FATIGUE BEHAVIOUR OF A THICK PLATE OF ALUMINIUM ALLOY 7475

M. Lorente, G. Atxaga, A.M. Irisarri, M. San Martín and L.M. Plaza

Fundación INASMET. C. Portuetxe 12. 20009 San Sebastián.

ABSTRACT

The influence of the presence of a notch, the orientation of the specimens and the ratio between the minimum and the maximum stresses on the fatigue behaviour of a 50 mm thick plate of a 7475 aluminium alloy in the T7351 condition has been analysed. Tests showed no significant difference between the fatigue performance of longitudinal and long transverse either smooth or notched specimens. As expected notched specimens exhibited markedly shorter lives than smooth ones. Scanning electron microscope examination of the failed specimens revealed that fracture surfaces were covered by typical fatigue striations but ductile dimples were observed in some zones indicating a certain contribution of a static fracture mechanism. Particles associated to these dimples corresponded to the aluminium-iron-chromium type, confirming the negative influence of the iron content on the fatigue behaviour of this alloy.

INTRODUCTION

The aircraft industry demands a lot from the materials it uses. Even if these demands have shifted over the years, they have always moved in the direction of lower weight, increased resistance to fatigue and corrosion, higher damage tolerance and long-term durability. Aluminium alloys have been and still remain the main structural material for heavy cargo and passenger airplanes. As their size increased, designers needed thicker materials. Aluminium alloy plate is used in a large number of aerospace applications, ranging in complexity and performance requirements from simple components through primary loading structures in aircraft such as the most recently developed commercial transport aircrafts; Airbus A340 and the Boeing 777 [1].

The last one, contrary to many earlier predictions, that pointed that it would be built of about 70% of polymer matrix composites, it was rolled out as an aluminium airplane with improved but not radically new alloys [2]. Moreover, due to technical problems encountered during the development of the aluminium-lithium alloys such as excessive anisotropy of mechanical properties, crack deviations and too low stress-corrosion threshold their use in Airbus A340 was restricted to the secondary structure of the wing, which represents only about 6% of the weight of the airplane, while up to 60% of this weight corresponds to conventional high strength aluminium alloys [3].

Wrought high strength aluminium materials have predominantly consisted of alloy 2024 (aluminium-copper-magnesium) and alloy 7075 (aluminium-zinc-magnesium-copper) for many decades but the later realisation that static strength is not necesarily the most important property directed the research effort towards the enhancement of toughness, fatigue and corrosion resistance, even where this involves a certain loss of strength, by reductions in impurity levels. Alloy 7475, which has the maximum percentages of iron and silicon strictly limited, was developed for sheet and plate applications that require and a high level of guaranteed fracture toughness. It possesses the highest strength-toughness combinations available in an aluminium alloy and it has been possible to use this alloy for lower wing skin and fuselages instead of 2024 [4].

The growing gap between airplane cost-per-seat and yield-per-passenger has forced aircraft designers to focus on ways to reduce manufacturing costs. One consequence is that complex components machined out of thick plate increasingly are replacing parts previously machined from die forgings or fabricated from sheets and extrusions. This means that aluminium alloy plate producers face increasingly challenging performance targets. Improved properties including short transverse ductility, fatigue performance and fracture toughness are required. As a consequence, the fatigue performance of thick plate in aerospace applications has arisen increased importance. Materials specifications requiring uniaxial fatigue testing for release certification purposes are being introduced.

The objective of this paper is to analyse the fatigue behaviour of a 50 mm thick plate of alloy 7475 in the T7351 condition.

EXPERIMENTAL PROCEDURE

Material chosen for this study consisted in one 50 mm thick plate of the alloy 7475, whose chemical composition is shown in Table 1.

