CHAPTER ONE

INTRODUCTION

1.1 General

Heavy vehicle is made specially to work up on uneven road surface and it contains some (attachment) that to be used for such soil and it used upon (wheeled) or (trucked), this attachment use to help to generate very high power of pulling to be used for all types of soils. These vehicles are different in design, shape, establishment, capability and attachment.

The heavy vehicle national law (HVNL) classified the heavy vehicle into three groups.

The first class (special purpose vehicle). A special purpose vehicle is a motor vehicle or trailer, other than agricultural vehicle or a tow truck, built for a purpose other than carrying goods, special purpose vehicle include a mobile crane, drill rig, dozer, armored vehicle, etc.

The second class is for freight carrying vehicles. The vehicle in this groups is the general freight carrying vehicle that are longer 19m require specific networks that are capable of handling these longer vehicle, this class include buses, livestock, vehicle carriers, etc.

The third class is the heavy vehicle which, together with it is load does not comply with prescribed mass or dimension requirement. A truck and dog trailer combination consisting of rigid truck with 3 or 4 axle towing a dog trailer with 3 or 4 axles weighting more than 42.5 ton.

Heavy vehicles are been used in the military section. Those vehicles used in military side have to satisfy some requirement, as light movement, reliability and the possibility of maneuverability [1].

The armored fighting vehicle is one of those heavy vehicle used in the military. It is a combat vehicle, protected by strong amour and generally armed with weapons, which combine operational mobility, tactical offensive, and defensive capabilities it can be wheeled or tracked.

Wheeled vehicle multipurpose or special purpose military wheeled platforms which transport personnel and all classes of supply, to include equipment and dry or liquid cargo. They perform general or specific missions, and support all war fighting functions (Movement and Maneuver, Intelligence, Fires, Sustainment, Command and Control, and Protection). They are specially designed vehicles, or commercial vehicles modified to meet certain military requirements, and are capable of safely operating on primary and secondary roads at highway speeds [1].

WMZ551B Wheeled armored vehicle is a personnel carrier, 6*6 wheels driven, equal wheel base armored combat vehicle with high cross- country capabilities. The vehicle is fitted with independent dual cross – arm suspensions, differential lock between the axles and wheels, safe pressure bullet –proof tires, water propellers and front and central axle steering, giving the equipment high mobility, pass- through capability and traveling stability.
In wheeled armored vehicle, the steering system is an integrated power steering mechanism. It designed to provide vehicle movement in given direction. During operation in Sudan, bad weather and off- roads, remarked that there is a repeated mechanical failure in the steering mechanism [2].

1.2 Problem statement

In the Wheeled armored vehicle (WMZ551B), a repeated failure is detected in the steering mechanism at the movable joint assy. this failure occurred in significant number of the vehicles been used.

1.3 Objectives:

The objective of this study is to investigate the repeated failure of movable joint in a heavy vehicle through the following tasks:

A. Establishment of the tensile stress-strain diagrams of movable joint material for armored WMZ551B.
B. Identification of the failure mechanism of the joint part.
C. Proposing a solution for the failed part.
D. Apply finite element analysis for the failure part.

1.4 Scope

This research aim to investigate the cause of failure of the movable joint in (WMZ551B) Wheeled armored vehicle experimentally using metallurgical study (scanning electron microscope), chemical analysis (EDS) and mechanical tests.

1.5 Significance of study

In military site, Sudan depends on imported vehicles due to political constrains. These vehicles and spare parts are very expensive and consume the hard currency.

When these imported vehicles are bad qualities. As an example of the absence of quality control, a movable joint is a part of the steering mechanism of combat vehicle, it is remark there is a repeated failure, decreasing the tactical efficiency and lead to critical situation in operation theatre because these vehicles being out of service. So engineers should make up their minds to overcome the technology constrains and look after an adequate solution.

CHAPTER TWO

LITERATURE REVIEW

2.1 Preface

Vehicles operated in the army are primarily used as carriers of weapons, necessary combat and logistics equipment and as means of transportation and protection of sub-units of infantry. Conformity to all requirements placed on military vehicles in a single vehicle is impossible and results mainly from mutually exclusive requirements, e.g. high resistance of a vehicle to enemy fire (high weight) and its dynamic characteristics. Thus, depending on the predicted use of military vehicles, they have been given specific performance characteristics. The diversity of vehicle characteristics caused the creation of a multitude of such vehicles differing in, e.g. use, maximum acceptable total weight (combat), and ability to overcome obstacles, level of resistance to fire and others. Military vehicles' diversity caused the need to classify them for various reasons. The effects of assumed different classifications of military vehicles are described in appropriate normative documents. It is often difficult to find a common part in the accepted classifications, which causes misunderstandings between interlocutors using different classifications. This results mainly from the possibility to classify a given military vehicle to different groups, types of adopted classification. Attempts to merge several classifications into one are also not uncommon, the fact of which speaks of the incomprehension of the problem, which often leads to unexpected effects. The difficulty of establishing an unequivocal terminology and classification of military vehicles had formed the base for this work [1].

2.2 Military vehicles classifications

The Encyclopedia of military Technology classifies armored equipment in relationship to the tasks it is supposed to realize on the field of battle, which has been presented on Fig 2.1.

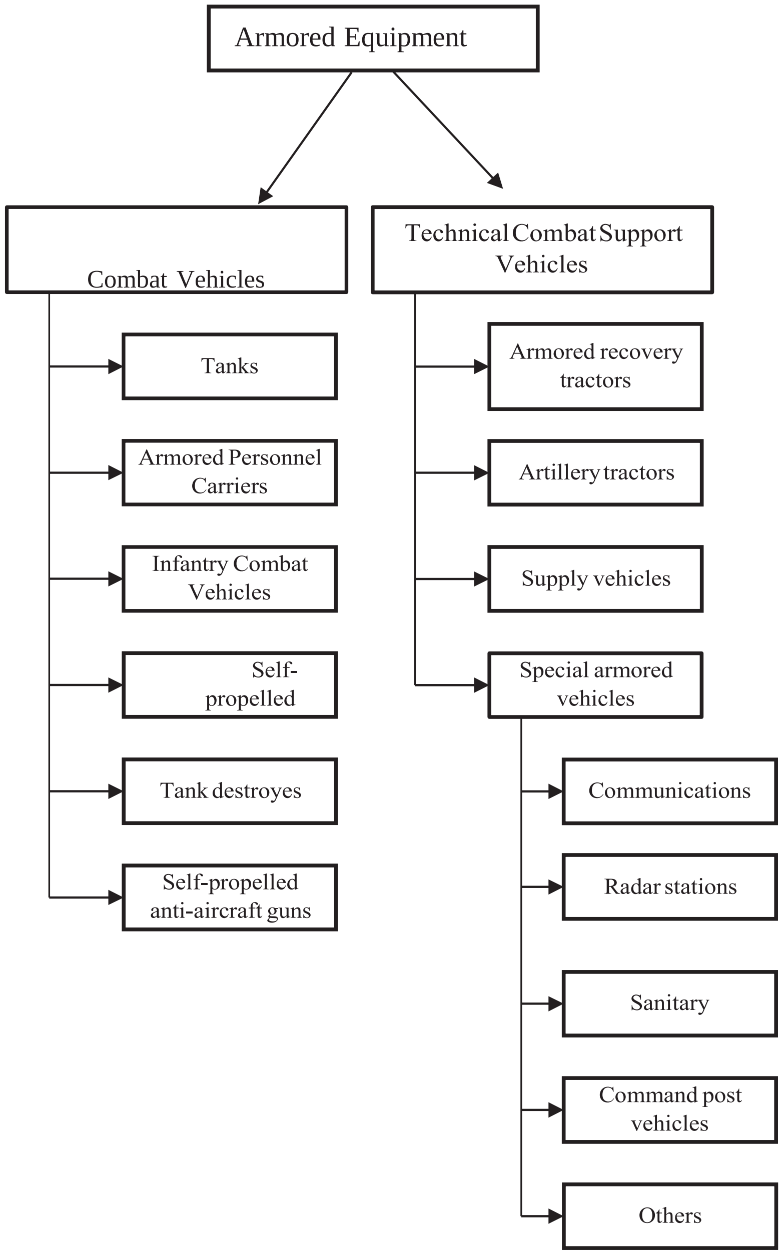


Figure 2.1 Military vehicle classifications [1]

2.3 Wheeled armored vehicle (WMZ551B)

The Armored vehicle (WMZ551B) is a personnel carrier, 6X6 all-wheels driven. It has an equal axle base with high cross- country capabilities and fitted with winch for self-recovery. the vehicle is fitted with independent dual cross – arm suspensions, differential lock between the axles and wheels, safe pressure bullet –proof tires, water propellers and front and central axle steering, giving the equipment high mobility, pass- through capability and traveling stability.

2.3.1 Major subsystems and component parts:

The vehicle is powered by a 4- stroke, 8- cylinder, and air-cooled, turbo-charged V- shape diesel engine. The transmission consists of transmitting parts such as the clutch, rear and compound boxes, gearbox (with transfer case), driving box, steering arm, wheel reduction gear, of which the controls are located in the driver's compartment.

The running gear consists of the suspension and wheels. The suspension is of the independent dual cross- arm type fitted with spiral springs and hydraulic shock absorbers and the tires are of the bulletproof meridian type.

The vehicle is divided into three compartments, i.e. the driver's compartment, the power compartment and passenger's compartment. The hull is fully enclosed and made of armor steel that provides protection of occupants and equipment against fires from small arms. The brake system and the attached air supply system use a full air pressure braking mechanism of the air supply and brake drive [2].

2.3.2 Technical Specifications of WMZ551B Wheeled armored

Table 2.1 shows the main parameters for armored vehicle type WMZ551B. The vehicle is 6X6 drive and weighted 16000 kg. The vehicle can carry up to 12 persons included the crew. The vehicle length is 6.727 m with 2.8 m width. The maximum output torque from the steering mechanism is 5590 Nm at rated pressure of 10 MPa.

Table 2.1 Armored WMZ551B Technical Specifications [2]

Weight	16000kg
Drive	6*6
Crew	3
Passenger	9
Length (hull)	6727mm
Width (hull)	2800mm
Power- to- weight ratio	14.7 kw/t
Steering wheel diameter	550mm
Output shaft torque	5590Nm (at 10 MPa)
Rated power output	320hp
Max engine torque	1100 Nm (at 1600 rpm)
Rated pressure	10 MPa

2.3.4 Steering system

In wheeled armored vehicle (6*6) wheel drive, the steering system is an integrated power steering mechanism. It designed to provide vehicle movement in given direction. Steering the vehicle in the motion on land is carried out by turning of wheel of two front axle , It mainly consist of steering wheel, all-directional transmission shaft, power steering (including control valve, power cylinder and steering mechanism), steering pump and steering liver system as shown in figure 2.2 . The movement of steering liver system by means of rack and sector gear mesh that drive the vertical arm shaft and causes the steering vertical arm to swing, thus achieving the steering movement. Steering movable joint assay is equipped in the steering liver system as shown in figure 2.3 [2].

Pradeep and patnaik in their study for the tie rod of passenger car found that the geometrical imperfections and modified boundary conditions greatly influence the critical load magnitudes [3].

