THERMAL FATIGUE OF SELECTED (Al-Ni) ALLOYS

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الملخص

يتناول هذا البحث تجربة الكلل الحراري لمجموعة مختارة من سبائك الألومنيوم - نيكل المحتوية على 14، 28، 36، 44، 52 % من وزنها نيكل، حيث تم تعريض عينات منشورية الشكل من هذه السبائك للتسخين بلهب الأوكسيسيتلين ثم التبريد المفاجئ بالهواء. أجريت هذه الاختبارات عند ثلاث قيم من درجات الحرارة وهي 350، 450، 550 درجة مئوية، حيث كان مقياس مقاومة هذه السبائك للكلل الحراري هو عدد الدورات الحرارية التي تحملتها العينة قبل تشرخها.

أظهرت نتائج هذا البحث أن عدد الدورات الحرارية التي تستطيع العينة تحملها يعتمد أساسا على درجة حرارة الاختبار وكذلك على مكوناتها وتركيبها الكيميائي لها. فيما يخص تأثير درجة الحرارة تبين أنه بزيادة درجة الحرارة فإن مقاومة السبيكة للتشرخ الحراري تنخفض بإضطراد. كذلك أوضحت النتائج أن معظم السبائك المحتوية على نسب عالية من ألومنيد النيكل نوع Al_3Ni عانت ضعفا في تحملها للدورات الحرارية بينما السبائك المحتوية على ألومنيد النيكل نوع Al_3Ni_2 تمتعت بمقاومة أفضل نسبيا حتى وإن كانت نسبة هذا الالومنيد قليلة.

ABSTRACT

Thermal fatigue tests have been conducted on five aluminium-nickel alloys containing 14, 28, 36, 44 and 52 weight % nickel. The specimens in a prismatic shape were heated by an oxy-acetylene flame to the test temperature followed by rapid air-cooling. The maximum test temperatures were 350, 450 and 550^oC and the number of cycles required to initiate a crack was taken as a measure of thermal fatigue resistance. Test results showed that the number of cycles to failure depends primarily on temperature and alloy composition. It is concluded that increasing the test temperature significantly reduced cycles to failure. As for composition, most alloys of higher percentages of Al_3Ni aluminide showed less resistance to thermal fatigue. On the other hand, alloys containing Al_3Ni_2 aluminide, even in a small percentage, exhibited better resistance to fatigue failure.

KEYWORDS: Advanced Materials; Intermetallic Compounds; Thermal Fatigue; Al-Ni alloys.

INTRODUCTION

High temperature materials are finding an increasing demand in many fields such as turbines, jet engines, and space technology. Intermetallic phases are regarded as highly promising structural materials for applications where excellent mechanical properties and oxidation resistance at moderate and high temperatures are needed.

Aluminides are one of these intermetallics that are composed of aluminium which is the phase for providing the necessary oxidation resistance by forming a thin film of alumina (Al_2O_3) in oxidizing environments, that is often compact and protective [1].

The low density of such aluminides is achieved due to the presence of aluminium in their composition. The other element (iron, nickel, titanium,…etc) is to enhance the melting temperature of these alloys. In addition to the low density requirements of such aluminides, thermal fatigue may considered to be an important engineering characteristic, and is therefore a matter of vital concern, when selecting an alloy for a fluctuating temperature applications.

Thermal fatigue usually refers to the cracking of a piece of material if it is heated and cooled in such a way that thermal stress gradient exists across it. These thermal stresses are seldom large enough, in practice, to cause a static failure, but repeated applications may lead to fatigue failure. Thermal fatigue test is not standardized to the same degree as tension testing, creep testing, or fatigue testing. Therefore, thermal fatigue is generally investigated by subjecting components, or specially shaped specimens, to repeated heating and cooling cycles until they crack.