TABLE 1
CHEMICAL COMPOSITION OF THE ALUMINIUM ALLOY PLATE

Alloy	Zn	Cu	Mg	Fe	Si	Cr	Al
7475	5.6	1.6	2.4	0.09	0.10	0.20	Balance

This plate was received in the T7351, condition, that is, solution treated after a high temperature soaking time to achieve a nearly homogeneous solid solution, rapidly cooled to prevent precipiation of the solved phases, stress relieved by stretching and two stage to obtain the desired precipitation hardening. The strength that can be obtained after this treatment is lower than in the T6 condition (aged at the maximum strength) but with the advantages of higher toughness and better exfoliation and stress corrosion cracking resistance.

Tensile and fracture toughness tests specimens were machined from this plate, at two depth locations (1/4 thickness and centre). Four 12.5 mm diameter round tensile tests specimens were obtained at each depth location; two in the longitudinal and two in the long transverse orientations. Tensile tests were carried out at room temperature following ASTM E-8-95a standard [5]. Three 25 mm thick compact tension (CT) fracture toughness were machined at each location in the L-T and T-L orientations, according to ASTM E-399-90 orientation code [6]. Fracture toughness tests were also performed at room temperature.

6.5 mm diameter round smooth specimens for fatigue tests were machined at the same locations and orientations than tensile tests ones. Moreover, 6.5 mm diameter notched specimens (K_t=3) were also obtained at these plate locations and orientations. All the fatigue tests were performed at room temperature, using stress ratios of R=-1, 0 and 0.5 for smooth specimens and only R=0 for notched specimens.

After failure, at least one half of each broken specimen was examined by means of scanning electron microscopy and the phases that contributed to the failure process were identified by energy dispersive X-ray spectrometry.

RESULTS AND DISCUSSION

As it is shown in figure 1 the microstructure of the alloy is constituted of recrystallised grains elongated in the rolling direction and unrecrystallised regions. The use of higher magnification revealed that these unrecrystallised regions contain a very fine subgrain structure. This type of microstructure is usually found in hot worked 7XXX aluminium alloys, especially in the more highly worked regions near the surface, where critical deformation has caused coarse recrystallised grains to form [7]. Some relatively large particles were detected in the microstructure. Energy dispersive spectrometry revealed that most of them were constituted by aluminium, iron and copper forming probably the phase Al_7Cu_2Fe, although differences in the contents of these elements were found in the various particles. Most of the remaining particles, that were detected by optical or scanning electron microscopy possess also a certain amount of iron in their composition associated to different amounts of other elements such as aluminium, copper, iron, zinc, chromium, magnesium, silicon or titanium. Moreover, some iron free particles formed by aluminium-magnesium-silicon, aluminium-copper-zinc, aluminium.titanium-copper-chromium-zinc or aluminium-magnesium-silicon-titanium were observed. Detection of the finest particles probably will require the use of transmission electron microscopy.

TABLE 2

MECHANICAL PROPERTIES OF THE PLATE AT THE VARIOUS DEPTH LOCATIONS AND ORIENTATIONS

Location	Orientation	Y.S.(MPa)	UTS (MPa)	Elongation (%)	K_Q (MPa.m$^{1/2}$)
¼ thickness	L-T	421	492	10.4	51
¼ thickness	T-L	423	496	10.2	48
Centre	L-T	416	487	10.0	49
Centre	T-L	417	489	10.2	47

Table 2 exhibits the average values obtained in the tensile and fracture toughness tests at the different depth locations and orientations. It can be easily seen that do not exist any significant influence of neither the location nor the orientation of the specimens on these average values. Values at the centre of the plate are just a little below those recorded at ¼ thickness. Fracture toughness in the T-L orientation were slightly lower than T-L ones at both depth locations but differences cannot be considered significant. These results seem to contradict other ones previously published by Bucci [8] where clearly higher values in the L-T orientation were obtained. The most plausible explanation would be based on the differences in the rolling process used for producing the plates studied in each work. The plate studied in the present paper exhibits a great similarity in the properties in the longitudinal and long transverse orientation. Unpublished results showed that fracture toughness in the L-S orientation is markedly lower than those in the two other orientations, in good agreement with Bucci's observation [8]. Results recorded in the L-T and T-L orientations are so high that specimens used for these tests were not thick enough to obtain valid K_{IC} values according to the established requirements and just K_Q values are reported.

