini spacecraft impose very strict requirements on the optical mount in the camera a system. The next generation systems represented by the camera to be used on the Cassini spacecraft use an imaging design having higher performance goals and which are very sensitive to dimensional errors. The optical supports must satisfy requirements for very low thermal expansivity and temporal stability more rigorous than ever required before. Not only must the material meet the dimensional stability requirements, it must also be machineable and have mechanical strength required for its use.Once a tolerance has been specified to bind the amount of allowable instability, the next step is to determine the potential source of instability and control them to meet the specification. The common types of instability are given below[2]

2.2 Types of dimensional instabilities

1. A distortion or dimensional change occurring as a function of time in fixed environment (temporal instability)
2. A distortion or dimensional change, measured under a fixed environment, after exposure to a variable environment.
3. A distortion or dimensional change, measured under a fixed environment, and depending upon theenvironmental path used to reach the fixed environment.

2.3 Sources of dimensional instability in material

1. External stress effect applied to a component may give rise to an anelasticity, mechanical hysteresis and micro-plastic strain.
2. Alternations of internal stresses may cause dimensional instability.
3. Microstructure change e.g. due to change in vacancy concentration, atom re-arrangement and ordering ,precipitations and resolution of second phase may also give rise to dimensional instability.
4. Temperature may cause dimensional changes and deviation from perfectly hookean behaviour, because the elastic modulus E is not a constant, but a function of temperature.

2.4 Dimensional stability of INVAR36

Alloys of iron and nickel such as Super Invar (Fe-Co-Ni) and INVAR 36 (Fe-36Ni) are known to have remarkably low coefficients of thermal expansion (CTE) near room temperature. Though Super Invar has superb dimensional stability at room temperature, it is not suitable for use as supports in precision instruments due to its highly composition-dependent, irreversible phase transformation and temperature dependent temporal stability. It is also very difficult to fabricate also intended to stabilize and/or stress relieve. INVAR 36 has more practical applications since it is easier to fabricate and has low CTE over a wide range of temperatures. The CTE of INVAR 36 has been reported to vary from –0.6 to +3.00ppm/°C in the temperature range of –70° to +100° C. With careful controls, it is commercially practical to produce INVAR 36 with a narrower range of CTE values, e.g. 0.8 to 1.6 ppm/°C in the range of 30° to 100° C.Prior studies conducted on commercial Invar alloys indicate that impurities have a pronounced effect on the coefficient of thermal expansion. The thermal expansion is also affected by thermal and mechanical treatments.[4]

2.5 Temporal stability of Invar36

Almost since its invention in 1896, invar has been known to be a dimensionally unstable pendulum rod material. Data published in 1927 showed a dimensional growth of 50 ppm over a 27-year interval. The growth was exponential, gradually slowing down with time. Invar's growth today still follows the same exponential pattern, although shrinkage is occasionally observed. Invar's instability was tied to the presence of impurities, especially carbon. The lower the level of impurities, the more stable the invar is. Invar's impurity level has been reduced over the years, so that today's invar, using the advanced melting and manufacturing process, is more stable than it was 20 years ago. So temporal stability of Invar stats that expands with age, even at constant temperature. Its growth over time depends on many factors, the most important are [14]:

- Time since final machining,
- Carbon content,
- Heat treatment,
- Ambient temperature
- Manufacturing process
- Residual stresses and microstructure

Also great importance of the heat treatment of Invar. The heat treatment reduces the temporal growth of the Invar by effectively aging it. Invar’s temporal growth does not continue on forever at high rates; it tapers off with time and the heat treatment causes the Invar to age prematurely, thus decreasing its temporal growth.

2.6Effect of chemical composition on INVAR’s stability

In the alloy of the present invention the essential elements are nickel, cobalt, manganese, and iron. Nickel and cobalt are both austenite stabilizers and work together to provide the very low expansion coefficient of the composition of the present invention.