It is to be mentioned that bulk researches [2-5] were focused on the thermal fatigue of ferrous alloys and super alloys,. As for nickel aluminides, many researches see for example [2,3] were concentrated on the high nickel content aluminides, particularly $AlNi_3$ which has high density. With respect to the light weight perspective, the present work is directed to (Al-Ni) alloys containing lighter nickel aluminides (Al_3Ni and Al_3Ni_2).

EXPERIMENTAL WORK

Materials

The materials used in this work are:

i) Aluminium of 99.83% purity in the form of billets and of chemical composition given in Table (1).

Table 1: Chemical composition of aluminium

Element	P	Si	Ti	Zn	Cu	Mn	Mg	Al
Wt. %	0.110	0.050	0.0047	0.0034	0.0005	0.0007	0.0007	Bal

ii) Nickel of 99.99% purity in the form of crowns and of chemical composition given in Table (2).

Table 2: Chemical composition of nickel

Element	Zn	Fe	Cu	Pb	S	Co	Ni
Wt. %	0.0020	0.0010	0.0005	0.0003	0.0003	0.0002	Bal

Casting

Graphite mold is used to produce specimens of a prismatic shape of the dimensions shown in Figure (1). Aluminium is first melted in non-ferrous high frequency induction furnace (1 MHz, 200KW). Nickel is then added to the aluminium melt and frequently stirred. Degasification process is performed by blowing argon gas via a silicon tube. The temperature and time of casting are dependent on the weight of the alloy to be melted. The casting conditions are predicted in Table (3).

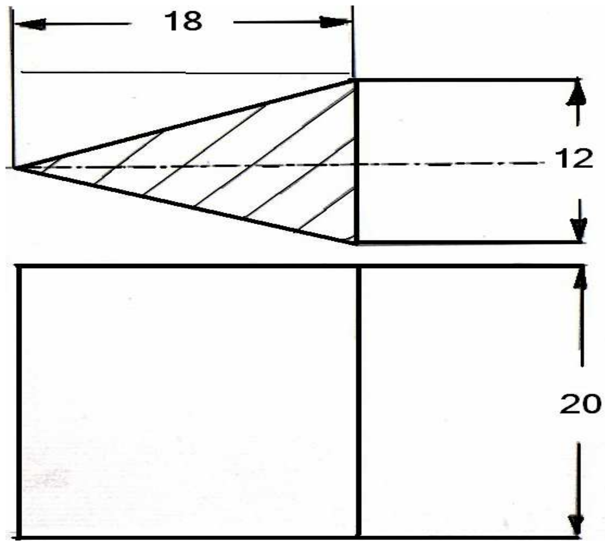


Figure 1: Dimensions (in mm) of the prismatic specimen.

Table 3: Casting conditions

Alloy designation	Casting temperature (°C)	Casting time (min)
Al – 14 Ni	914	25
Al – 28 Ni	1070	40
Al – 36 Ni	1200	50
Al – 44 Ni	1443	35
Al – 52 Ni	1652	50

Thermal fatigue test

Thermal fatigue test is conducted using a hand-made test set up shown in Figure (2). Two prismatic test specimens are diametrically fixed in a rotated disc.

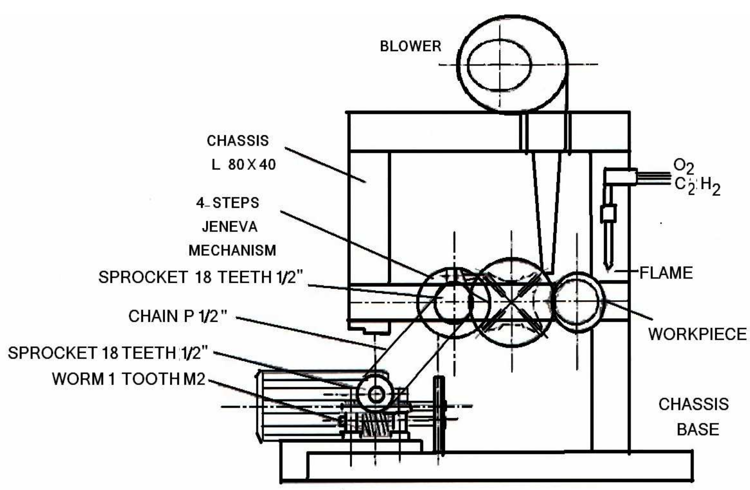


Figure 2: Schematic diagram of thermal fatigue test machine.