Fractographic examination of these specimens revealed that microvoid coalescence was the operating mechanism. Some particles remained inside the ductile dimples, allowing to identify those that have contributed to the failure. Energy dispersive spectrometry revealed that the majority of the particles which were present in the fracture surfaces corresponded to the Al_7Cu_2Fe phase in very good agreement with the metallographic observations. A more detailed description of the fractographic analysis of these samples is presented in reference [9].

Fatigue tests results for smooth and notched specimens are shown in figures 2 and 3, respectively. A very slight influence of the specimen depth location on the fatigue life of the material was observed and so no distinction between specimens machined at each location is included in these graphs. Moreover, no significant effect of the specimen orientation on the fatigue performance was found. As expected, for the same mean stress, an increase in the stress amplitude leaded to a decrease in the fatigue life or, if the value that is kept constant is the stress amplitude, an increase in the stress ratio induces a decrease in the fatigue life.

In order to facilitate the analysis of these fatigue data the use of constant life diagrams was proposed. These diagrams plot the minimum stress, both tensile and compressive , along the x-axis and the maximum stress along the y-axis. This representation was proposed by Haigh and is, therefore, commonly referred to as the Haigh diagram. They give information about the influence of maximum, minimum, mean and alternating stresses on the fatigue performance of the alloy and can be used for evaluating the in-service lives of components.

Constant fatigue life lines collected in a Fatigue Data Book [10], for a plate of this same alloy 7475, together with the results obtained in the present work for smooth specimens, are shown in figure 4. It can be seen that good agreement is only found for short lives that is when specimens were tested under high stress levels. However, under low stress amplitudes, specimens tested in the present work exhibited shorter lives with respect to data included in reference [10]. One explanation for these discrepancies in the low stress amplitude results would be based in the highest strenght of the material included in the graph of the Fatigue Data Book. This is probably true for two heat treating conditions (T651, T7651), but the third treatment (T7351) is the same that was given to the plate studied in the present work. Moreover, as no distinction between the data obtained from the material in the various heat treating condition, and strength, was made in reference [10] comparison of the results is more difficult.

Fractographic examination of the broken specimens revealed that most of the fracture surfaces were mostly covered by striations than in those that were tested at highest stress amplitudes exhibited a wavy front and many secondary cracks. Nevertheless, in some zones the presence of large particles was observed in both alloys. These particles have a negative effect on the fatigue performance, accelerating the failure process, as their decohesion to the surrounding matrix generates microvoids that facilitate the crack propagation. Most of these particles are formed by aluminium, copper, chromium and iron and those formed by aluminium, copper and iron that constituted the greatest number in the tensile and the fracture toughness specimens were scarcely detected. A more detailed description of the fractographic facets is included in reference [9] although no explanation to this different contribution of the particles to failure in the tensile, fracture toughness and fatigue tests was found.

Small amounts of chromium are intentionally added to this alloy to modify the dynamic recovery and thus to control static recrystallisation in hot worked products. It combines with other elements such as aluminium, copper or zinc, entering in the composition of the particles denominated dispersoids, which are formed by solid state precipitation. In his study on the stress corrosion cracking behaviour of the alloy 7075, Byrne [11] also observed the presence of chromium rich particles, located in the grain boundaries or in the matrix, in the fracture surfaces, but the chemical composition of their particles is different from these found in the present work. In the present case both the nature and the size of the particles seem to indicate that they have been formed during the solidification and have not been solved during the posterior heat treatments and do not correspond really to dispersoids.