The thermal expansion coefficient of the composition increases dramatically, when **COBALT**is less than about 0.5 w/o or greater than about 5.5 w/o. preferably about 1-2 % cobalt is present. The coefficient of thermal expansion of the present composition is also sensitive to **NICKEL**content. Nickel much in excess of about more than 36 % also causes unacceptable increases in the thermal expansion coefficient. Accordingly, nickel content is limited to a maximum of about 36 %. The reduced nickel content of the composition relative to Invar destabilizes the austenitic structure since cobalt is not as strong as austenite stabilizer as nickel is. Accordingly, without more, the present alloy could undergo martensite transformation at an unacceptably high temperature. The martensite transformation start temperature, Ms, can be lowered by providing a minimum of about 32.0 w/o, nickel in this composition. To achieve both a very low average coefficient of thermal expansion and a significantly lower Ms Temperature, the combined amount of nickel and cobalt is preferably about 36–37.5 w/o.

MANGANESE has a strong austenite stabilizing effect in the nickel-cobalt-iron system of Super Invar. Additions of manganese, however, also strongly increase the average coefficient of thermal expansion. The inclusion of about 0.4–0.8 w/o, preferably at least about 0.6 w/o, manganese lowers the Ms Temperature without appreciably increasing the thermal expansivity of the composition.

CARBON is usually present in the composition due to the realities of melting practice. Greater carbon content and other impurities in Invar lead to greater temporal growth. Carbon is the most critical impurity however. The growth of the 0.02% carbon content sample was less than that for the 0.06% carbon content sample by 4 ppm over 300 days. But is not advised to remove all the carbon from the material composition but it is intentionally kept very low, maximum preferably no more than about 0.012 w/o. Carbon is a strong austenite former and as such it is beneficial to the alloy. However, carbon significantly increases the coefficient of expansion and therefore can be tolerated only in minute amounts.[14]

3. QUALIFICATION TESTS

To ensure successful vehicle and payload operation, space programs subject hardware to extensive ground testing. Thermal tests demonstrate the performance and operation of units, subsystems, payloads, and entire space vehicles in thermal environments that are at minimum, realistic simulations of flight conditions. Qualification tests also validate the planned acceptance program, including test techniques, procedures, equipment, instrumentation, and software.

Each type of flight item that is to be acceptance tested undergoes a corresponding qualification test, with the exception of some structural items. The test item is produced from the same drawings that are used for production of the flight hard-ware. Its production uses the same materials, tooling, manufacturing processes, and level of personnel competency as are used for production of the flight hardware.To demonstrate design, the qualification environment exposes the qualification hardware to conditions more severe than expected during the operational life of the flight hardware. It considers not only the most extreme flight environments, but also the maximum number of cycles that can be accumulated in acceptance testing and retesting. Because of the severity of this environment, qualification hardware is not flown. For reliability testing of material for years of service life under exposure of temperature, the thermal cycling test is to be done on material as per MIL standards.[8]

3.1 Thermal expansion behavior of Invar

Most solid materials expands when their temperature is increased. This expansion is attributed to the thermal vibration of individual atoms associated with the temperature rise. As each atom vibration with increased amplitude, it occupies additional space. Actual value of CTE related to the strength of atomic bonds, which influence both the elastic module and melting point.

In orbiting telescope subjected to alternating periods of sunlight and darkness, temp. Changes and temp. Gradients would occur in telescope mirror supporting structure. This could cause shifts in both axis and spacing of the secondary mirror relative to primary mirror, thereby impairing the quality of image. To minimize this problem, methods could be devised to hold the entire telescope assembly with low thermal expansion and stable material.With respect to processing variables, the coefficient of thermal expansion (CTE) of invar alloy can be reduced substantially by rapid cooling from annealing temperature and by cold working.

	Mean linear CTE, 10^{-6}/ ^{o}C	
Temperature range 21^{o} to 93^{o}C (70 to 200^{o}F)	830^{o}C (1525^{o}F), slow cool	830^{o}C (1525^{o}F) quench
	2.0	0.63

Table-1 effect of cooling rate on thermal expansion of invar

At least a portion of the large effect of rapid cooling on the expansion coefficient is attributed to the presence of carbon in material. When invar is slowly cooled from the annealing temperature, any carbon in solution tends to precipitate in the form of tiny graphite particles. These graphite particles act to increase the expansively. By rapid cooling from the annealingtemperature, the carbon in solution is prevented from precipitating and lower expansion coefficients are obtained.