The rotation of the disc can be mechanically controlled in such a way that one of the two test specimens is upon cooling whereas the other one is upon heating at the same time for about thirty seconds. Heating is accomplished by means of oxy-acetylene flam that can be controlled by adjusting the gas pressure to maintain the required test temperature. Cooling is carried out using an air blower situated 30 mm above the specimen surface. Dummy specimens of 2 mm diameter hole drilled through the mid-way of the leading edge from each alloy composition are used for temperature measurements. The temperature of the knife-edge can be measured by inserting the thermocouple tip inside this hole. The test is discontinued when the first crack appears on the leading edge of the test specimen. The crack could be seen using an optical pyrometer sighted on the test section leading edge of the specimen. The thermal fatigue resistance is based on the number of thermal cycles required to initiate a crack. These cycles could be measured by means of a pulse counter.

RESULTS AND DISCUSSION

Effect of temperature on the number of cycles to failure

Figure (3) shows the effect of temperature (T) on the number of cycles to failure (N) of different (A1-Ni) alloys. It can be seen from this figures that increasing the test temperature has led to a remarkable decrease in cycles to failure for all alloys.

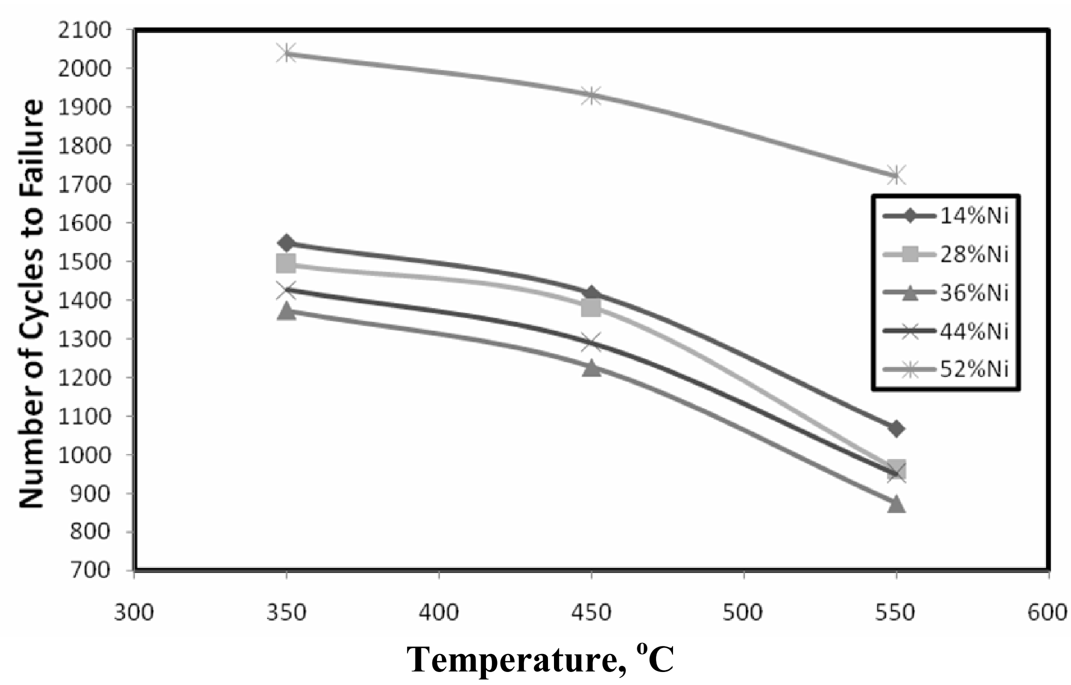


Figure 3: Average number of cycles to failure as a function of temperature with different (Al-Ni) alloys.

