MODELING AND EXPERIMENTAL VERIFICATION OF MULTIPHASE STEEL FOR COMPONENTS SUBJECTED TO FATIGUE LOADING

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ABSTRACT

This research is done to acquire microstructure combinations that resist fatigue loading more than typical conventional microstructure (tempered martensite) and to study the effects of microstructure on fatigue properties of multiphase steels. A multiphase (polygonal ferrite and martensite) microstructure is developed. 2D and 3D square models with variation of ferrite fraction are used as local models and placed in front of the CT specimen in a global model. The ferrite shapes are from actual microstructure of multiphase material. It is found that the plastic zone size changes, as the ferrite fraction varies, and saturated at approximately 65% and 60% for 2D and 3D modelling, respectively. The influence of a ferrite areal fraction within a martensite matrix on fatigue crack propagation is studied. The variation of the areal fraction is achieved by means of intercritical thermal treatment, which specifically aims at optimizing the resistance to fatigue loading. The steels are annealed at different temperatures followed by water quenching and tempering process. Within the intercritical annealing temperature range, the areal fraction of ferrite increases with decreasing soaking temperature. Fatigue crack propagation tests are conducted according to ASTM E647-00 to obtain fatigue crack growth, FCG behaviour. It is found that the highest fatigue strength is achieved when the ferrite areal fraction is approximately 65%, which in this particular test, corresponds to 748 ^{0}C annealing temperature. It is concluded and is verified by computational modelling that appropriate thermal treatment can contribute to a significant improvement of fatigue properties and strength. The optimum ferrite fraction found from both computation and experiment is approximately 60% –65%.

ABSTRAK

Kajian ini dijalankan untuk memperoleh kombinasi mikrostruktur yang menentang kelesuan lebih daripada mikrostruktur tipikal konvensional (martensit terbaja) dan untuk mengkaji kesan mikrostruktur pada sifat lesu keluli berbilang. Oleh itu, mikrostruktur berbilang (poligon ferit dan martensit) telah dibangunkan. Model segiempat 2D dan 3D dengan variasi pecahan ferit telah digunakan sebagai model setempat dan diletakkan di hadapan spesimen CT dalam model global. Dalam hal ini, bentuk ferit terbentuk daripada mikrostruktur sebenar bahan berbilang. Didapati bahawa perubahan saiz zon plastik sebagai pecahan ferit berbeza, dan tepu pada anggaran 65% dan 60% masing-masing bagi model 2D dan 3D. Seterusnya pengaruh keluasan pecahan ferit dalam matriks martensit pada perambatan retak lesu telah juga dikaji. Perubahan keluasan pecahan dicapai dengan cara rawatan pengkhususan haba, yang bertujuan untuk mengoptimumkan rintangan beban kelesuan. Keluli disepuh lindap pada suhu yang berbeza diikuti oleh pelindapkejutan air dan proses pembajaan. Dalam julat suhu penyepuhlindapan kritikal, keluasan pecahan ferit meningkat dengan pengurangan suhu rendaman. Ujian kelesuan perambatan retak telah dijalankan mengikut ASTM E647-00 untuk mendapatkan sifat pertumbuhan retak lesu, FCG. Didapati bahawa kekuatan kelesuan tertinggi tercapai apabila keluasan pecahan ferit adalah dalam anggaran 65%, di mana dalam ujian tertentu, ia sepadan dengan suhu 748 ^{0}C. Dirumuskan dan disahkan oleh model pengiraan bahawa rawatan haba yang sesuai telah menyumbang kepada peningkatan ketara kepada sifat kelesuan dan kekuatan. Pecahan ferit yang optimum didapati dengan cara pengiraan dan eksperimen dianggarkan berada pada julat 60% - 65%.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	-	Two-dimensional
3D	-	Three-dimensional
ASTM	-	American Society for Testing and Materials
CAE	-	Computer Aided Engineering
CT	-	Compact tension
DPS	-	Dual phase steel
FCG	-	Fatigue crack growth
FCP	-	Fatigue crack propagation
FEA	-	Finite element analysis
GDS	-	Glow discharge spectrometer
HSLA	-	High strength low alloy
IHT	-	Intercritical heat treatment
MPM	-	Multiphase material
MVC	-	Microvoid coalescence
MVF	-	Martensite volume fraction
PZ	-	Plastic zone
SEM	-	Scanning electron microscopy