Moreover, De Sanctis and Lazzeri [12] showed the marked contribution of chromium rich large inclusions or incoherent dispersoids on the fatigue behaviour of a rapidly solidified 7XXX aluminium alloy and recommended to replace chromium by zirconium as the element added to control the recrystallisation process. This conclusion is partially supported by the fractographic observations of the fatigue specimens of an alloy 7050, where zirconium and no chromium was added. Logically no chromium rich phases were found in the fracture surfaces of the specimens of this alloy. However, coarse particles of different nature (mainly aluminium-copper-iron and aluminium-magnesium-silicon) were observed in the fracture surfaces of these specimens [9] and no improvement in the fatigue performance was achieved. A more homogeneous distribution of chromium in the molten alloy would probably lead to a larger optimisation in the fatigue behaviour of the alloy 7475.

Moreover, the recommended more strict control on the maximum iron content will also contribute to improve the fatigue behaviour as the amount of this element to form the coarse particles will be lower and their number and size will decrease. Nevertheless, this reduction in the iron percentage it is not an easy task as iron is the most usual impurity in aluminium alloys and is hardly eliminated, increasing the cast of the product.

CONCLUSIONS

a.- It was not absorved any clear influence of the specimen depth location or orientation on the fatigue performance. However, a significant negative effect of the notches on the fatigue resistance of the alloy was observed

b.- Fractographic examination of the broken specimens revealed that fracture surfaces were mainly covered by fatigue striations although some coarse aluminium-iron-copper-chromium particles, that have accelerated the failure process, were also detected.

d.- The nature and size of these particles seem to indicate that they have been formed in the solidification and no solved in the solution heat treatment and do not correspond to dispersoids formed by solid state precipitation.

e.- Comparison between the fatigue performance of thick plates of the 7475 and 7050 alloys indicates that the substitution of chromium by zirconium as the element added to form the dispersoids and to control the recrystallisation process do not produce any significant improvement in the fatigue behaviour as chromium rich coarse particles that accelerated the failure process in the alloy 7475 are replaced by aluminium-copper-iron or aluminium-magnesium-silicon but the negative effect of particles is still evident.

f.- A more strict control of the iron content limiting the maximum percentage to even lower value would contribute to improve the properties of the alloy as this element forms coarse particles that accelerates the failure.

ACKNOWLEDGEMENT

Plates used in the present study were supplied by Gamesa Aeronáutica which is gratefully acknowledged. Authors wish to thank also to the Basque Government for the support given to the research programme from which the present paper has been obtained.

REFERENCES

1. Aluminium Alloys Take-Off (1998). *Materials World*. July. pp 407-408

2. Staley J.T, Liu J. and Hunt W.H. (1998) *Advanced Materials & Processes* **152**, 4, pp 17-20

3. Schöen M (1992) Materiales Utilizados en Aeronáutica. *Jornadas sobre Materiales Avanzados para Aeronáutica y Espacio*. San Sebastián.

4. Crane F.A.A. and Charles J.A. (1985) *Selection and Use of Engineering Materials*. Butterworths pp 216-244

5. ASTM E-8M-95a. *Standard Test Methods for Tension Testing of Metallic Materials*. Annual Book of Standards. Vol 03.01

6. ASTM E-399-90. *Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials*. Annual Book of Standards. Vol 03.01

7. Microstructure of Alloys (1984). In: *Aluminum: Properties and Physical Metallurgy* ASM. pp 58-104

8. Bucci R.J. (1979). Engng. Fract. Mech. 12 pp 407-441

9. Irisarri A.M and Atxaga G. (2000). *Fractographic Study of Two Damage Tolerant Alumium Alloys*. To be presented at this Conference.