This tendency is to be expected since the thermal strains are usually proportional to the cyclic temperature range at the surface. Therefore, the crack initiation and propagation would be expected to increase with increasing thermal strains which in turn reduce the fatigue life. Most materials exhibit reduced cycles to crack initiation with increasing temperature.

The above behavior may partially be explained in terms of the simple well known equation.

$\epsilon_T = \alpha \, \Delta T$ (1)

Where:

ϵ_T = Thermal strain, α = Coefficient of thermal expansion, ΔT = Temperature change

According to the above equation the main parameter influencing the thermal strain is the temperature change ΔT. Nevertheless, the effect of thermal expansion coefficient (α) appeared to be less pronounced. That is because the value of α for the same alloy does not change much as a result of such low range of temperature changes. The values of ΔT are 105, 120, and 145^{o}C for 350, 450, and 550^{o}C maximum test temperatures respectively. Thus, the curves of Figure 3 would have the same tendency if ΔT would have been used as an abscissa of Figure 3 instead of temperature (T). It is worthwhile to indicate that such behavior had been early reported by many workers [6, 7] in the field of thermal fatigue.

Effect of nickel content on the number of cycles to failure

The averages of cycle to failure of different (A1-Ni) alloys are given in Table (4) and plotted in Figure (4). Two distinct zones could be distinguished in Figure (4). The first zone includes (A1-Ni) alloys of 14, 28, and 36 wt% Ni, and the second zone consists of 44wt% Ni and 52 wt% Ni.

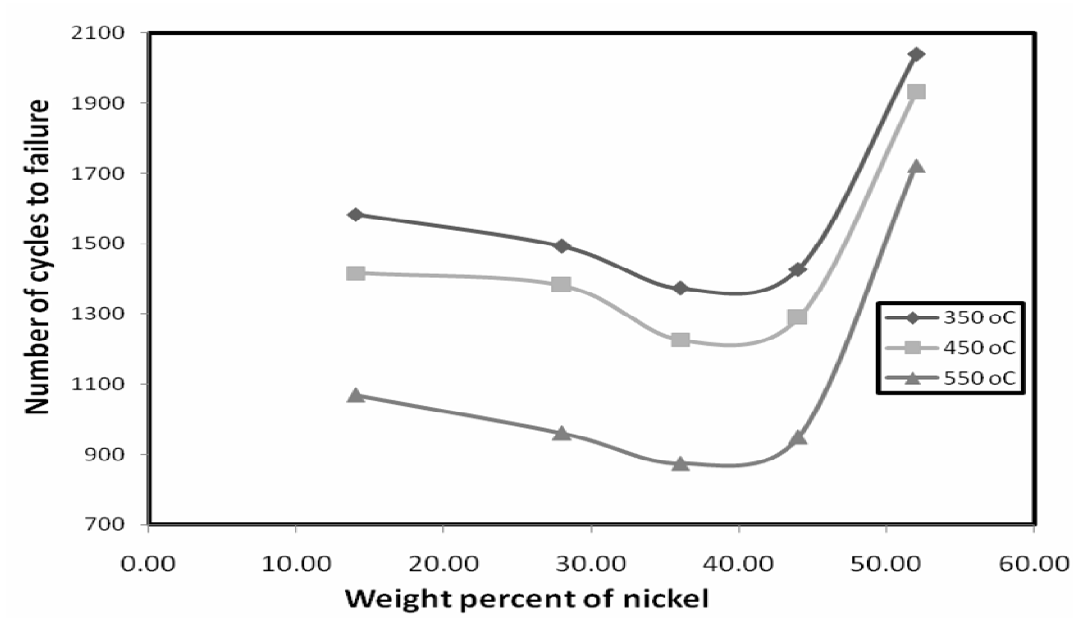


Figure 4: Average number of cycles to failure as a function of nickel content with different temperatures.