Cold working is yet another way to reduce CTE of invar alloys , cold working is known to improve the micro yield strength of Invar, cold drawing annealed + water quenched invar36 to a reduction level of only 15%-35% reduced the CTE from its initial value of 0.47x10^{-6}/ ^{o}C to zero Greater reduction caused the CTE to slightly negative and increased $\sigma_y(10^{-6})$ from its initial value of 40-60MN/m2(6 to 8.5 ksi) to 340MN/m2(45-48 ksi). It is evident from this discussion that the original Fe-36Ni invar alloy, containing residual impurities, is not a zero thermal expansion material. However though control of composition and processing, it is possible to significantly reduced invar's expansivity and, in some cases, to develop zero or slightly negative expansion coefficient.

Thermal expansion measures the fractional change in size per degree change in temperature at a constant pressure. Several types of coefficients have been developed: volumetric, area, and linear. Which is used depends on the particular application and which dimensions are considered important. For solids, one might only be concerned with the change along a length, or over some area."Linear expansion coefficient" is the fractional change in length per degree of temperature change. Assuming negligible effect of pressure, we may write:

$\alpha_L = \frac{1}{L}\frac{\partial L}{\partial T}$ Where L is a particular length measurement and dL/dTis the rate of change of that linear dimension per unit change in temperature.

4. IMPROVEMENT OF DIMENSIONAL STABILITY BY HEAT TREATMENTS

Dimensional stability can be maximized in most metallic materials by complete removal of residual stresses in combination with a stable micro structure, invar is no exceptional. Slow cooling from the annealing temperature comes very close to meeting both the requirements and as demonstrated by lement products excellent dimensional stability at room temperature. Unfortunately, slow cooling also produces thermal expansion coefficient that may be greater than the desire in particular application. In such cases, water quenching is often employed to achieve lower α values giving rise to high residual stresses and unstable microstructure. With passage of time at room temperature or slightly above, residual stresses can gradually diminish, leading to a length decrease in rod specimen, and the carbon in solid solution can gradually rearrange itself into a more stable configuration, leading to a length increase.[5]

The potential dimensional instabilities resulting from water quenching to achieve low α can be greatly minimise by appropriate thermal treatments. These thermal treatments are designed for two purposes

1. To reduce residual stresses sufficiently so that they will no longer be subjected to gradual reduction at the service temperature
2. To rearrange the carbon atom to a configuration that is not subjected to further change at the service temperature

Residual stresses reduction is accomplished most readily at elevated temperature although stress relaxation can occur at low temperature if sufficient time is allowed. For nearly complete removal of residual stresses in invar in time of 1 hr or less, temperature near 560°C required. However Lement has shown that treatments 425°C to 560°C results in large increase in α because of graphite precipitations. The highest allowable temperature for stress relieving Invar without precipitating graphite appears to be about 315°C (600°F)

Unlike stress relieving, rearrangement of carbon atoms in the Fe-Ni lattice is not necessarily fevered by high temperature. In order to achieve the stable microstructure after stress relieving artificial accelerated aging is to be done on material.[7]

Based on the above observations, lement recommended a series of thermal treatments to provide both a low α and good dimensional stability.

These heat treatment processes consisted of

1. **830°C (1525°F)**, 30 min water **quench**; this treatment is designed to place all of the carbon in solution; rapid cooling will minimize the precipitation of graphite particles. This treatment is done to get lowest thermal expansion and hardness.
2. **300°C (600°F)**, 6 hr. air cool (**stress relieving)**; this treatment is designed to reduce residual stresses introduced by quenching. Without it, processing may give rise to unacceptable distortion and/or the material can suffer from service problems such cracking. The treatment is not intended to produce significant changes in material structures, mechanical Properties.
3. **100°C (205°F)**, 48 hr. air cool (**aging**); this treatment is designed to rearrange carbon atom into a relatively stable configuration. This heat treatment does not decrease dimensional stability or tensile/compressive strength. It is designed to develop the optimum combination of dimensional stability, strength and micro yield for the ultra-pure INVAR 36 material of the invention.