LIST OF SYMBOLS

a	-	Crack length
B	-	Specimen thickness
da/dN	-	Fatigue crack growth rate
E	-	Young modulus
Fe-C	-	Iron carbon
K	-	Stress intensity factor
K_{TH}	-	Threshold stress intensity factor
m	-	Paris coefficient
N	-	Number of load cycles
P	-	Load
R	-	Load ratio
r_p	-	radius of the plastic zone
W	-	Specimen width
α	-	Ferrite
γ	-	Austenite
σ	-	Stress
σ_{ys}	-	Yield stress
Θ	-	Angle
ζ	-	Fatigue striation spacing constant

LIST OF PUBLICATIONS

JOURNAL NO.	JOURNAL
1	Y. Prawoto, R. Idris, N. Kamsah, N. Tamin. Two-dimensional modeling to compute plastic zone in front of compact tension sample of a multiphase material. *Computational Materials Science*. (2009). 47: 482 - 490.
2	Y. Prawoto, R. Idris, N. Kamsah, N. Tamin. Three-dimensional modeling to compute plastic zone in front of crack in compact tension sample of multiphase material. *Computational Materials Science*. (2011). 50: 1499-1503.
3	Roslinda Idris, Yunan Prawoto. Influence of ferrite fraction within martensite matrix on fatigue crack propagation : An experimental verification with dual phase steel. *Material Science and Engineering A*. (2012). 552: 547-554.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The microstructure of conventional steels often makes it impossible to obtain concurrently good ductility and high strength. However, some applications, especially in the transportation industries, require economical high strength steel with good formability [1]. It is generally understood that among other forms of microstructure available in industrial steel, martensite has the best tensile properties [2]. However, at the same time it also has poor toughness due to its brittleness. It has been known and practiced extensively that tempering increases the toughness while sacrificing the material's tensile properties. Tempered martensite, also formerly known as sorbite, is the microstructure resulting from quenching followed by tempering.

To achieve weight reductions and fuel saving in the vehicles and to fulfill the energy and resource requirements, a new kind of steel named as multi-phase steel was developed. This type of steel exhibited a microstructure which was constituted basically on ferrite and martensite. Multi-phase is of interest because of better ductility and could provide a high mechanical resistance than other steels. They are very important for the automotive industry since they reduce weight and cost and also improve the fatigue life of products of many car parts such as wheels, radiator support, doors, spring support, etc (see Figure 1.1) [2]. The service life of many components of this type is dependent on materials fatigue life which is an important consideration in material selection.

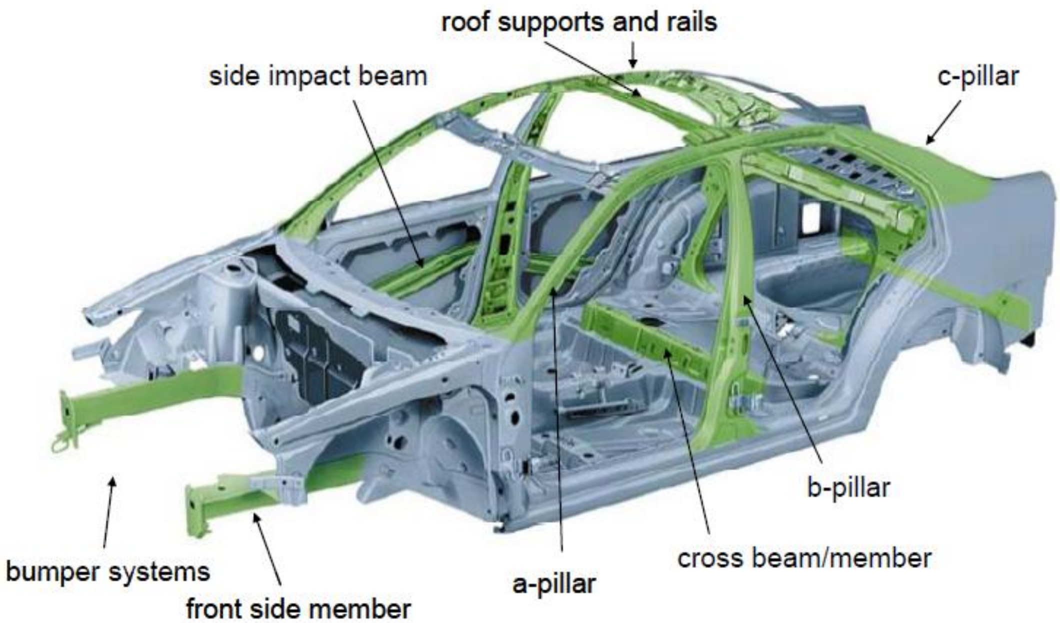

Figure 1.1 Example of car parts needs to improve the fatigue life [2]