10. Fatigue Data Book: Light Structural Alloys (1995) ASM International, pp 110-111

11. Byrne S.C. (1986) In *Aluminum Alloys; Their Physical and Mechanical Properties*
Vol II. EMAS Ltd. pp 1095-1107

12. De Sanctis and Lazzeri L. (1992) *Fatigue Fract. Engng. Mater. Struct.* **15,** 3, pp 249-263

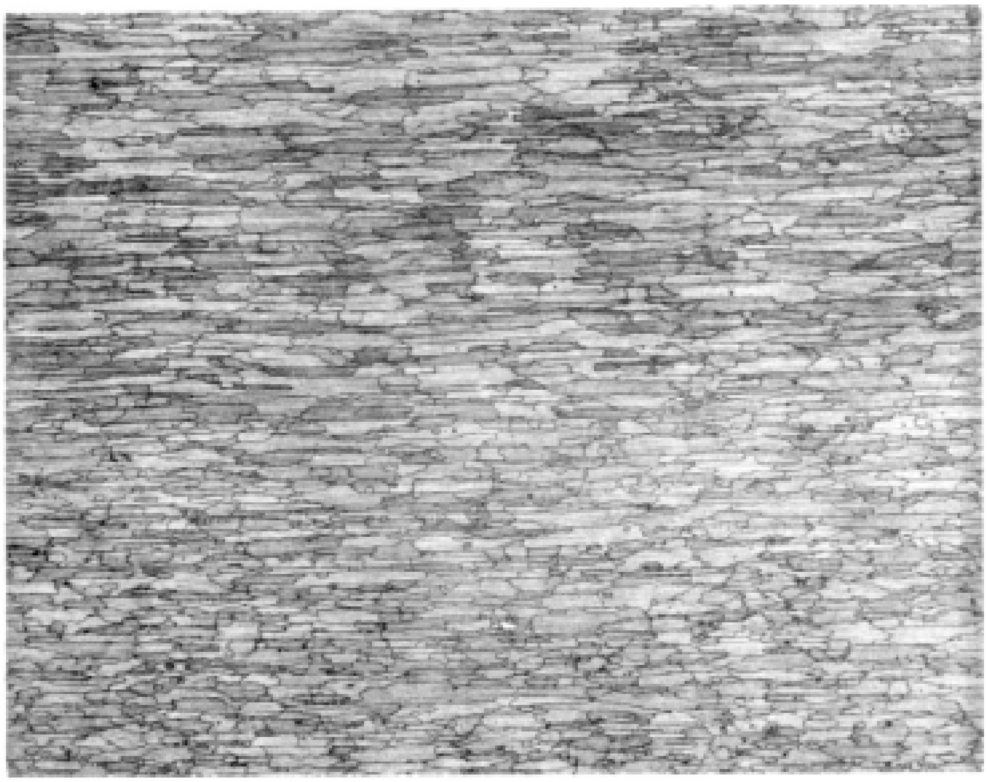


Figure 1. Micrograph (X100). Microstructure of the plate in the longitudinal direction showing elongated grains.