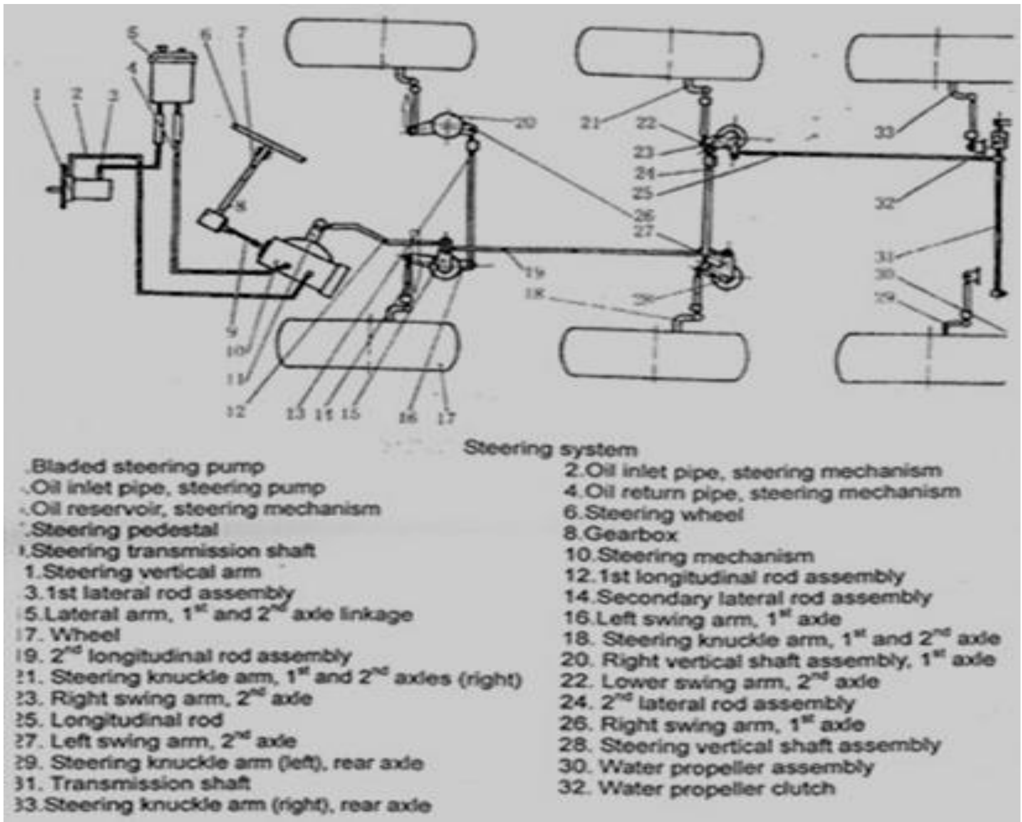


Figure 2.2 Steering system of armored vehicle (WMZ551B) [2].

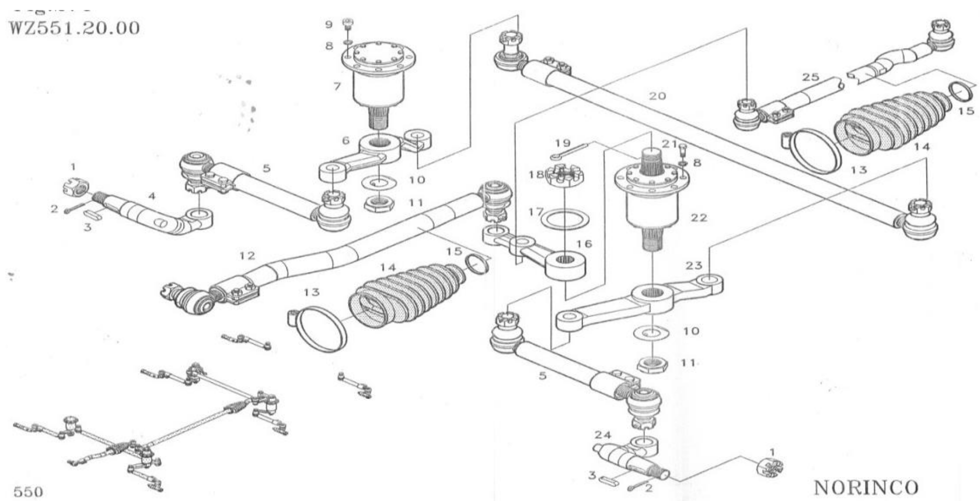


Figure2.3 Steering linkage for Armored type WMZ551B [2].

2.4 Failure of Elements

Failure can be defined, in general, as an event that does not accomplish its intended purpose. Failure of a material component is the loss of ability to function normally. Components of a system can fail one of many ways, for example excessive deformation, fracture, corrosion, burning-out, degradation of specific properties (thermal, electrical, or magnetic), etc. Failure of components, especially, structural members and machine elements can lead to heavy loss of lives. Even though the causes of failure are known, prevention of failure is difficult to guarantee. Causes for failure include improper materials selection, improper processing, inadequate design, misuse of a component, and improper maintenance. It's the engineer's responsibility to anticipate and prepare for possible failure; and in the event of failure, to assess its cause and then take preventive measures.

Structural elements and machine elements can fail to perform their intended functions in three general ways: excessive elastic deformation, excessive plastic deformation or yielding, and fracture. Under the category of failure due to excessive elastic deformation, for example: too flexible machine shaft can cause rapid wear of bearing. On the other hand sudden buckling type of failure may occur. Failures due to excessive elastic deformation are controlled by the modulus of elasticity, not by the strength of the material. The most effective way to increase stiffness of a component is by tailoring the shape or dimensions. Yielding or plastic deformation may render a component useless after a certain limit. This failure is controlled by the yield strength of the material. At room temperature, continued loading over the yielding point may lead to strain hardening followed by fracture. However at elevated temperatures, failure occurs in form of time- dependent yielding known as creep. Fracture involves complete disruption of continuity of a component. It starts with initiation of a crack, followed by crack propagation. Fracture of materials may occur in three ways brittle/ductile fracture, fatigue or progressive fracture, delayed fracture. Ductile/brittle fracture occurs over short period of time, and distinguishable. Fatigue failure is the mode in which most machine parts fail. Fatigue, which is caused by a critical localized tensile stress, occurs in parts which are subjected to alternating or fluctuating stress. Stress-rupture occurs when a metal has been statically loaded at an elevated temperature for a long time, and is best example for delayed fracture [4].

2.5 Fracture Mechanism

Fracture is a form of failure, and is defined as the separation or fragmentation of a solid body into two or more parts under the action of stress. Fracture that occurs over a very short time period and under simple loading conditions (static i.e. constant or slowly changing) is considered here. Fracture under complex condition, for example alternating stress, is considered in later sections.

The process of fracture can be considered to be made up of two components, crack initiation followed by crack propagation. Fractures are classified w.r.t. several characteristics, for example, strain to fracture, crystallographic mode of fracture, appearance of fracture, etc. Table.2.2 gives a brief summary of different fracture modes.

Table 2.2 Different fracture modes.

Characteristic	Terms used	
Strain to fracture	Ductile	Brittle
Crystallographic mode	Shear	Cleavage
Appearance	Fibrous and gray	Granular and bright
Crack propagation	Along grain	Through grains

The shear fracture is promoted by the shear stresses occur as result of extensive slip on active slip plane. While the cleavage fracture is controlled by tensile stresses acting normal to cleavage plane. A shear fracture surface appears gray and fibrous, while a cleavage fracture surface appears bright or granular. Actual fracture surfaces often appear as mixture of fibrous and granular mode. Based on metallographic examination of fracture surfaces of polycrystalline materials, they are classified as either transgranular or intergranular fractured. The transgranular fracture as the name go by, represents crack propagation through the grains, whereas intergranular fracture represents the crack that propagated along the grain boundaries. The fracture can also characterize as ductile or brittle fracture depending on the ability of a material to undergo plastic deformation during the fracture. A ductile fracture is characterized by considerable amount of plastic deformation prior to and during the crack propagation. On the other hand, brittle fracture is characterized by micro-deformation or no gross deformation during the crack propagation. Plastic deformation that occurs during ductile fracture, if monitored, can be useful as warning sign to the fracture that may occur in later stages. Thus brittle fracture shall be avoided as it may occur without warning. Since deformation of a material depends on many conditions such as stress state, rate of loading, ambient temperature, crystal structure; ductile and brittle are relative terms. Thus the boundary between a ductile and brittle fracture is arbitrary and depends on the situation being considered. A change from the ductile to brittle type of fracture is promoted by a decrease in temperature, an increase in the rate of loading, and the presence of complex state of stress (due to a notch).

Under the action of tensile stresses, most metallic materials are ductile, whereas ceramics are mostly brittle, while polymers may exhibit both types of fracture. Materials with BCC or HCP crystal structure can be expected to experience brittle fracture under normal conditions, whereas materials with FCC crystal structure are expected to experience ductile fracture. Figure.2.4 depicts characteristic macroscopic fracture profiles. The profile shown in figure 2.4(a) is representative of very high ductility represented by close to 100% reduction in cross-sectional area. This kind of failure is usually called rupture. It is observed in very soft metals such as pure gold and lead at room temperature and other metals, polymers, glasses at elevated temperatures. Most ductile metals fracture preceded by a moderate amount of necking, followed by formation of voids, cracks and finally shear. This gives characteristic cup-and-cone fracture as shown by figure 2.4(b). In this central interior region has an irregular and fibrous appearance. Figure-2.4(c) presents the typical profile of brittle fracture which is usually transgranular. It occurs in most ceramics and glasses at room temperature, long-chain polymers below their glass transition temperatures, certain metals and alloys below their ductile-to-brittle transition temperatures [4].

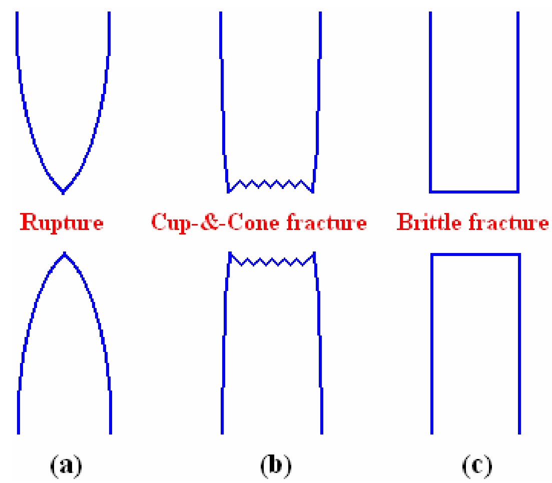


Figure 2.4 Fracture profiles.

Detailed and important information on the mechanism of fracture can be obtained from microscopic examination of fracture surfaces. This study is known as fractography. This study is most commonly done using scanning electron microscope (SEM). Common microscopic modes of fracture observed include cleavage, quasi-cleavage, and dimpled rupture. Characteristic feature of cleavage fracture is flat facets, and these exhibit river marking caused by crack moving through the crystal along number of parallel planes which form a series of plateaus and connecting ledges. Quasi-cleavage fracture is related but distinct from cleavage in the sense that fracture surfaces are not true cleavage planes. This often exhibit dimples and tear ridges around the periphery of the facets. Dimpled rupture is characterized by cup-like depressions whose shape is dependent on stress state. The depressions may be equi-axial, parabolic, or elliptical. This dimpled rupture represents a ductile fracture. Table.2.3 distinguishes two common modes of fracture.

Table 2.3 Ductile Verse Brittle fracture.

Parameter	Ductile fracture	Brittle fracture
Strain energy required	Higher	Lower
Stress, during cracking	Increasing	Constant
Crack propagation	Slow	Fast
Warning sign	Plastic deformation	None
Deformation	Extensive	Little
Necking	Yes	No
Fractured surface	Rough and dull	Smooth and bright
Type of materials	Most metals (not too cold)	Ceramics, Glasses, Ice

2.5.1 Ductile fracture

Most often ductile fracture in tension occurs after appreciable plastic deformation. It occurs by a slow tearing of the metal with the expenditure of considerable energy. It can be said that ductile fracture in tension is usually preceded by a localized reduction in cross-sectional area, called necking. Further it exhibits three stages

(1) after onset of necking, cavities form, usually at inclusions at second-phase particles, in the necked region because the geometrical changes induces hydrostatic tensile stresses,

(2) The cavities grow, and further growth leads to their coalesce resulting in

formation of crack that grows outward in direction perpendicular to the application of stress,
(3) Final failure involves rapid crack propagation at about 45^{o} to the tensile axis. This angle represents the direction of maximum shear stress that causes shear slip in the final stage. During the shear slip, crack propagates at a rapid speed around the outer perimeter of neck leaving one surface in form of cup, and the other in form of cone. Thus it is known as cup-and- cone fracture. In this central interior region has an irregular and fibrous appearance, which signifies plastic deformation. Different progressive stages of ductile fracture are shown in figure 2.5.