Multi-phase steels can be obtained from the presence of martensitic and austenite islands dispersed in a ferrite matrix. These steels are produced by transforming the pearlite areas of ferrite-pearlite microstructure in low carbon steel to austenite by heating into the ferrite-austenite (α-γ) region and followed by quenching process. There are several factors that significantly affect the microstructure of multi-phase steel, namely the chemical composition of steel, temperature of intercritical annealing and the rate of cooling after annealing. The strength of such steels is determined mainly by the volume fraction of martensite, whereas the ductility is determined by the volume fraction of ferrite.

There is no doubt that controlling and determining the FCP rate is the most essential part of the fracture mechanics design approach. The best way to acquire it is by knowing the metallurgical mechanisms as well as the continuum mechanics of fatigue crack propagation. Nonetheless, it is difficult to combine these approaches since in the area where the continuum mechanism approach can be used, the metallurgical influence is small and vise versa, see Figure 1.2 [3]. Furthermore, research on microstructure often lacks the continuum mechanics approach; the same way research on continuum mechanics lacks microstructural observation.

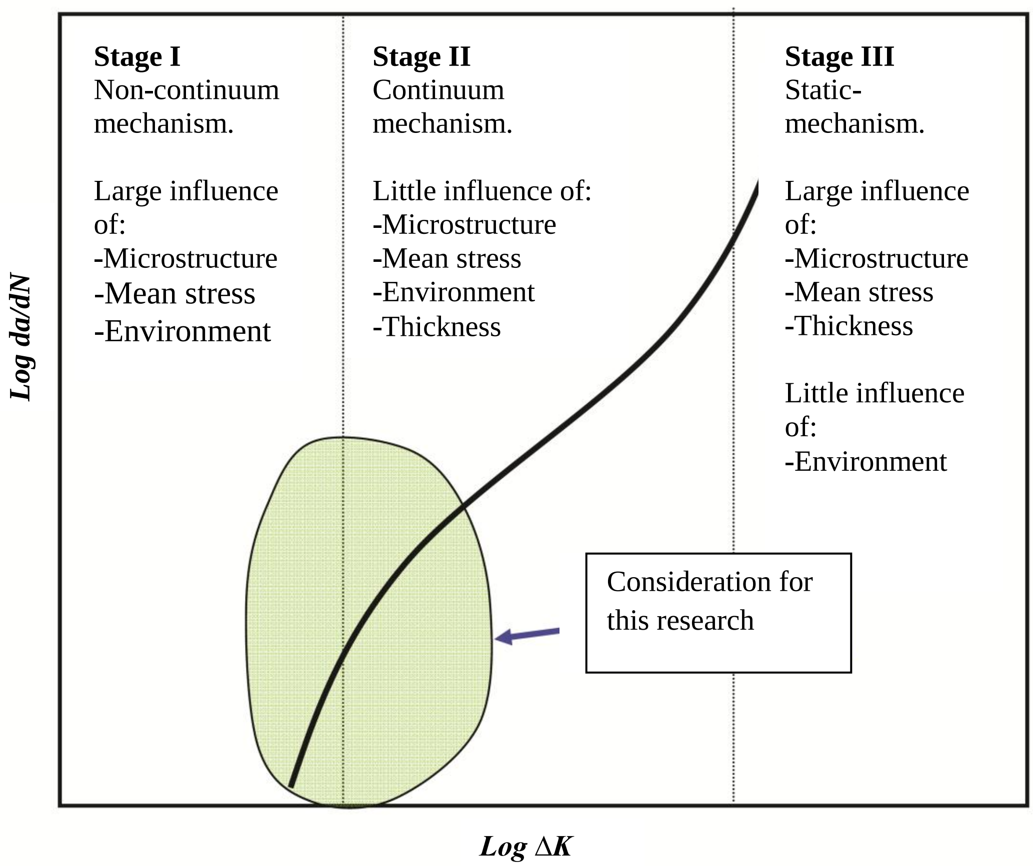

Figure 1.2 Schematic plot of the area grouping and their mechanisms [3]

In this research, the conceptual design, as well as the computation results and parts of the static and impact experiments are discussed lightly. In contrast, the discussion is focused on the fatigue crack propagation experimental procedure and the verification of the results with computational results. This research was done to obtain an optimized sample that grains its fatigue performance from its high toughness yet possesses high tensile properties due to its tailored microstructure. The objective ultimately is to achieve a microstructure that resists fatigue more than the microstructures conventionally available, and in an economical manner.