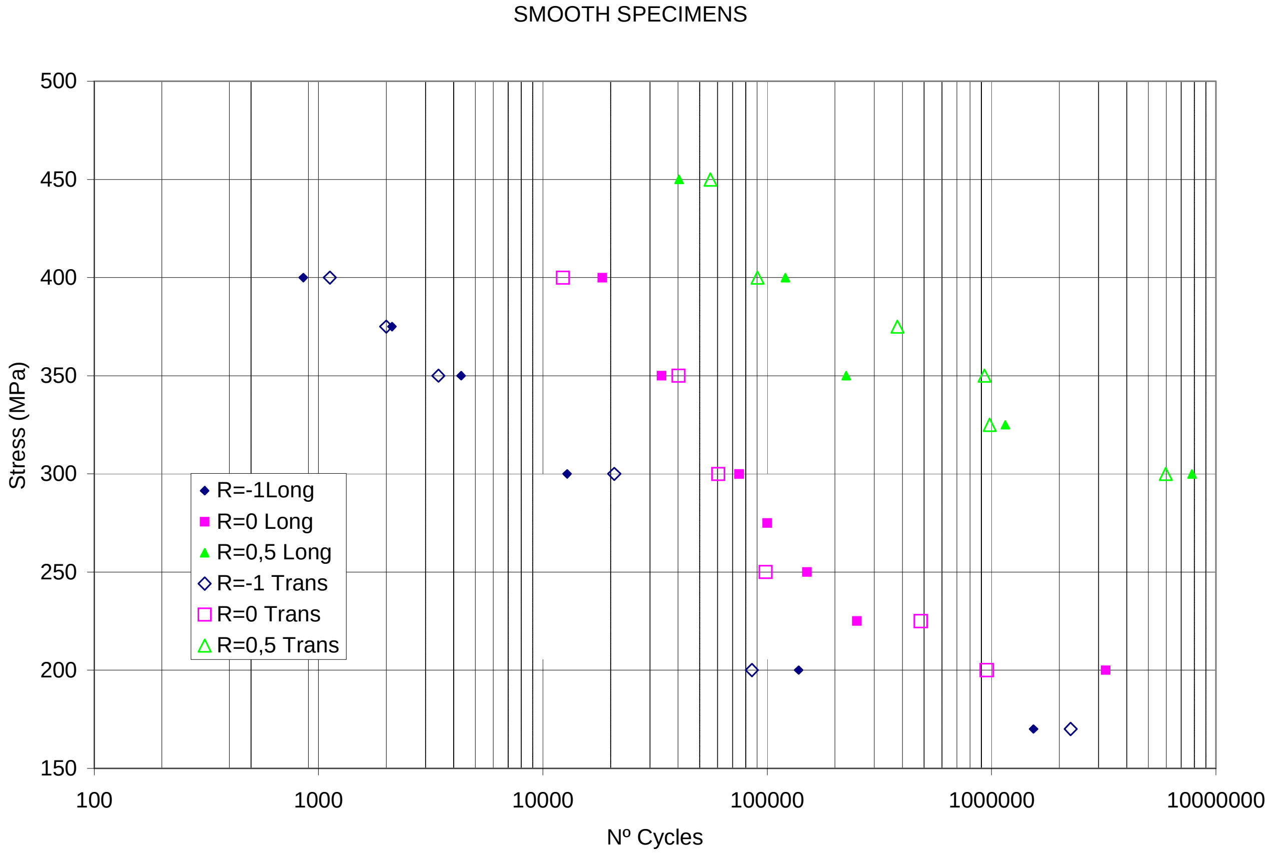
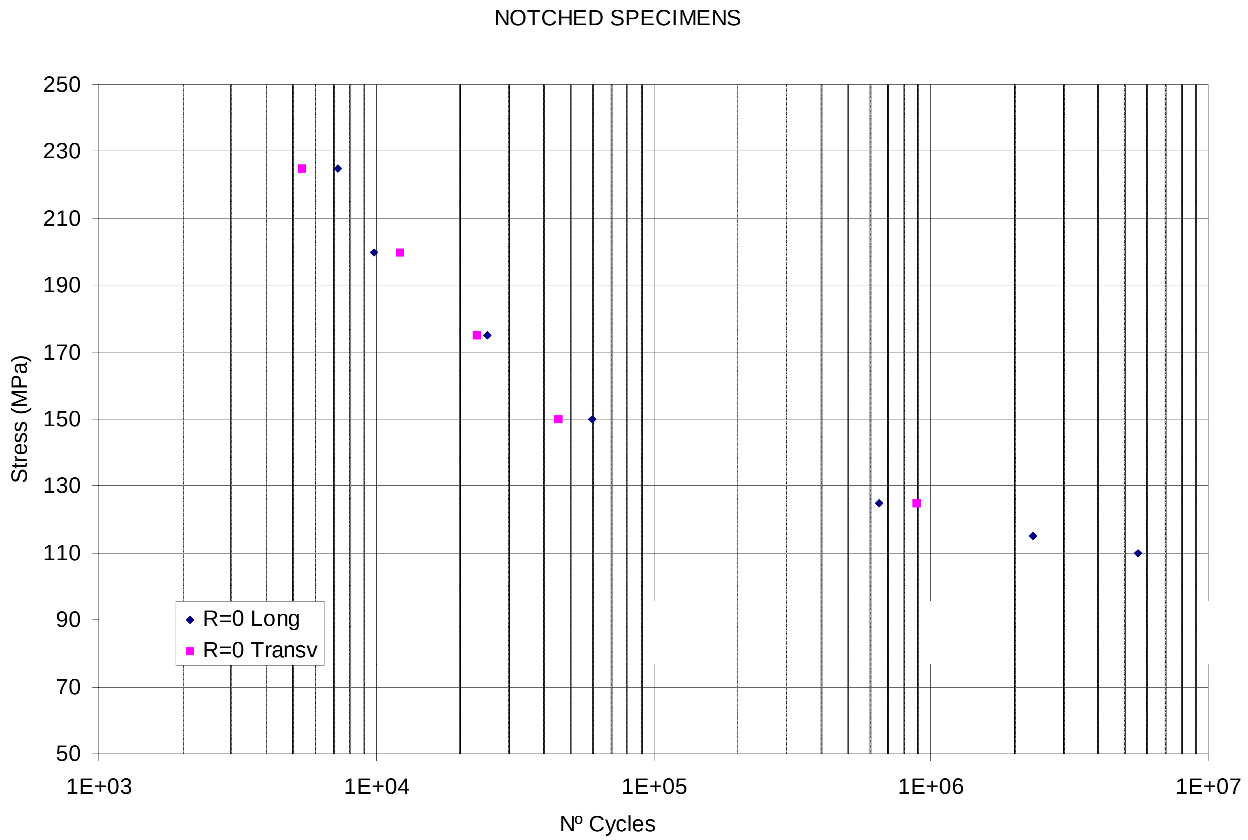