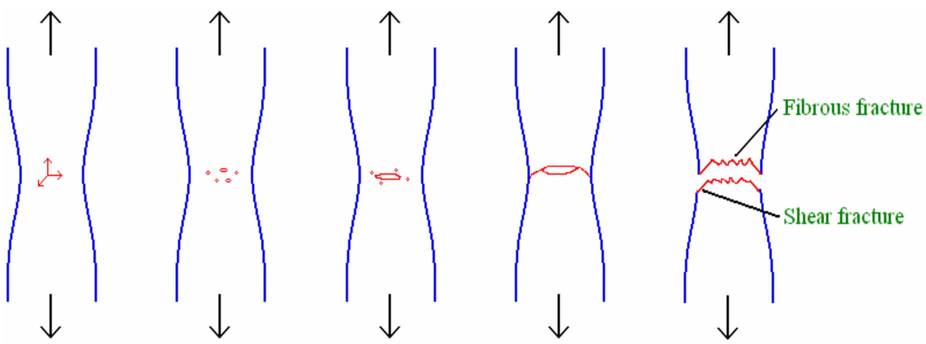


Figure 2.5 Stages of ductile tensile fracture.

The voids are thought to be nucleated heterogeneously at sites where further deformation is difficult. These preferred sites mainly consists of foreign inclusions, second-phase particles like oxide particles, or even voids those can form at grain boundary triple points in high-purity metals. It has been observed that concentration of nucleating sites had a strong influence on ductile fracture as true strain to fracture decreases rapidly with increasing volume fraction of second phase particles. In addition, particle shape also has an important influence. When the particles are more spherical than plate-like, cracking is more difficult and the ductility is increased. This is because dislocations can cross slip around spherical particles with ease than around plate-like particles thus avoids buildup of high stresses.

More details of fracture mechanism can be obtained from fractographic study of the fracture surface. At high magnification under microscope, numerous spherical dimples separated by thin walls are found on the ductile fractured surface. This is an indication that surface had formed from numerous holes which were separated by thin walls until it fractures. Dimples formed on shear lip of cup-and-cone fracture will be elongated attaining parabolic shape which is indication that shear failure took place [5].

2.5.2 Brittle fracture

The other common mode of fracture is known as brittle fracture that takes place with little or no preceding plastic deformation. It occurs, often at unpredictable levels of stress, by rapid crack propagation. The direction of crack propagation is very nearly perpendicular to the direction of applied tensile stress. This crack propagation corresponds to successive and repeated breaking to atomic bonds along specific crystallographic planes, and hence called cleavage fracture. This fracture is also said to be transgranular because crack propagates through grains. Thus it has a grainy or faceted texture. Most brittle fractures occur in a transgranular manner. However, brittle fracture can occur in intergranular manner i.e. crack propagates along grain boundaries. This happens only if grain boundaries contain a brittle film or if the grain-boundary region has been embrittled by the segregation of detrimental elements.

In analogy to ductile fracture, as supported by number of detailed experiments, the brittle fracture in metals is believed to take place in three stages –

(1) Plastic deformation that causes dislocation pile-ups at obstacles,
(2) Micro-crack nucleation as a result of build-up of shear stresses,
(3) Eventual crack propagation under applied stress aided by stored elastic energy.

As mentioned earlier, brittle fracture occurs without any warning sign, thus it needs to be avoided. Hence brittle fracture and its mechanism have been analyzed to a great extent compared to ductile fracture. Brittle fracture usually occurs at stress levels well below those predicted theoretically from the inherent strength due to atomic or molecular bonds. This situation in some respects is analogous to the discrepancy between the theoretical strength shear strength of perfect crystals and their observed lower yield strength values. It is a relatively new section of materials study under mechanical loading conditions. Using fracture mechanics concept it possible to determine whether a crack of given length in a material with known toughness is dangerous at a given stress level. This mechanics section can also provides guide lines for selection of materials and design against fracture failures [5].

2.5.3 Fatigue Failure

Failures occurring under conditions of dynamic or alternating loading are called fatigue failures, presumably because it is generally observed that these failures occur only after a considerable period of service. Fatigue failure usually occurs at stresses well below those required for yielding, or in some cases above the yield strength but below the tensile strength of the material.

These failures are dangerous because they occur without any warning. Typical machine components subjected to fatigue are automobile crank-shaft, bridges, aircraft landing gear, etc. Fatigue failures occur in both metallic and non-metallic materials, and are responsible for a large number fraction of identifiable service failures of metals. A typical fatigue-fracture surface looks like the one shown in figure-2.6. The fatigue crack nucleates at the stress concentration. Generally, the fatigue fracture surface is perpendicular to the direction of an applied stress. A fatigue failure can be recognized from the appearance of the fracture surface, which shows a smooth and polished surface that corresponds to the slow growth of crack, when the crack faces smoothen out by constant rubbing against each other and a rough/granular region corresponds to the stage of fast growth, after critical conditions is attained where member has failed in a ductile manner when cross section was no longer able to carry the applied load. The region of a fracture surface that formed during the crack propagation step may be results in characteristic pattern of concentric rings spread over the smooth region of the fracture surface, known as beach marks or striations, radiating outward from the point of initiation of the failure, as shown in figure-2.6. Beach marks (also known as clamshell pattern) are macroscopic dimensions and may be observed with the unaided eye. These markings are found for components that experienced interruptions during the crack propagation stage. Each beach mark band represents a period of time over which crack growth occurred. On the other hand fatigue striations are microscopic in size and subject to observation with the electron microscope (either TEM or SEM). The relatively widely spaced striations are caused by variations in the stress amplitude during the life of the component. On a much finer level, a large number of striations may be sometimes being seen. The width of each striation here is equal to the distance by which the crack grows during one cycle. Any point with stress concentration such as sharp corner or notch or metallurgical inclusion can act as point of initiation of fatigue crack.

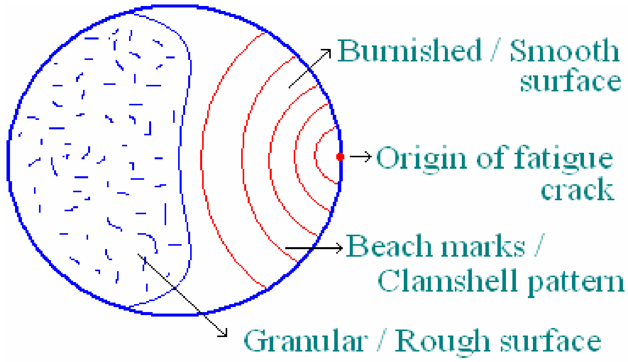


Figure 2.6 Schematic of fatigue fracture surface.

There are three basic requirements for the fatigue fracture to occur.
(a) A maximum tensile stress of sufficiently high value
(b) A large enough variation or fluctuation in the applied stress
(c) A sufficiently large number of cycles of applied stress.

The stress cycles that are evident in fatigue studies are characterized using many parameters, such as mean stress, alternating stress, stress ratio and amplitude ratio [5].

Based on structural changes that occur during fatigue, fatigue failure process can be divided into two stages. The first stage is the crack initiation, which includes the early development of fatigue damage that can be removed by suitable thermal anneal. The slip-band or crack growth, involves the deepening of initial crack on planes of high shear stress. This is also known as stage-I crack growth. The crack growth on planes of high tensile stress involves growth of crack in direction normal to maximum tensile stress, called stage-II crack growth. The final ductile failure occurs when the crack reaches a size so that the remaining cross-section cannot support the applied load.
Fatigue failures usually are found to initiate at a free surface or at internal flaws such as inclusions where the local stress causes some heterogeneous permanent flow leading to formation of a small crack. Fatigue failures start as small microscopic cracks and, accordingly, are very sensitive to even minute stress raisers.

It has been observed that diffusion processes are not necessary to the formation of fatigue cracks. The initiation of a fatigue crack does not lead to immediate failure, rather, the crack propagates slowly and discontinuously across the specimen under the action of cyclic stress. The amount of crack motion per cycle depends on the material and the stress level; high stresses favor larger crack growth increments per cycle. Eventually, the crack propagates to the point where the remaining intact cross section of material no longer can support the applied load, and further crack propagation is rapid, leading to catastrophic failure. The final fracture surface is composed of an area over which there was slow crack propagation and an area where the crack moved rapidly. Final fracture can be either ductile or brittle type.

In polycrystalline metals, during a fatigue test slip lines appear first on crystal whose slip planes have the highest resolved shear stress. As time goes on and the number of stress cycles increases, the size and number of slip bands (clusters of slip lines) increase. The extent and number of slip bands are also a function of the amplitude of the applied stress; higher stresses give larger values. In fatigue, under cyclic loading, the slip bands tend to group into packets or striations in a slip band. Each striation represents the successive position of an advancing crack front that is normal to the greatest tensile stress. Ridge kinds of striations are called extrusions while, while crevice striations are known as intrusions, and both tend to be formed depending on the crystal orientation. It has been shown that fatigue cracks initiate at intrusions and extrusions. Table-2.4 summarizes deformation features under static and cyclic loading. With increasing numbers of cycles, the surface grooves deepen and the crevices or intrusions take on the nature of a crack. When this happens, stage-I of the crack-growth process has begun i.e. stage-I crack propagates along persistent slip bands, and can continue for a large fraction of the fatigue life. Low applied stresses and deformation by slip on a single slip plane favor stage-I growth. On the other hand multiple-slip conditions favor stage-II growth. The transition from stage-I to stage-II is often induced when a slip-plane crack meets an obstacle such as a grain boundary. The rate of crack propagation in stage-I is generally very low on the order of nm per cycle compared with that in stage-II where it is in order of μm per cycle. Thus, from a practical viewpoint, stage-II is of importance than stage-I. Stage-I growth follows a slip plane, whereas stage- II growth does not have this crystallographic character. The fracture surface of stage-I is practically featureless. On the other hand, stage-II shows a characteristic pattern of striations, which occurs by repetitive plastic blunting and sharpening of the crack tip. Table.2.5 distinguishes stage-I from stage-II crack growth.

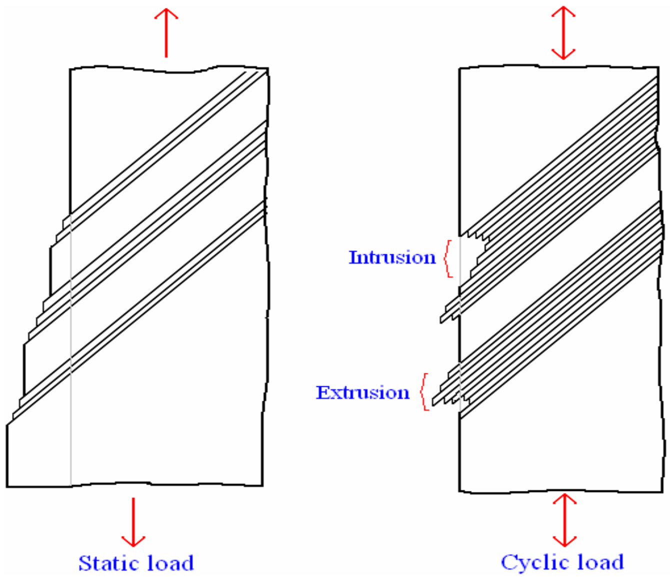


Figure 2.7: Comparison of slip bands formed under (a) static loading and (b) cyclic loading.

Table 2.4 Deformation under static and cyclic loads.

Feature	Static load	Cyclic load
Slip (nm)	1000	1-10
Deformation feature	Contour	Extrusions Intrusions
Grains involved	All grains	Some grains
Vacancy concentration	Less	Very high
Necessity of diffusion	Required	Not necessary

Table 2.5 Fatigue crack growth: stage-I Vs stage-II.