The trend of the three curves is the same for each Zone. However, the behavior of the curves is absolutely reversed in the two zones. In the first zone, the fatigue life is gradually reduced as a result of increasing nickel, whereas in the second zone, the alloys withstand much more cycles before failure, Moreover, it is observed that the rate of increasing of fatigue cycles in the second zone is approximately four times grater than the rate of decreasing of the cycles in the first zone.

Table 4: Thermal fatigue test results

Alloy designation	Number of cycles to failure		
	350°C	450°C	550°C
Al -14 Ni	1597	1413	1100
	1523	1447	1082
	1493	1425	1031
	1580	1385	1058
Average	1548	1417	1069
Al -28 Ni	1504	1358	986
	1519	1386	951
	1461	1412	937
	1488	1370	969
Average	1493	1382	961
Al -36 Ni	1359	1237	833
	1404	1218	900
	1333	1256	917
	1392	1195	848
Average	1373	1227	875
Al -44 Ni	1405	1281	978
	1380	1324	957
	1446	983Ex	942
	1417	1265	923
Average	1427	1290	950
Al-52 Ni	2051	1581Ex	1692
	2018	1895	1748
	2064	1937	1739
	2022	1963	1714
Average	2039	1931	1723

Ex= Excluded value

The above behavior may partially be explained in view of the individual phases present in each zone (Table 5) as predicted from A1-Ni phase diagram, (Figure 5) [8]. From Table (5), one can realize that the inflection of the curves of Figure 4 at 36 wt% Ni seems to be related to the presence of nickel-rich aluminide (Al_3Ni_2) at the expense of eutectic mixture of Al-14 Ni, Al-28 Ni, and Al-36 Ni alloys.

The microstructure investigation of various test specimens indicates that Al_3Ni aluminide appeared to be less resistance to thermal cycling. For example Al_3Ni aluminide (dark phase) of Al-28 Ni alloy, (Figure 6) is observed to be more damaged than the eutectic mixture. Consequently, it can be concluded that the reduced fatigue life of these alloys may be due in part to the increase in the amount of Al_3Ni aluminide as nickel content is increased. However, such behavior was not noticed in Al-44Ni alloy even though it posses the highest percentage of Al_3Ni aluminide (Table 5). That may be regarded to the formation of nickel-rich aluminide Al_3Ni_2 (15 wt %) as indicated above.

Table 5: The percentages of phases in various (Al-Ni) alloys

Alloy designation	Eutectic mixture (wt. %)	Al_3 Ni aluminide (wt. %)	Al_3Ni_2 aluminide (wt. %)
Al-14 Ni	78	22	-
Al-28 Ni	40	60	-
Al-36 Ni	17	83	-
Al-44 Ni	-	85	15
Al-52 Ni	-	25	75