1.2 Objective of the Research

The main objective of the present research is to investigate and to provide a better understanding of the effects of heat treatment on the mechanical properties of multi-phase steels. The primarily objective of the research are:

1. To obtain microstructure combination that can resists to fatigue loading more than typical conventional microstructure (tempered martensite) and the effect of microstructure on fatigue properties of multi-phase steels.
2. To acquire the optimize phase composition of the microstructure which presumably the combination between polygonal ferrite and martensite by means of computational approaches.
3. To formulate heat treatment method for producing the optimum microstructure.

1.3 Scope of the Research

The scopes of this research work are:

1. Model creation and computational approach by using finite element method (Abaqus CAE) for two-dimensional, 2D modeling.
2. Model creation and computational approach by using finite element method (Abaqus CAE) for three-dimensional, 3D modeling.
3. Sample making and heat treatment to produce multi-phase material.
4. Fatigue crack propagation test to get the optimized sample which have the best characteristics resist to fatigue loading.
5. Fractography analysis by using Scanning Electron Microscope (SEM).

1.4 Methodology of the Research

To achieve the objective of this study, several methods have been used in the implementation of this research. These methods can be briefly explained as follows.

a) Computational method

   Two-dimensional, 2D and three-dimensional, 3D of plane strain models are developed to estimate the plastic zone size in front of a crack. 2D and 3D square models with variation of ferrite fraction are used as local models and placed in front of the CT specimen in a global model. The model is developed and meshed in ABAQUS/CAE (ABAQUS pre-processor).

b) Experimental procedure

   i. Sample making and heat treatment

      Compact tension samples appropriate for fatigue crack propagation and static test are made prior to heat treatment.

ii. Metallographic analysis

The microstructures of the samples are examined from the point of view of microstructure and chemical composition in term of the specific changes due to heat treatment. The quantitative approach is considered in Chapter 3, using image analysis coupled with scanning electron microscopy.

iii. Fatigue crack propagation testing

The heat treated samples are investigated with fatigue crack propagation testing and are carefully examined in terms of microstructure and mechanical properties, to achieve the optimized characteristics that resist to fatigue loading.

iv. Fractography analysis

The fatigue striations spacing formed on the fracture surface of the samples are analyzed using scanning electron microscopy (SEM). The quantitative relationships between microstructure and mechanical properties are investigated.

1.5 Significant of the Research

It is concluded that appropriate thermal treatment can contribute to a significant improvement of fatigue properties and strength, which is verified by computational modeling. The variations of the areal fractions are achieved by means of intercritical thermal treatment, which specifically aims at optimizing the resistance to fatigue loading.

1.6 Thesis Structure

The thesis comprises of five chapters. A brief explanation on every chapter is described as follows.

Chapter one, the introduction overviews the application and importance of multi-phase steel and highlights it as an important element of the automobile industries. It discusses the research objectives, scope, methodology, significant of the research and thesis structure.

Chapter two highlighted the theory of fracture mechanics and the formation of multi-phase steel that resist to fatigue loading. It covers the literature review on metallurgical mechanism of fatigue cracking and methodology for assessment of the influence of ferrite fraction within martensite matrix on fatigue crack propagation, the literature on the formation of multi-phase steels that resist to fatigue loading and also other researchers works on determination of the quantitative relationship of the multi-phase steel for specific application.

Chapter three narrates in details the research methodology of this research. It proposed improvement for life prediction methodology by discussing a research frame work employed in this research and presenting step by step process in accomplishing the results in the form of research methodology flow chart. This chapter gives adequate details regarding computational approach and detailed experimental procedures carried out throughout this research work.

Chapter four narrates the final discussion of this research. The results of the computational method and the experimental data are discussed comprehensively and are validated for model predictions.

Finally, the conclusions for the whole research and future recommendations are presented in chapter five.

1.7 Summary

In this chapter presented the definition to the problem, the objective and the scope of the project. An explanation of the methodology and significant of the project and also the report structure are enhanced in this chapter.

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