	Stage-I	Stage-II
Stresses involved	Shear	Tensile
Crystallographic	Yes	No
Crack propagation rate	Low (nm/cycle)	High (μm/cycle)
Slip on	Single slip plane	Multiple slip planes
Feature	Feature less	Striations

The region of fatigue fracture surface that formed during the crack propagation step can be characterized by two types of markings termed beach marks and striations. Both of these features indicate the position of the crack tip at some point in time and appear as concentric rings that expand away from the crack initiation site(s), frequently in a circular or semicircular pattern. Beach marks (sometimes also called clamshell marks) are of macroscopic dimensions, found for components that experienced interruptions during the crack propagation stage. Each beach mark band represents a period of time over which crack growth occurred. Striations are microscopic in size, and each of it is thought to represent the advance distance of a crack front during a single load cycle. Striation width depends on, and increases with, increasing stress range. There may be literally thousands of striations within a single beach mark. The presence of beach marks/striations on a fracture surface confirms that the cause of failure in fatigue. Nevertheless, the absence of either or both does not exclude fatigue as the case of failure [6].

2.6 Fracture Appearance and Mechanisms of Fracture

Fractography is the science of revealing loading conditions and environment that caused the fracture by a three- dimensional interpretation of the appearance of a broken component. If the specimen is well preserved and if the analyst is knowledgeable, the fracture appearance reveals details of the loading events that culminated in fracture. An understanding of how cracks nucleate and grow microscopically to cause bulk (macroscale) fracture is an essential part of fractography. The ability to accomplish this resides in interpretation of fracture surface features at both the micro- and macroscales. It is important that examination of the fracture surface and adjacent component surface be done starting at low magnification with sequential examination of features of interest at increasing magnification. It is only in this way that significant features are identified as to location on the macroscale fracture surface. Stated differently, potential explanations for cause for failure must be consistent with both macroscopic and microscopic features. The ultimate purpose of fractography and the other methods of failure analysis is the determination of the (technical) root cause of failure, which may arise from various conditions such as inappropriate use, an unanticipated operating environment, improper prior fabrication, improper or inadequate design, inadequate maintenance or repair, or combinations thereof. Possible root causes also include design mistakes such as inadequate stress analysis, alloy selection, improper mechanical/thermal processing, improper assembly, and failure to accommodate an adverse operating environment. Fractography provides a unique tool to determine potential causal factors. It provides information about whether the material is used above its design stress or not. The failed component had or did not have the properties assumed by the design engineer. In addition to information of whether a discontinuity was critical enough to cause failure.

Tables 2.6 list some general types of macroscale and microscale fractographic features, which are described in more detail in this article. In summary form, the following are key features in distinguishing between montonic versus fatigue fracture and ductile versus brittle fractures (on either a macroscale or microscale): Monotonic versus fatigue fracture: Beach marks and striations indicate fatigue, but their absence does not confirm fracture from monotonic loads. Fracture surfaces from fatigue do not always reveal beach marks and fatigue striations. Macroscale ductile versus brittle fracture: Macroscale ductile fracture is revealed by obvious changes in cross section of the fracture part and/or by shear lips on the fracture surface. Macroscale brittle fractures have fracture surfaces that are perpendicular to the applied load without evidence of prior deformation. Macroscale fracture surfaces can have a mixed-mode appearance (brittle-ductile or ductile- brittle). The brittle-ductile sequence is more common on the macroscale, while the appearance of the ductile portion is typically microscale in a ductile-brittle sequence. Microscale ductile versus brittle fracture: Microscale ductile fracture is uniquely characterized by dimpled fracture surfaces due to microvoid coalescence. Microscale brittle fractures are characterized by either cleavage (transgranular brittle fracture) or intergranular embrittlement [7].

Table 2.6 Macroscale Fractographic Features

Mark/Indication	**Implication**
Visible distortion	Plastic deformation exceeded yield strength and may indicate instability (necking, buckling) or post-
Visible nicks or gouges	Possible crack initiation site
Fracture surface orientation relative to component geometry and loading conditions	Helps separate loading modes I, II, III Identifies macroscale ductile and brittle fracture.
Both flat fracture and shear lips present on fracture surface	Crack propagation direction parallel to shear lips Mixed-mode fracture (incomplete constraint)
Tightly closed crack on surface	Possible cyclic loading Possible processing imperfection, e.g., from shot peening, quench cracks
Radial marks and chevrons (v-shape)	Point toward crack initiation site Show crack propagation direction

Crack arrest lines (monotonic loading) (u-shape)	Lines point in direction of crack propagation Indicate incomplete constraint
Crack arrest lines (cyclic loading) (beach marks, conchoidal marks)	Indicates cyclic loading Propagation from center of radius of curvature Curvature may reverse on cylindrical sections as crack propagates
Ratchet marks	More likely in cyclic loading Indicates initiation site(s)
Adjacent surface and or fracture surface discoloration	May indicate corrosive environment May indicate elevated temperature
Oxidized fingernail on fracture surface	Possible crack initiation site
Fracture surface reflectivity	Matte: ductile fracture or cyclic loading Shiny: cleavage likely Faceted (“bumpy”) and shiny; intergranular fracture in large grain size

2.7 Ductile and Brittle Behavior

Perhaps most importantly, the question of whether a fracture is ductile or brittle is almost always addressed in a failure analysis. Ductile and brittle are terms often used to describe the amount of macroscale plastic deformation that precedes fracture. The presence of brittle fracture is a concern, because catastrophic brittle fracture occurs due to the elastic stress that is present and usually propagates at high speed, sometimes with little associated absorbed energy. Fracture occurring in a brittle manner cannot be anticipated by the onset of prior macroscale visible permanent distortion to cause shut down of operating equipment, nor can it be arrested by a removal of the load except for very special circumstances.

It must be pointed out, however, that the terms ductile and brittle also can be and are applied to fracture on a microscopic level. At the macroscale, ductile fracture by the microscale ductile process of microvoid formation and coalescence is characterized by plastic deformation and expenditure of considerable energy, while microscale brittle fractures by cleavage are characterized by rapid crack propagation with less expenditure of energy than with ductile fractures and without macroscale evidence of plastic deformation. The point is that the terms ductile and brittle are used to describe both appearance (macroscale behavior) and mechanism (microscale behavior). The macroscale view of ductility is neither more nor less correct than the microscale definition for the fracture mechanism.

The specific meaning of ductile and brittle may carry different connotations depending on background, context, and perspective of the reader. It is therefore important to clearly identify whether a ductile or brittle fracture is being described in terms of macroscale appearance or microscale mechanisms. It is also important to note that there is no universally accepted dividing line for macroscale ductile and brittle behavior in terms of strain at fracture or in terms of energy absorption. For example, large fracture strain is desirable for forming operations, and material selection may be based on the relative ductility observed during tensile testing.

Materials that do not show obvious necking in a tensile test are sometimes described as brittle, but that is not a generally accepted or valid meaning of the term. For example, the absence of obvious necking may be due to the geometry of the specimen. Relative ductility observed during tensile testing also is an arbitrary basis for defining macroscale ductility. For example, that a material has "adequate" ductility when the reduction in area (RA) is between 26 and 18% and "limited" ductility when the RA is between 18 and 2% and is brittle when the RA is below 2% has been suggested. Strain hardening exponents (n) for most structural alloys are typically in the range of 0.05 to 0.2, which translates to a RA in the range of 5 to 22% before necking instability is attained. Thus, few materials that are not cold worked would neck before 2% strain and would be considered brittle in this criterion for metal forming operations.

Another set of criteria may apply in structural design, where analytical expressions to determine allowable loads are based on whether failure is ductile or brittle. Some (arbitrary) value of tensile elongation or reduction in area (RA) is required to define whether a (ductile) distortion energy yield criterion or a (brittle) maximum normal stress or maximum shear criterion (perhaps modified by a normal stress term, as the Coulomb-Mohr model) is used in design. Ductile behavior also is often associated with high energy absorption at fracture, and adequate toughness or ductility may be evaluated and defined by impact data, where criteria to determine whether the fracture is ductile or brittle involves some minimum level of absorbed energy at the service temperature of interest, say 14 or 20 J.

The macroscale definition of ductile versus brittle behavior also may be misleading about material behavior. For example, when subjected to large compressive hydrostatic loads, "brittle" materials may behave in a ductile manner. The fracture strain of ductile materials increases with an increase in loading conditions containing a large compressive hydrostatic component relative to the deviatoric component of stress and decreases with an increase in the tensile-hydrostatic stress component.

It is also possible for ductile fracture to require little energy for initiation or propagation if strain-hardening capacity is low. From the perspective of "safe" design, materials that are inherently ductile but can behave in a brittle manner in service require the most caution. Many engineering materials are ductile and some are inherently brittle, but those behaviors can be altered.

Possible reasons for brittle behavior of ductile materials include loading conditions and the internal state of stress created by the part geometry and the geometry of any imperfections in conjunction with the operating environment (chemically reactive and/or high or low temperature). The inherent ductile behavior of metallic material also can be drastically reduced by improper heat treatment (e.g., incipient melting, temper embrittlement, improper age hardening) by processing (hydrogen embrittlement due to plating baths).

Smaller amounts of plastic deformation might be determined via careful measurement if the surfaces of the component are relatively smooth. The ability to see a neck in a tensile specimen depends on the amount of strain hardening and to some extent, the amount of strain-rate hardening. Plastic flow via slip can occurs without visual evidence if there is no hardening to force the neck to grow along the length of the specimen. There may be microstructural evidence or microscale fractographic evidence of plastic deformation, but it occurs over a sufficiently small volume that it is not visually apparent. In some instances, small amounts of plastic deformation may be visible at the macroscale, such as the twisting of extrusion marks around the axis of the component (torsion loading). Two halves of a bending fracture can often be brought into close proximity to determine if a small amount of plastic bending has occurred (for example, by placing the two components on a flat surface). This is a helpful technique in the examination of threaded cylindrical sections. However, it is of extreme importance that two fracture surfaces not be brought into actual physical contact. Doing so can destroy microscale fractographic information. Sometimes plastic strain can also be seen in such an instance by examination of the surface of the component adjacent to the fracture. Plastic strain will result in a roughening of the surface if the grain size is very large. Conversely, the presence of a large grain size may be visible (detected) by roughening of the surface for a component with a distortion of the original geometry [8].

The surface profiles that can be used to identify small-scale plastic strain. Profilometer traces are obtained from matching regions on each half of the fracture surface. If the two traces cannot then be brought into alignment, it is likely that there has been some plastic deformation associated with fracture. Obviously, if a piece has dropped out of the surface, there may be no matching but neither has there been any plastic deformation. It is also important to clarify whether the term ductile refers to Plastic strain accumulated prior to the nucleation and growth of a crack, the process of crack nucleation, or the process of crack growth [7].

The microscopic mechanism of fracture in the annealed material is a ductile mechanism (microvoid coalescence), and macroscopic deformation preceded fracture. Thus, there is little confusion in describing the fracture as ductile on both the macroscopic and microscopic scales of observation. However, in cold worked material there is plastic deformation (presumably compressive) during manufacturing, and the presence of prior cold work may explain the absence of the macroscopic necking. Metallographic observation and/or hardness testing would determine the material condition and clarify the effect of previous cold working on the fracture appearance, which could be either ductile or brittle at the microscale [9].

2.8 Macroscopic Ductile and Brittle Fracture Surfaces

As noted in the previous section, there is no universally accepted dividing line between ductile and brittle behavior at the macroscale in terms of strain at fracture, nor is there a defined dividing line in terms of energy absorption. The terms ductile and brittle also can be and are applied to fracture on a microscopic level. Therefore, it is desirable to first provide a working definition of macroscopic ductile and brittle fracture.

In the context of this article, a fracture is brittle at the macroscale if it is on a plane normal to the maximum normal stress (condition 4 in Figure (2.8)). A fracture is considered to be macroscopically ductile when the fracture surfaces are inclined to an imposed load (slant fracture or plane-stress).

Toughness is higher under conditions of plane stress, as the additional work expended in work-hardening deformation contributes to fracture resistance under load. A fracture surface displaying both types of planes can be described as a mixed mode fracture or alternatively, by indicating the presence of shear lips on the fracture surface.