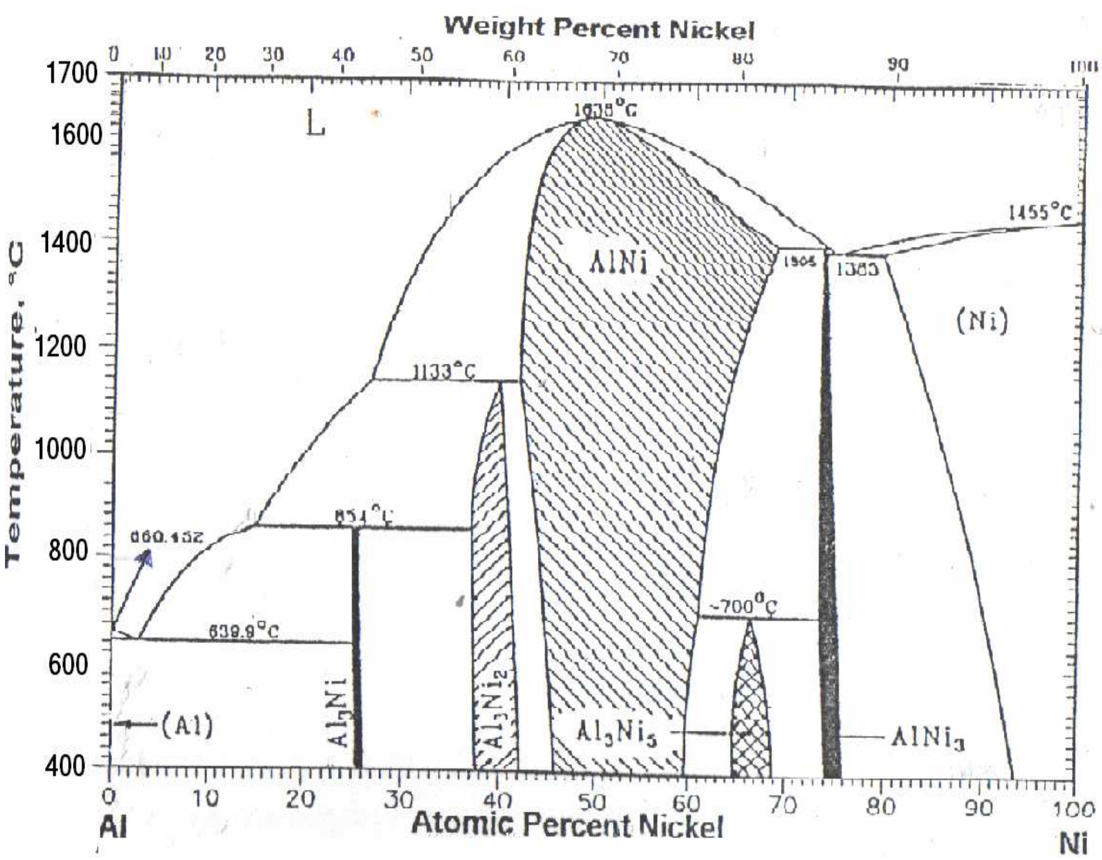


Figure 5: Aluminum- nickel phase diagram [8].

This observation may partially be attributed to the existence of Al_3Ni_2 aluminide. The presence of this phase however did not appear to have significant influence on the cycles to failure. It just impairs limited improvement in the fatigue resistance of Al-44 Ni alloy since it comprises only 15% of the composition of this alloy. Nevertheless, the detrimental effect of Al_3Ni aluminide on the cycles to failure seems to be dominated over the beneficial effect of Al_3Ni_2 aluminide. On contrast, the substantial increase in the cycles to failure of Al-52 Ni alloy could be regarded as a consequence of its higher amount (75%) of nickel-rich aluminide Al_3Ni_2.