Steps 2 and 3 must be done in the order indicated. Reversing them would nullify the benefits of the 100°C treatment. Temperature other than indicated can also be employed in certain situation for example step 2 might be done at 205 ° to 260°C but, appreciably longer times would be required or less stress relieve would be accomplished[1].

5. CONCLUSION

Dimensional stability of most required while dealing with space based optical applications, hence to control it and keep it within specific limits is necessary. Invar is suitable and widely used material for space applications because it has lowest thermal expansion over any metal and its mechanical / dimensional stability properties can be controlled and modified with set of heat treatment and coldworking processes. Also care must be taken while choosing the composition for invar because each element plays key role in thermal expansion, mechanical properties and material stability. The dimensional stability depends on 3 parameters: temperature, time,and stress(both internal and external). The residual stresses induced in material while manufacturing and machining plays vital role in instability. Material stability is also affected by microstructure change, phase transformation, and precipitations. Dimensional stability of invar can be improved by 3 steps of heat treatment processes as discussed. Before sending components into space it must be go through qualification and acceptance tests on ground in thermal environments that are realistic simulations of flight conditions. The extreme limits are sets for reliability testing of material according to different standards.

ACKNOWLEDGEMENT

I would like to thank ISRO (Indian space research organization) for allowing me for my dissertation research work and giving me opportunity to work with one of the successful and high-tech organization. My sincere thanks to Mr.AnupVora (Head, GLMD, SAC, ISRO) and Mr. Sanjay Gupta (Sci-engr, SAC, ISRO) for rendering all kinds of help and technical discussion necessary.

REFERENCES

[1] c.w marschall and R.E maringer, “ dimensional instability, An introduction” pergamon press, new York(1977)

[2] Bernard samuel lement “The dimensional behaviour of invar” american soc. For metals, 43-1072, MIT, cambridge, massachusetts,1951

[3] Alix preston “Stability of materials for use in space-based interferometric Missions “ by university of florida 2010

[4] R.A. pauqion , moderator ‘ Dimensioanl stability workshop’ SPIE proc 1335(1990)

[5] Jacobs, S. F., M. Norton, J. W. Berthold III , "Dimensional Stability of Fused Silica and Several Ultralow Expansion Materials," International Symposium on Thermal Expansion of Solids, Lake of the Ozarks, 1973

[6] Justice, B. "Dimensional Stability of Four Mirror Materials, Concluding Report," New York, Corning Glass Works, 1972

[7] Steven R. Patterson “Dimensional Stability of Superinvar” Lawrence Livermore National Laboratory 2010

[8] Military standard : launch , upper-stage, and space vehicles . MIL-STD-1540c

[9] Jeffrey M. Steele, Dennis A. Thompson, Stephen F. Jacobs “Temperature and Age Effects on the Temporal Stability of Invar” Optical Sciences Centre, University of Arizona, Tucson, Arizona 1992

[10] Effect of surface polishing on the microstrain behavior of telescope mirror material, boeing company, NASA report CR-112217

[11] Marschall, C.w maringer “Micro mechanical properties and dimensional stability of materials for use in orbiting observatories” pergamon press, new York1972

[12] T. Yokoyama, K. Eguchi, “An harmonicity and Quantum Effects in Thermal Expansion of an Invar Alloy”, Phys. Rev. Lett. 107 (2011) 065901

[13] Y. Zhao, A.P. Wu, W. Yao, Z.M. Wang, Y.S. Sato, Microstructure and mechanical properties of Nd:YAG laser welded Invar 36 alloy, Mater. Sci. Forum. 675-677, 2011

[14] Scott gibb“An introduction to invar” unversity of Arizona, 2016