Figure 2.8 shows the variation in fracture toughness of fracture surfaces for an inherently ductile material. As section thickness (B) or preexisting crack length (a) increases, plane strain conditions develop first along the centerline and result in a flat fracture surface. With further increases in section thickness or crack size, the flat region spreads to the outside of the specimen, decreasing the widths of the shear lips. When the minimum value of plane-strain toughness (KIc) is reached, the shear lips have very small width.

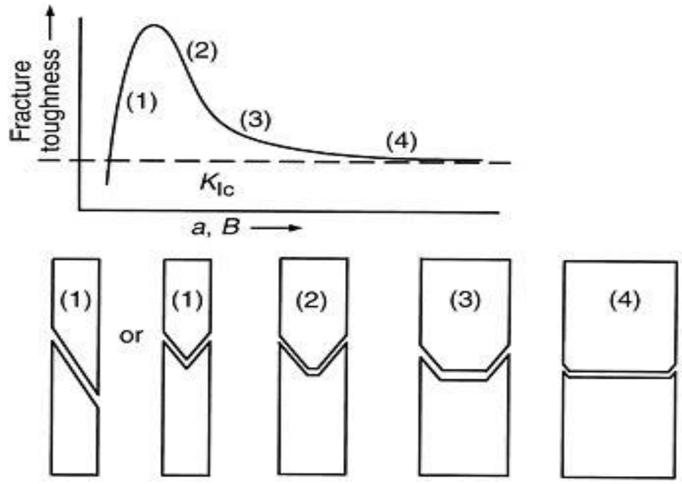


Figure 2.8 Schematic of variation in fracture toughness and macro-scale features of fracture surfaces for an inherently ductile material.

The local state of stress created by a load on component geometry may cause crack propagation (i.e., critical fracture) that results in a fracture surface with a macroscale appearance; that is totally ductile, totally brittle, Initially brittle, then ductile, Initially ductile, then brittle or Mixed mode (ductile and brittle)

In the latter two cases (4 and 5), the ductile appearance may not be directly visible at the macroscale. Initially, ductile fractures (case 4) are usually associated with rising-load ductile tearing, or the initial ductility may be inferred by transverse strain at the crack tip. The size of the plastic zone may be microscale in this case. Mixed- mode ductile and brittle cracking (case 5) would be inferred due to the presence of an intimate mixture of cleavage and microvoid coalescence at the microscale or by the presence of shear lips at the macroscale [9]. The fracture appearance that occurs depends on the microstructure (strength and ductility) of the material and the degree of constraint associated with the presence of a crack like imperfection. Constraint and fracture appearances are discussed further in following paragraphs, and the macroscopic conditions associated with the onset of critical fracture (i.e., stress and crack size) are also briefly described in terms of fracture mechanics. However, it also must be noted that some of the above criteria are based on macroscopic conditions or appearances and do not consider the microscopic mechanisms (i.e., slip, twinning, viscous flow, cleavage) that cause fracture. A fracture may appear to be macroscopically brittle, but the cracking process may occur by a ductile mechanism. Examples in which the cracking mechanism is ductile but for which there is no or little visual macroscopic distortion include: monotonic loading of a component containing a cracklike imperfection (plane-strain microvoid coalescence fracture induced by part and crack geometry), long-life cyclic loading, and elevated temperature failure (intergranular creep fracture). These examples are discussed in subsequent sections of this article, but the major point here is that the terms ductile and brittle should be used carefully with respect to the scale of observation or the description of fracture mechanisms. The distinction is important, because macroscopic brittle fractures can occur from the microscopic mechanism of ductile cracking.

The Constraint is created by longer cracks, thicker sections, and a decreased crack tip radius. If the material is inherently brittle (say a steel below the ductile-brittle transition temperature, DBTT), crack initiation is expected at or near the preexisting crack like imperfection and the crack is expected to propagate in a microscale brittle manner.

When the material has some inherent ductility, the fracture process is influenced by component and crack geometry creating various fracture surface features. The purpose here is not to discuss microscopic details of fracture initiation and crack propagation but rather to characterize the macroscopic appearance. The features to be considered are:

Crack blunting and crack propagation on a plane of maximum shear stress

Loss in constraint due to crack propagation with a macroscale transition from plane strain flat fracture (normal to the load) to plane stress slant fracture

Mixed mode fracture and incomplete constraint resulting in shear lips and crack arrest lines

Creation of constraint by subcritical crack growth resulting in a fracture surface predominantly flat after a small initial ductile region (which may not be macroscale visible)

As previously noted, ductile cracking by microvoid coalescence can result in a macroscale brittle fracture when the cracking is constrained by the geometry of the part and/or crack. With geometric constraint, plastic strain may be concentrated and lead to fracture without visible macroscale deformation. The microscale cracking mechanism is "ductile," but geometric constraint limits macroscale distortion. This type of fracture may best be referred to as "plane-strain microvoid coalescence," following the previous definition of macroscale brittle fracture and also characterizing the microscopic process of cracking. The geometry of the part and/or crack is thus one factor that may influence the macroscale deformation of the fracture process (distinct from the microscale mechanisms of cracking, which are discussed later in this article). Shear Lips and Crack Arrest Lines. Consider first the effects of section thickness for an intermediate value of crack length and a "sharp" crack tip. For thin sections there is little constraint imposed by a stress concentrator so that the fracture process occurs essentially under conditions of plane stress, resulting in complete slant

fracture (condition 1 in Fig.2.8). As the section thickness increases, constraint, which is higher along the centerline than at the free surfaces, becomes sufficiently large to create plane-strain conditions and result in flat fracture (Fig. 2.8, condition 4). The slant fracture surfaces (Fig. 2.8, conditions 2 and 3) are described as shear lips, or alternatively, the fracture can be described as mixed mode. Orientation of the shear lips may be used to identify the crack initiation location, which is helpful since chevrons or radial marks may not be present. The direction of crack propagation is parallel to the shear lips [9].
Further increases in section thickness spread constraint toward the sides of the specimen, decreasing the width of the shear lips and ultimately resulting in a fracture that is essentially 100% flat. (Figure. 2.8, condition 4). (There is still a vanishingly small shear lip unless the material is inherently brittle.)[10].

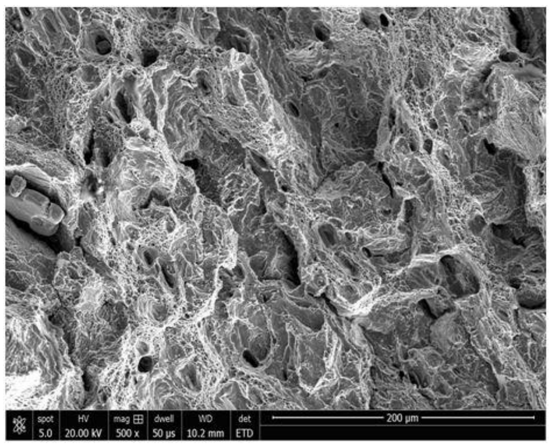


Figure 2.9 fracture surface of high Mn steel sample after rolling which shows a combined brittle and ductile fracture. The features are many ductile dimples, voids indicating the ductile failure, and cleavage planes (flat planes with small atomic steps indicating brittle fracture [10].

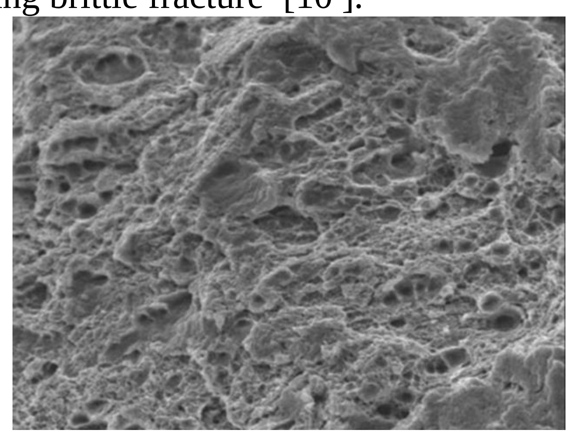


Figure 2.10 A high magnification SEM photomicrograph of the ductile overload fracture surface along one side of the pre-existing crack area (upper right region of Figure 8). No indications of fatigue failure were noted between the ductile overload and crater/hot crack [10].

2.9 Classification of Fracture Processes

Fracture processes are classified based on quite different individual aspects. The reason for that is the tremendous variety in which fracture processes appear and the diverse reasons leading to failure. First and foremost, a fracture depends on the properties of the considered material because the damage processes happening on a micro-structural level in the material determine its characteristic behavior. These microscopic structures and failure mechanisms vary diversely in the lineup of engineering materials. Just as important for fracture behavior is the type of external loading of the component. In this category one can differentiate between e.g. fractures due to static, dynamic or cyclic loading. Further important factors are the temperature, the multiaxiality of the loading, the rate of deformation and the chemical or environmental conditions [4].

2.10 Macroscopic Manifestations of Fracture

The macroscopic classification of fracture processes corresponds to the view of the designer and computation engineer. Fracture of a structure is inevitably connected to the propagation of one or more cracks which can eventually lead to entire rupture and loss of its load carrying capacity.

That is why particular emphasis is placed on the temporal and spatial progress of crack propagation. In fracture mechanics it is assumed that a macroscopic crack exists. This crack may be present from the very beginning due to a material defect or due to the component manufacturing. Often cracks originate in consequence of operational loading and material fatigue, which is the subject matter of the field of service strength of materials. After all, hypothetical cracks, which have to be assumed for purpose of safety assessment, are part of it as well. The macroscopic mechanical aspects of fracture can be categorized with respect to the load and fracture progression as follows:

(A)Type of loading

According to their temporal progress, mechanical loads are divided into static, dynamic and (periodically-cyclic or random) variable loads, the respective types of fracture to which they can be assigned. Fracture processes under static load are typical for load-bearing constructions e.g. in civil engineering. Impact, drop or crash processes are associated with highly dynamically accelerated deformations and inertia forces.

In mechanical engineering and vehicle construction, much attention needs to be paid to variable loads which can, in contrast to static loading, lead to cracks and crack propagation at considerably lower amplitudes.

About 60 % of all technical failures happen because of material fatigue or propagation of fatigue cracks.

(B) Orientation of a crack in relation to its principal stresses

As it is known from the classical theory of strength of materials, failure is in most cases controlled by the local stress which is clearly determined by the principal stresses σI, σII and σIII and their axes. Depending on the material, either hypotheses of the maximum principal stress (Rankine), the maximum shear stress (Coulomb) or extended mixed criteria (Mohr) are used. The macroscopic image of fracture is therefore often affected by the principle stress trajectories. A distinction is being made between:

The normal-planar crack or cleavage fracture exists, when the fracture faces are located perpendicularly to the direction of the highest principal stress σmax = σI.

The shear-planar crack or shear fracture exists, when the fracture faces coincide with the intersection planes of the maximum shear stress τmax = (σI − σIII)/2.

The situation is outlined for a simple tension rod in Fig. 2.11. However, it can be assigned to the local stress state at any point of the body. On a torsion rod (shaft) the fracture faces would run either vertically or inclined by 45◦ to the axis, depending on whether a shear or a cleavage fracture is assumed.

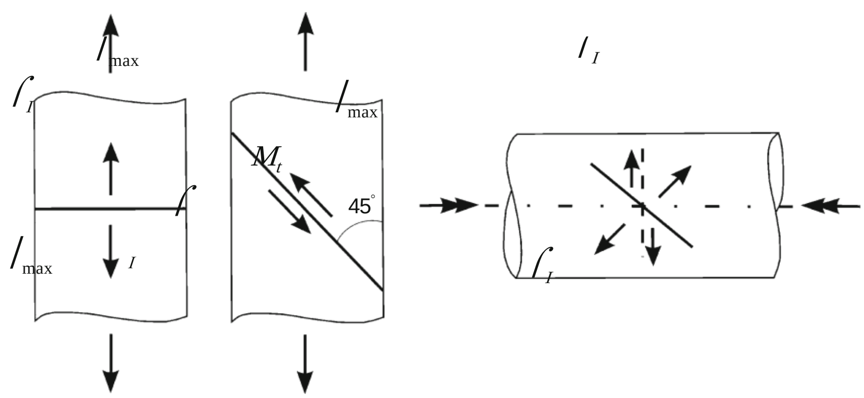


Figure 2.11 Orientation of crack surfaces with respect to principal stress directions

(C) Stability of crack propagation

In the initial situation, a crack has a specific size and shape. As long as it does not change, the crack is regarded as a static or stationary crack. The moment in which the crack propagation starts due to critical loading, is called crack initiation. The crack size now increases and the crack is called unsteady.