Figure 2. Fatigue tests results. Graph of the maximum stress versus number of cycles to failure. Smooth



specimens.

Figure 3. Fatigue tests results. Graph of the maximum stress versus number of cycles to failure. Notched specimens.

DIAGRAMA DE HAIGH

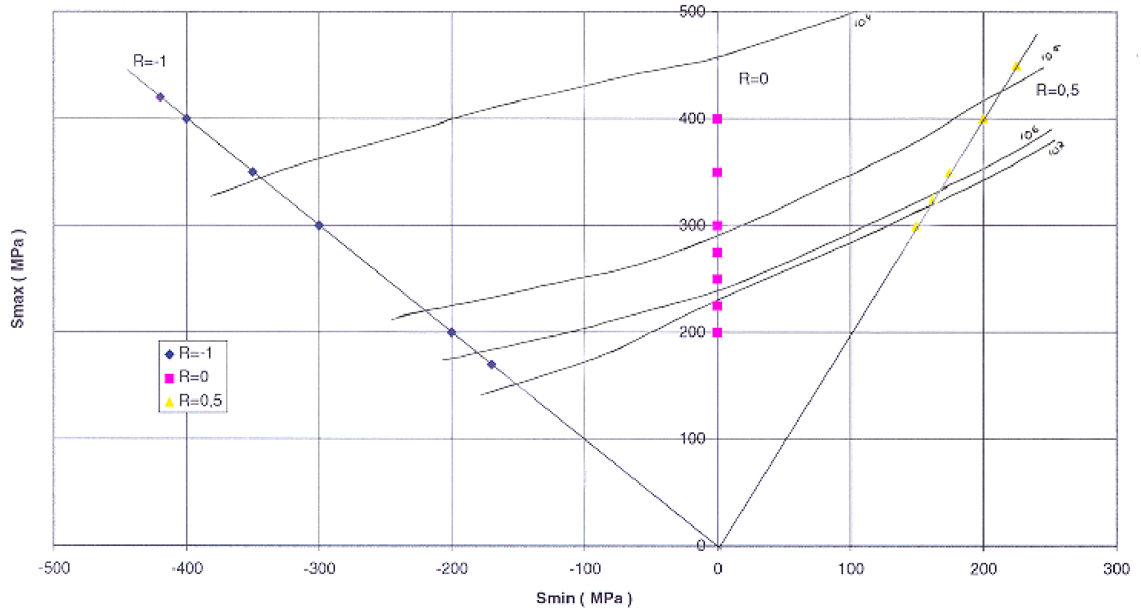


Figure 4. Haigh Diagram including the results obtained in the present work and those published in [9]