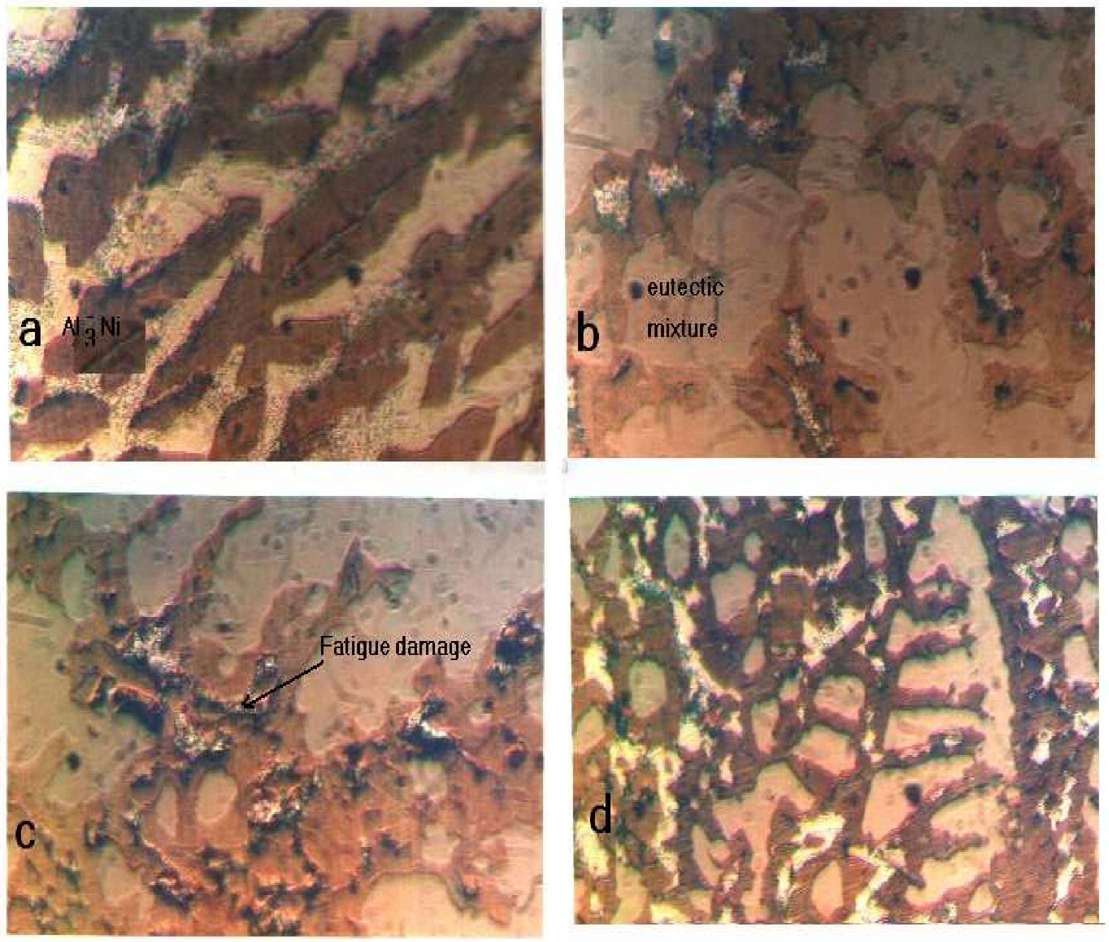


Figure 6: Microstructures of Al-28 % Ni alloy, (a) before testing, (b), (c), and (d) after testing at 350, 450, and 550°C respectively (400x).

The adversely effect of nickel on cycles to failure noticed in Figure 4 may also be explained in the light of the type of strain involved in each zone . In this aspect, plastic strain predominates in the alloys of 14, 28, and 36 wt% Ni that posses some ductility. Moreover, the most ductile alloy gives the longest endurance. Therefore, the slight decrease in the cycles to failure with increasing nickel- content in these alloys may be regarded as a result of a decrease in ductility as reported by korol'kov [9]. The decrease in their ductility of such alloys may be anticipated as a consequence of decreasing eutectic mixture that is more ductile than Al_3Ni aluminide as nickel content is increased.