An important feature of fracture is the stability of the crack propagation. The fracture process is then marked as unstable if the crack grows abruptly without the need to increase external loading. The critical condition is exceeded for the first time and persists without any additional energy supply.

Magnitude of inelastic deformations Depending on the amount of inelastic deformations or accumulated plastic work in the body that precede or accompany crack growth, distinctions are made between:

Deformation-poor or macroscopically brittle fracture the nominal stresses are far below the plastic yield limit, the plastic or viscoelastic zones are very small and the load-deformation diagram runs linearly until crack initiation.

Deformation-rich or macroscopically ductile fracture appears when the fracture process is connected with large inelastic deformations. The load-deformation diagram displays a distinctive non-linearity and the inelastic domains spread out over the entire cross-section (plastic limit load exceeded).

(D) Subcritical crack growth

In contrast to the above-mentioned types of crack propagation, there are fracture processes that happen far below the critical load and develop in a stable manner with a very low rate of growth, the term subcritical crack growth was introduced. The most important form of appearance is fatigue crack growth, whereby the crack gradually grows under alternating loads figure 2.12 [11].

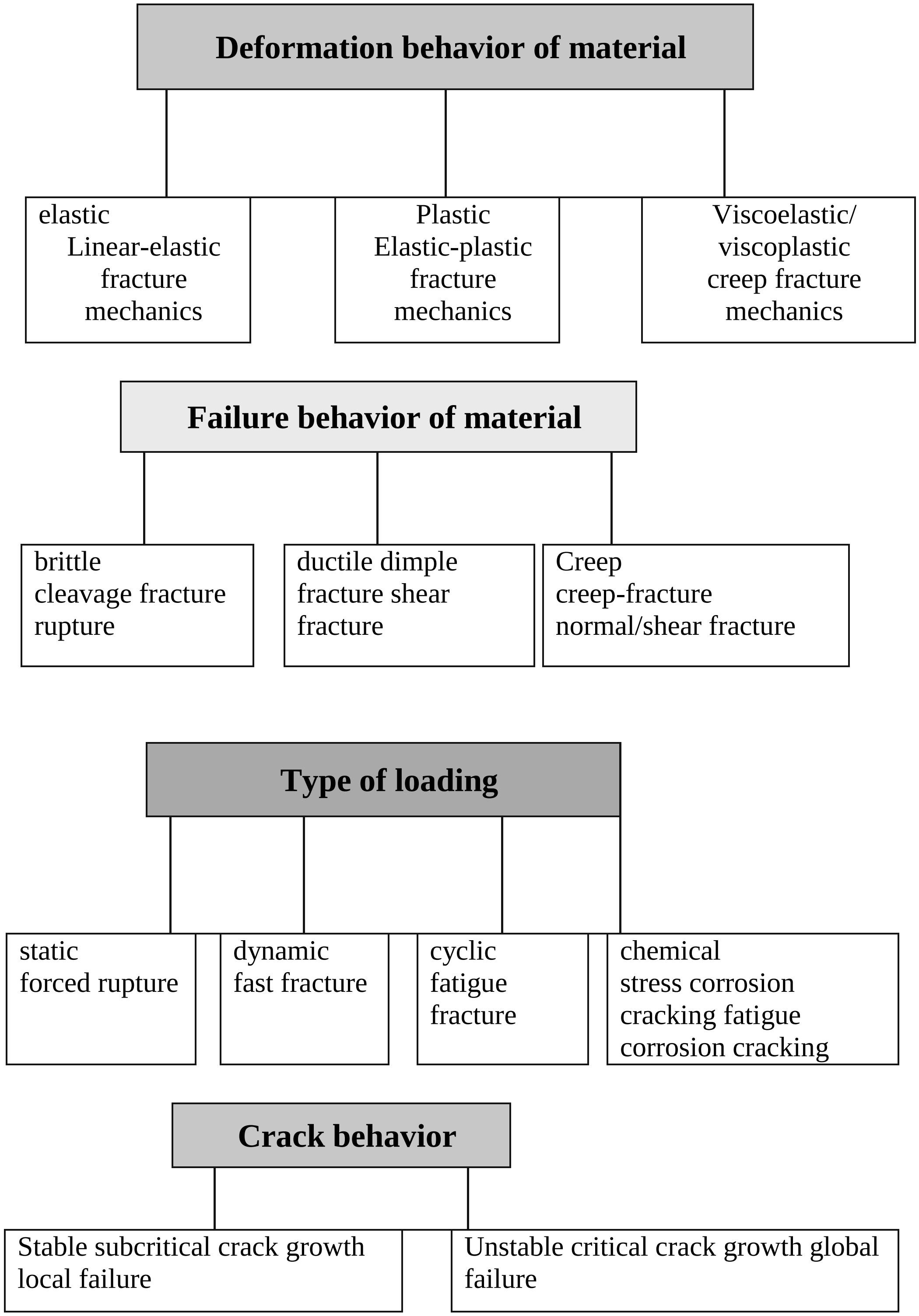


Figure 2.12 Classification of fracture processes [11].

CHAPTER THREE

METHODOLOGY

3.1 Preface

This chapter describes in adequate detail the approach in conducting the research. Procedures for preparation and performing the various materials testing are discussed. These include fractographic analysis for the fractured part, metallurgical study consisting chemical composition, mechanical testing consisting tensile and hardness tests for the movable joint.

3.2 Research Approach

This research is an experimental program in investigation the cause of failure of movable joint assy in wheeled armored vehicle (WMZ551B). The operational framework employed in the research is illustrated in figure 3.1.

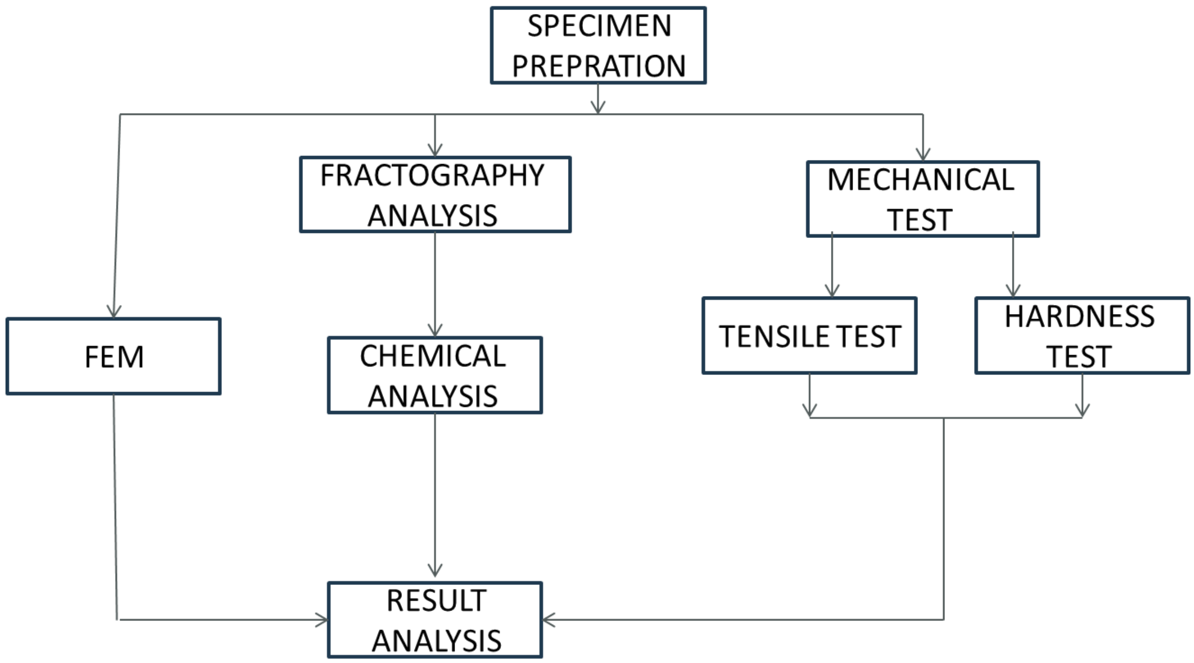


Figure 3.1 Operational Framework- Methodologies

3.3 Metallurgical Study

The metallurgical study consists of microstructure and chemical composition analysis. Microstructure of the surface and thickness cross section of the sample is required.

3.3.1 Chemical Analysis

Another common step in the metallurgical analysis of a failed component is the determination of the base metal chemical composition to determine whether the specified material was used in the manufacture of the part. The chemical composition of the steering movable joint was determined via Optical Emission spectrometer (OES).

3.4 Mechanical testing

3.4.1 Hardness Test

Hardness test for specimen is conducted using Rockwell machine. The specimens were prepared using electrical discharging machine (EDM) as shown in fig 3.2.hardness is performed at different locations on the surface and cross-section.

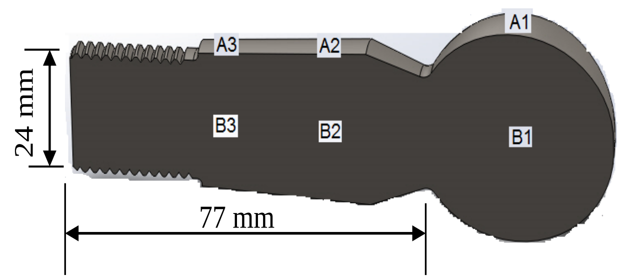


Figure 3.2 Geometry of hardness test specimen

3.4.2 Tensile Test

Determination of the mechanical properties of the metal can play an important role in the failure analysis of a part. Mechanical testing can help determine the inherent properties of the metal for comparison to the expected or specified properties of the part.

3.5 Fractographic Analysis

Fractography is defined as the study of fracture surfaces. The purpose of fractographic analysis is to reveal the morphology of the fracture surfaces and identify the mode of fracture. In this case, the fracture surface of the steering movable joint was cleaned in a mild alkaline detergent under ultrasonic agitation in order to remove loose foreign deposits. The fracture was then examined with a scanning electron microscope (SEM).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Preface

This chapter reviews the results of the conducted tests, including metallurgical characteristics and mechanical properties of the steering movable joint.

4.2 Chemical Analysis

A common step in the metallurgical analysis of a failed component is the determination of the base metal chemical composition to check whether the proper material was used in the manufacture of the component or not. The chemical composition of the steering movable joint was determined via Optical Emission Spectrometer (OES) with the results presented in Table 4.1.

The low carbon content of (0.208%) improved the resistance to carbide precipitation. The high content of chromium (0.873%) resulted in adherent, stable chromium oxide for corrosion resisting property of the material (Avner, 1974).

Table 4.1 Chemical composition (wt.%) for the part and $25CrMo_4$ for comparison**.**

Element	Steering joint	25CrMo4 Specification
C	0.208%	0.22-0.29
Si	0.122%	0.40
Mn	0.528%	0.6-0.9
Cr	0.873%	0.9- 1.2
Mo	0.167%	0.15-0.3
Ni	0.102%	N.S
Cu	0.039%	N.S
Ti	0.005%	N.S
V	0.019%	N.S
Nb	0.016%	N.S
Pb	0.018%	N.S
Fe	97.903%	N.S

4.3 Tensile Test

Determination of the mechanical properties of the metal can play an important role in the failure analysis of a part. The specimen dog – bone was prepared by electrical discharging machine (EDM) fig 4-1. Three specimens were tested for tensile, universal testing machine was used for conducting the tests at room temperature. Tensile behavior of the failure part is presented in term of engineering stress strain diagram.

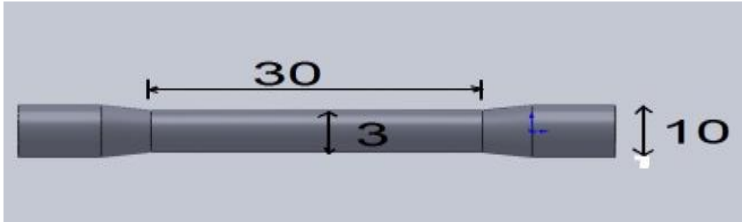


Figure 4.1 Tensile specimen

$\sigma = \frac{P}{A_o}$, $\varepsilon = \frac{\Delta L}{L_o}$ and $R_a = \frac{\Delta A}{A_o}$

Where

σ	is the engineering stress
ε	is the engineering strain
P	is the external axial tensile load
A0	is the original cross-sectional area of the specimen
L0	is the original length of the specimen
L1	is the final length of the specimen

4.3.1 Stress strain diagram

Figure 4.2 shows the stress strain curve of steering joint specimen. Tensile test of failure part at room temperature shows elastic modulus of 210GPa and yield stress of 720MPa, ultimate strength 950MPa and the fracture strain is 17% with 830MPa stress.

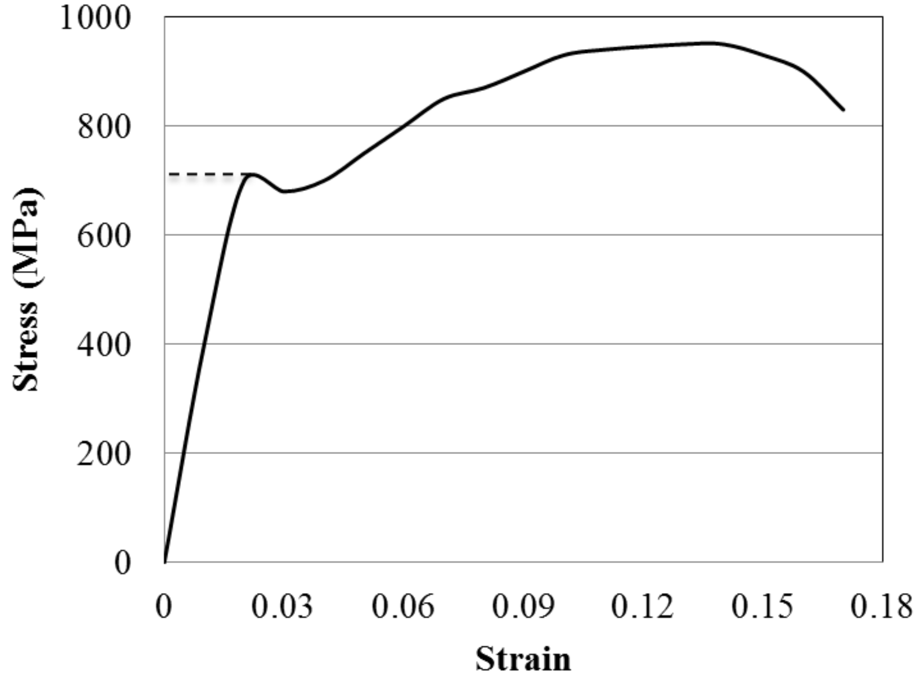


Figure 4.2 stress strain diagram for steering joint.

4.3.2 Failure Mechanism

The orientation of fracture plane for tension test of steering joint conducted at room temperature shown in figure4.3. The fractured surface of a cup and cone failure is shown. This suggests that failure is governed by the maximum principal stress.

Figure 4.3 Fracture of tensile specimen tested at room temperature

4.4 Hardness Test Results

Specimen for hardness test is prepared using electrical discharged machine (EDM). The test is performed using Rockwell hardness test machine. Hardness test is performed at three different locations at the surface and at the core of the specimen after cross sectioning as shown in Figure 4.4. Four reading points is taken at each location. Table 4.2 shows the hardness reading at the surface of the specimen.

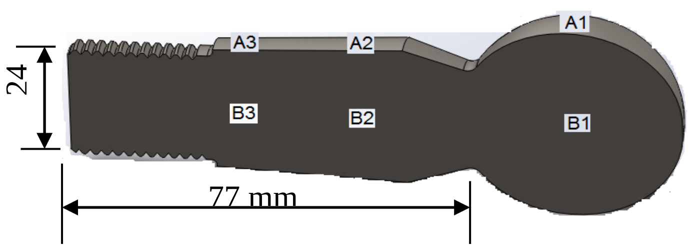


Figure 4.4 Geometry of hardness test specimen.

Table 4.2 Rockwell hardness data at the surface.

Data / Location	1	2	3	4	Average
A1	**59**	**59**	**60**	**59**	**59 HRC**
A2	**59**	**59**	**59**	**59**	**59 HRC**
A3	**60**	**60**	**60**	**59**	**60 HRC**

Figure 4.5 shows the hardness of the material taken at the different locations at the surface of specimen. The result shows constant hardness of high magnitude 60 HRC at these locations.

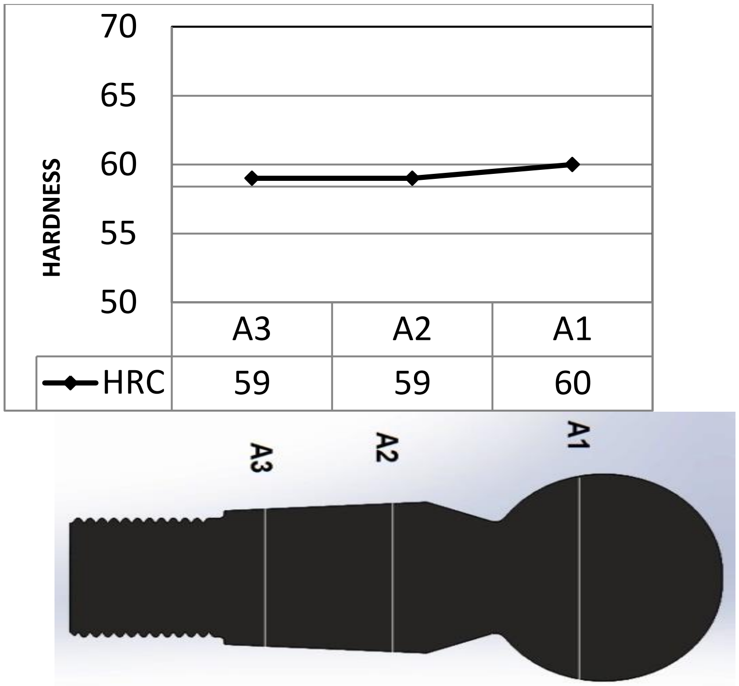


Figure 4.5. Specimen of hardness tested at the Surface.

Hardness test is obtained for the core of the movable joint of the steering system at three different areas. Three reading hardness data were taken for each region. The results were shown in table 4.3 with the average included in last column. The result was plotted in figure 4.6 and shows that the hardness inclined from 18 to 14 HRC which indicate soft material. The variation of material hardness shows that the surface is hard and brittle due to surface hardening at the outer surface; this high hardness on surface is required to obtain fine roughness to avoid wear at the joint.

Table 4.3 Rockwell hardness data at the core.

Data / Location	1	2	3	4	Average
B1	**18**	**18**	**18**	**18**	**18 HRC**
B2	**14**	**14**	**14**	**14**	**14 HRC**
B3	**14**	**14**	**14**	**14**	**14 HRC**

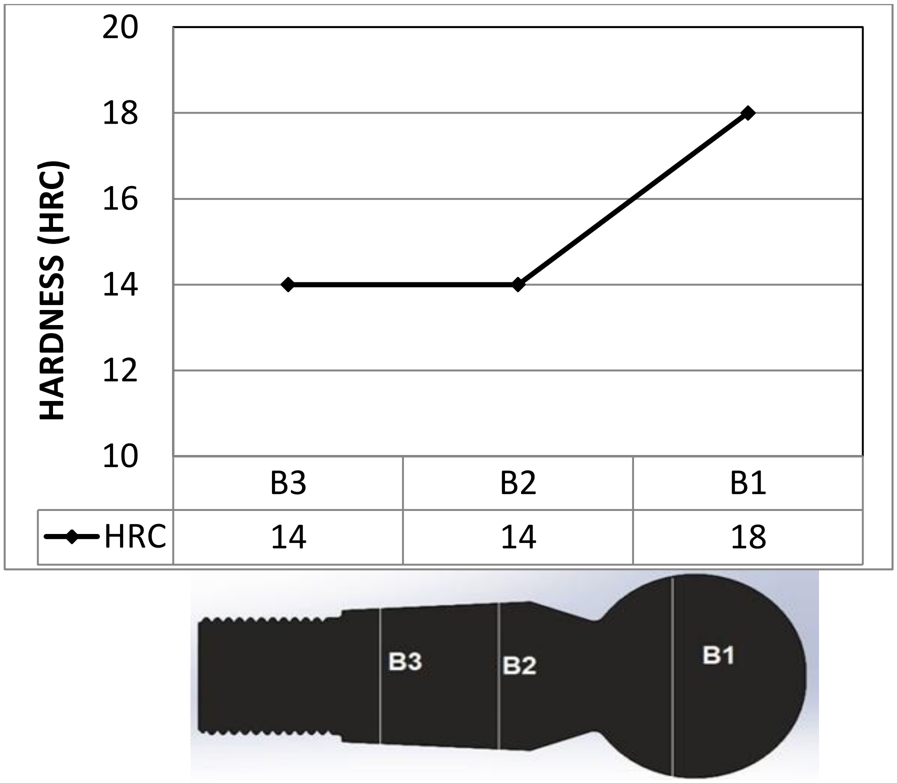


Figure 4.6 Specimen of hardness tested at the Core of the joint part.

4.5 Fractographic Analysis

The SEM examined fracture surface sample for the steering movable joint was cleaned in a mild alkaline detergent under ultrasonic agitation in order to remove loose foreign deposits. The fracture was examined with a scanning electron microscope.

Figure 4.7 shows a low magnification of the fractured area. Different fracture surface sites have been mapped and shown in detailed at higher magnification in sub sequent figures.

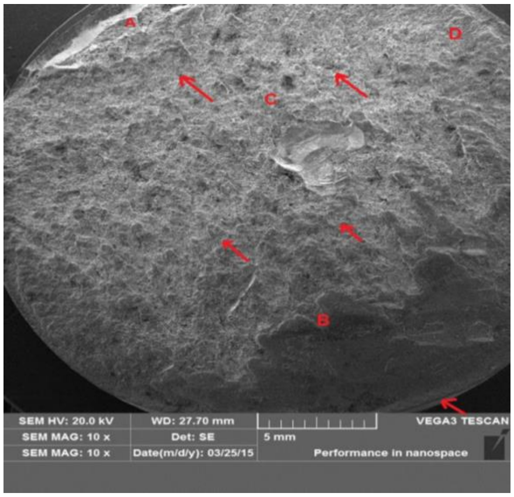


Figure 4.7 SEM micrograph of surface morphology for steering movable joint failure (10X)

Results in Fig 4.8 and Fig 4.9 shows the fracture surface of the failed part at the most upper part (region a) and lower area at (region b). It is noticeable that the fracture at region b shows flat cleavage area which is the initiation site of the crack. The fracture characteristic of this brittle nature at this region is coincided with the surface harden been made to this region. The fracture surface at the center part at region (c) illustrated in Fig 4.10 shows that the joint failure occurred due to excessive loading at the joint. Examination of the fractured surface revealed a combination of ductile and brittle overload (dimpled rupture and cleavage) fracture. No indications of progressive crack growth via fatigue noticed. The transition in fracture morphology coincided with the change in properties of the material. Final failure was flat cleavage which is indicative of fast, brittle fracture.