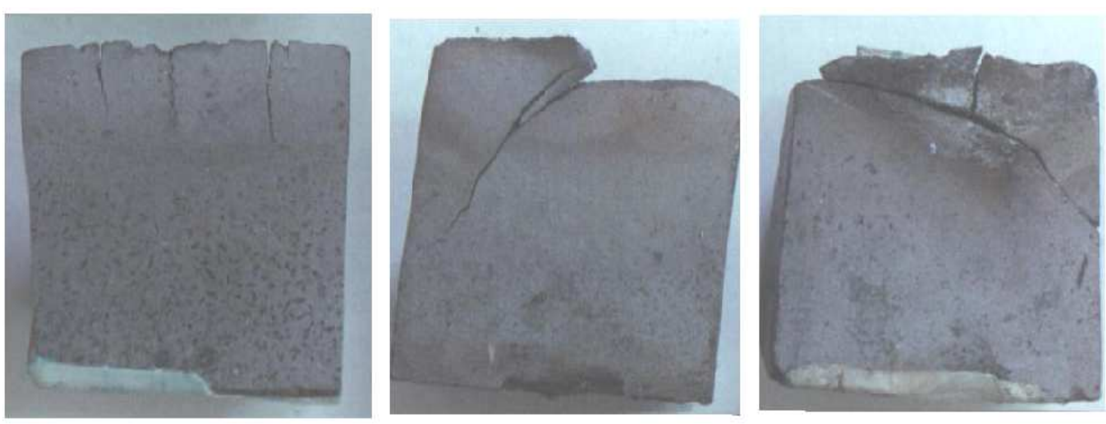
While the mechanism of plastic strain failure is possible for the alloys of the first zone of Figure 4, it is no longer so in limited ductility alloys of 44 and 52 wt. %Ni. In this regard, the fatigue failure seems to be governed by the ability of such alloys to resist elastic strain rather than plastic strain. Consequently, strength is more important than ductility. The substantial increase in the resistance to thermal fatigue of these alloys may therefore be related to the enhanced alloy strength as the amount of Al_3Ni_2 aluminide increases. Such increase in strength may be anticipated as regarding to the measured hardness (not reported) of the test specimens before and after thermal fatigue test. However, the hardness and therefore the strength at the actual test temperature are of more concern. In this regard, the hardness of Al_3Ni_2 aluminide is considered to be better than Al_3Ni aluminide. For example, the reported hardness of Al_3Ni_2 and Al_3Ni alumnides at 570°C are 500 HV and 200 HV respectively [10].

The above explanation may be substantiated by the mode of failure associated with each zone of Figure (4). It is observed that the specimens of lower percentages of nickel are mostly failed by the formation of what so called a semi-powdered layer followed by initiating a crack / cracks propagated deeply through this layer as indicated in Figure (7).

(a) (b) (c)

Figure 7: Thermal fatigue failure of lower nickel-content specimens, (a) 14% Ni , (b) 28% Ni, and (c) 36% Ni.

On the other hand, higher nickel content specimens (A1-44% Ni and A1-52% Ni) are observed to fail mostly by the initiation of a single crack. The crack appeared to be propagated parallel to the sharp edge of the test specimen leading, in many cases, to the splitting of small portions of this edge as shown in Figure (8). The splitting failure mode may indicate a relatively higher strength of such alloys.



(a) (b) (c)

Figure 8: Thermal fatigue failure of higher nickel-content specimens,(a) 44% Ni and (b),(c) 52% Ni.

It is to be emphasized that no mention has been made on the effect of the coefficient of thermal expansion, although it affects considerably the thermal fatigue behavior. The reason is that there is no significant difference between the values of thermal expansion for the alloys tested at such low temperature difference (ΔT) involved in this investigation. The above observation was early reported by Sergeev [11] who postulated that the variation in linear expansion coefficient of aluminum – nickel alloys as a function of composition and temperature may be considered to be too small.

CONCLUSION

Thermal fatigue resistance as represented by the number of thermal cycles to failure of (Al-Ni) alloys tested was found to sharply decrease with increasing temperature. The thermal fatigue resistance was found to be depending on the ductility and the strength of the alloy. If failure is governed by the minimum resistance to cyclic plastic strain, then the alloy should have good ductility as observed in alloys of 14, 28, and 36 wt% Ni. However, if elastic strain is more important, then the material should posse's high strength as observed in Al – 44 Ni and Al-52 Ni alloys.

As for the alloy composition (wt% Ni) , it may be postulated that it is better to work with nickelrich aluminide Al_3Ni_2 than aluminum - rich aluminide Al_3Ni as it offers good strength to the alloy and being much more resistible to thermal cycling .

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