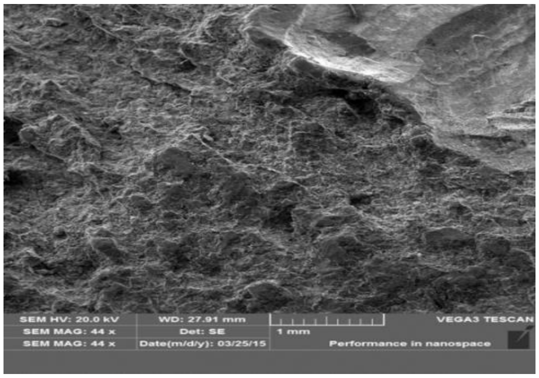


Figure 4.8 SEM micrograph of fracture surface morphology at upper left site (region a) (44X).

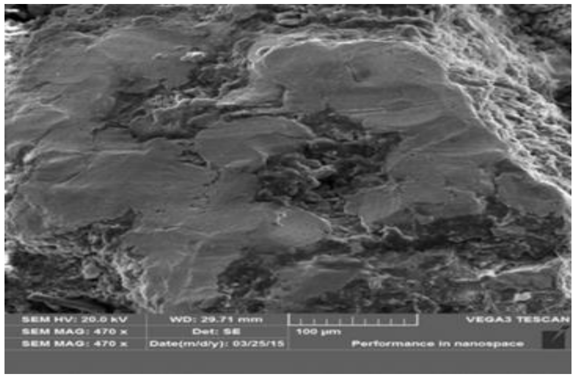


Figure 4.9 A high magnification SEM micrograph of fracture surface morphology at lower region (470X).

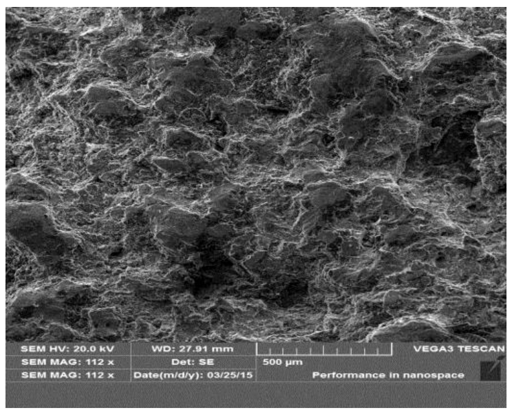


Figure 4.10 A high magnification SEM micrograph of fracture surface morphology at Centre region shows mixed fracture mode (112X).

4.6 Force Analysis at the Movable Joint.

In wheeled armored vehicle (6*6) wheel drive, the steering system is an integrated power steering mechanism. It designed to provide vehicle movement in given direction. Steering the vehicle in the motion on land is carried out by turning of wheel of two front axles.

The movement of steering liver system by means of rack and sector gear mesh that drive the vertical arm shaft and causes the steering vertical arm to swing, thus achieving the steering movement. The armored vehicle has a net weight of 16000 kg. the force analysis of the load transmitted to the movable joint is shown below with figure 4.11 showing a detailed drawing for the movable joint.

Load estimation

m= 16000kg

G= 1/6*16000*9.81=26133.3 N

The load acting in the steering arm is 26133.3 N

Maximum stress on the steering joint is defined by the equation

s = M*c/I + 4/3 G/A Where M*c/I is the bending stress and 4/3 G/A is the sheer stress.

M=26133.3*.047=1228.2 N

C=.03/2= .015m

$I = \pi d^4/64$= $\pi.03^4/64$ =3.976$* 10^{-8}$

R=.015m

$A = \pi r^2$ =.0007m^2

S = 1228.1*.015/3.976$* 10^{-8}$ + 4/3 26133.3/.0007

S=464.05$* 10^6$+49.77$* 10^6$=513 MPa

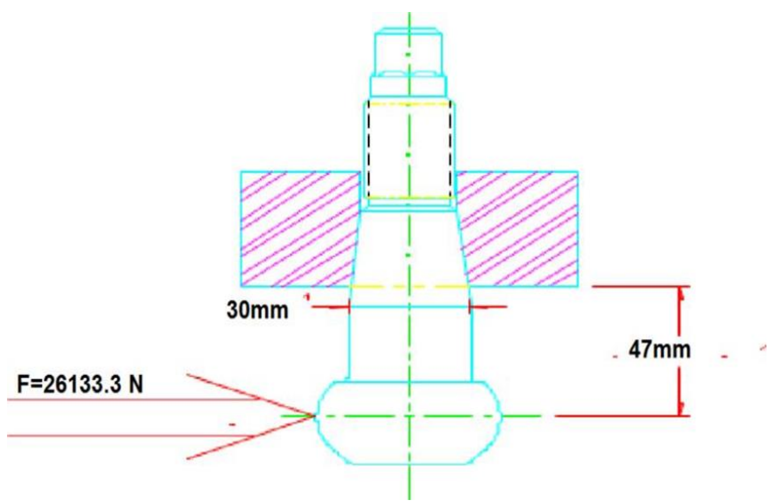


Figure 4.11 Geometry drawing of a movable joint part.

4.7 Finite Element Analysis for the Movable Joint.

Modeling is an important stage for performing and analyzing finite element of any part. Figure 4.12 shows the finite element model for the movable joint for heavy vehicle. The joint dimensions are mentions in figure 4.11 before. The threaded part were fixed from translate and rotation on all axis. The applied force at the ball is 26200 N.

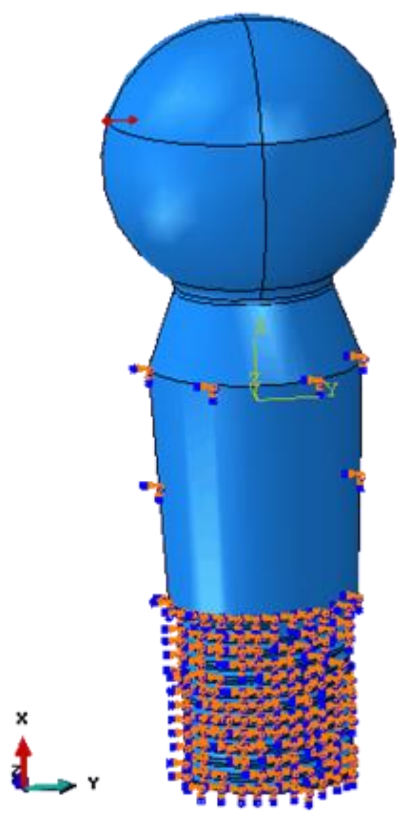
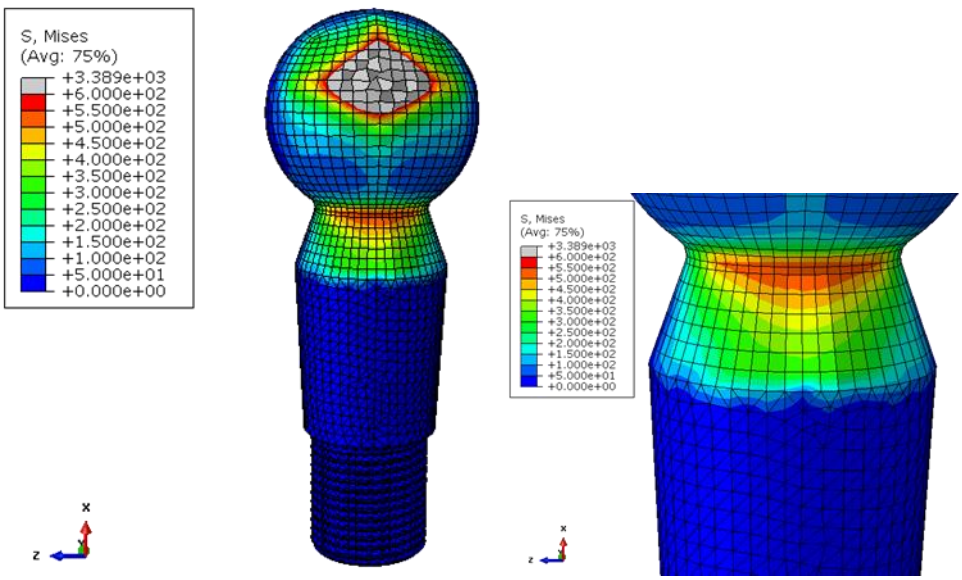


Figure 4.12 Finite Element Model for a movable joint part.

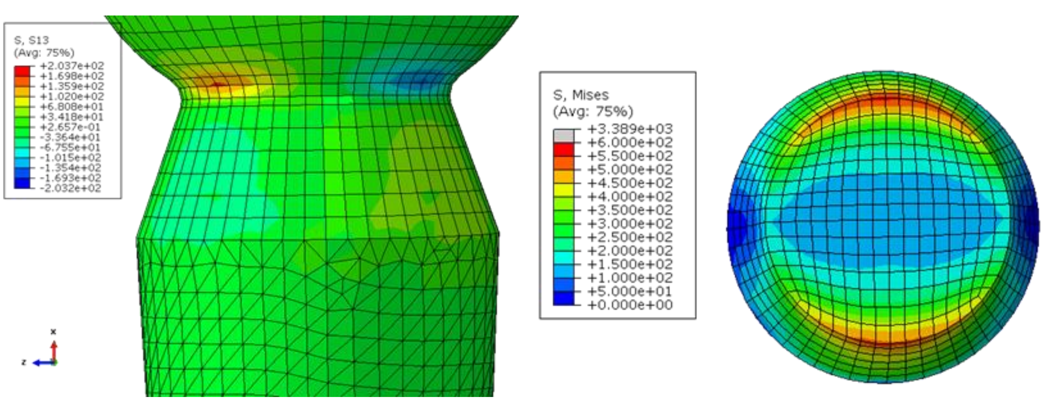
The result of stresses analysis of the movable joint. Figure 4.13 shows high stress concentration at the area of the necking below the ball, closer look is shown in figure 4.13b, this high stresses of 600MPa suggesting that the crack of the part start at this area and then propagate.



(a) (B)

Figure 4.13 Finite Element Model for a movable joint part

The shear stresses shown in figure 4.14 with high shear stress of 135 MPa occurred at the necked area below the ball of the joint. Figure 4.14b illustrate cross-section part and closer look for the applied shear force, with high magnitude acting on opposite directions which results in the initiation of the crack and the failure of the part.



(a) **(b)**

Figure 4.14 Shear stress at movable joint part

CHAPTER FIVE

CONCLUSIONS AND RECOMMEDTIONS

5.1 CONCLUSIONS

Failure of the steering movable joint has been investigated. Analytical analysis and experimental tests, including metallurgical characteristics and mechanical properties have been conducted. Analysis of the results leads to the following major conclusions:-

1. Chemical analysis of the section revealed that it did not meet the minimum carbon requirement of 25CrMo4 DIN 1.718, although the manganese, silicon, chromium levels were lower than specified, it was judged, in this case, not to have contributed significantly to the failure of the part.

2. Yield stress of failure part is found to be 720MPa and 17% strain to fracture with 830MPa stress. On this tensile fracture, a cup and cone failure is typical for ductile materials. Visual inspection shows the fracture is inclined at 45º which suggest a static failure at the maximum shear plane. Analytical analysis for the stress shows the combined stress is found to be 513MPa doesn't exceeds the yield stress of material, that indicate the failure not occur by mechanical properties influence.

3. The variability in the hardness tester suggests that the material is not homogeneous, the variation of material hardness shows the surface is hard and brittle due to surface hardening; High hardness on surface is required to obtain fine roughness to avoid wear.

4. Fractography analysis of magnified fracture surface of the failed part shows the fracture mode at the crack origin was characteristic of brittle intergranular cracking while fracture through the base metal consisted of

cleavage and dimples, the transition in fracture morphology coincided with the change in properties of the material. Final failure was flat cleavage which is indicative of fast, brittle fracture. By following the typical steps in the fracture analytical and experimental analysis process, it was determined that the steering movable joint failed due to lack of lubrication leading to high friction, particles expand due temperature rise then the seizing happened when the contact surfaces stuck together, then static fracture occurred.

5.2 Recommendations

There are few suggestions that can be carried out for the future work:

1. Finite element method can be carried out for the further analysis.
2. Implement the obtained result, lubrication system can be applied to the joint and test for the new results.

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