An Investigation of Multiaxial Loading and Plastic Deformations due to Fatigue of Different Materials

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ABSTRACT

Due to the lack of fatigue life prediction techniques which can effectively handle multiaxial loading, a reliable approach is to be considered for prediction of fatigue in stressed conditions. Fatigue life prediction under multiaxis random loading is an extremely complex and intractable phenomenon. A multiaxial fatigue failure criterion is needed to be studied. Predominant materials play an important role in estimating the remaining life of critical components. Fatigue is most common phenomenon of damaging metallic materials. Fatigue damage causes due to repetitive cyclic loading. Fatigue may results in cracks and crack grows in size at each load cycle and finally leads to fracture. Cracking is the first step in material defects. The multiplication of cracking phase and fatigue life are related to the density of strain energy. Fatigue damage is caused by the simultaneous effect of cyclic stress, tensile stress and plastic stress. Fatigue failure occurs due to multiaxial loading and plastic deformations were discussed. The review of different experiments carried by researchers on multiaxial loading and plastic deformation were studied, analyzed and presented in this paper. This paper provides brief information on damage mechanism which occurs in composite materials. The purpose is to identify the effect and causes due to multiaxial loading and plastic deformation on fatigue and to develop an idea to increase material resistance in various fatigue conditions.

Keywords: *Fatigue; Multiaxial loading; Strain energy; Plastic deformation*

1. Introduction

Engineering components are mostly subjected to repetitive loads during operations, and most of them did not withstand fatigue. Fatigue is weakening of material caused by repeated cyclic loading. Therefore, the material prediction of life is very important in order to prevent them from fatigue failure. The failure may occur when applied stresses are much less than the maximum stresses. Fatigue may result in cracks. These cracks are microscopic in the beginning, at each load cycle cracks grow in size and finally lead to fracture. Decrease in the stress ratio substantially reduces the effect of crack length on the fatigue limit. Multiaxial fatigue failure is one of the main failure modes of components hence its detailed study must necessary. In order to predict fatigue life under multiaxial stress condition there is need for developing suitable and appreciate methods. Plastic deformation occurs when a material is stretched, compressed, and bended or twisted because its tension, compression, bending or torsion exceeds its tensile strength. The energy of plastic deformation is also determined by the surface temperature of the sample (1). Material damage due to cyclic loading can be associated with input energy of the applied load. Based on different failure mechanisms for shear-type and tensile type failure, various parameters relating to the critical plane-strain energy density were presented in this paper. The focus of this study is on discussing simple and effective multiaxial fatigue failure parameters that can predict fatigue life under various loads. Fatigue damage occurs in three stages, starting with crack formation followed by crack growth and further ends to sudden failure, when the residual cross-section falls below applied load. In addition of these various damage mechanisms based on experiments were discussed.

The aim of this investigation is to review various fatigue failure of materials causes due to multiaxial loading and plastic deformation, whereas various damage models were also discussed. The purpose is to identify the effect causes due to multiaxial loading and plastic deformation on fatigue and develop an idea to increase a material resistance in various fatigue conditions.

2. Multiaxial fatigue related to critical strain density

The complex application and used of biaxial and triaxial stress components with different stress amplitude makes precise design or analysis impossible. Therefore, interest in multiaxial fatigue load has increased. Numerous studies of behavioral fatigue can be divided into three main approaches stress based, strain based and energy based. Critical plane is usually the plane at which the fatigue cracks occurs. X chen, S.xu and D. Huang (2) carried out multiaxial low-cycle fatigue experiments with 45 steels under a non-proportional loading. The effectiveness of low cycle fatigue criterion is evaluated under multiaxial fatigue condition. Specimens are obtained from 45 steel and undergoing a heat treatment of 85000C oil quenched and 65000c temper. The chemical composition of materials used during test was C0.42, Si0.24, Mn0.56, S 0.008, and P0.017. The experiments were carried out on a computerized test system, which included an IBM PC486 computer, an MTS 809 servo-controlled electro-hydraulic controller and a data acquisition system. The strain components of the samples were evaluated using an MTS tension torsion extensometer. The two fracture parameters are presented with respect to the critical strain density based on the concept of strain energy and critical plane and taking into account the different mechanism of fracture during shear and tensile failure. Based on different experiments performed the author tried to compare fracture parameter with various models such as Coffin-Manson approach, Shear critical plane model and Tensile critical plane model of Socie. Tensile damage occurs in 45 steel and shears damage in 42CrMo steel. The author develops new critical criteria for strain density in the strain plane provides good predictions for low cycle fatigue under non proportional loading. G. Glinka and co-authors (3) proposed multiaxial fatigue strain energy density parameter for critical plane. This parameter has the advantage that it is independent of load conditions, a universal energy curve and can be determine for various torsional, tension and bending stresses as well as for strain states. In order to evaluate whether parameter W* can correlate fatigue data obtained under different multiaxial loading condition. Authors in this work check three sets of experiments carried by different researchers. The result of experiments were analyzed and plotted in a form of W* vs Nf diagram. In a first set of experiment specimen used is thin wall SAE 1045 Steel. Specimen undergoes tension and torsion loading. The second set of experiment carried out on a notched SAE1045 Specimen and it tested with reverse bending, twisting, and simultaneous twisting and bending. Both test results were analyzed and plotted in a graph. Fig 1 (a) and (b) shows a graph of W* against Nf obtained for various loading conditions.

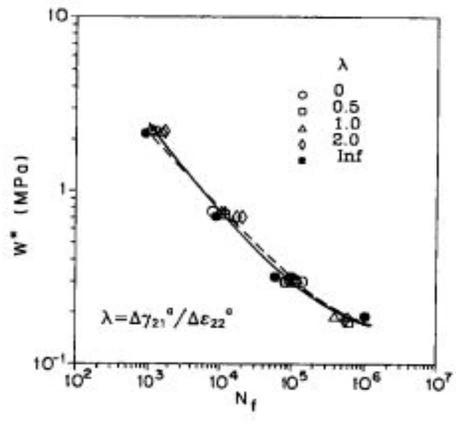

Fig1 (a): Strain energy density W* vs. Experimental fatigue life Nf SAE1045

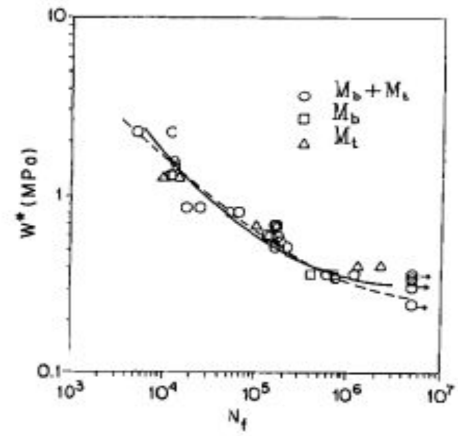

Fig1(b): Strain energy density W* vs. Experimental fatigue life Nf data for notched shaft specimen.

For SAE 1045 Steel, the unique relationship between log W* and log Nf shown in fig can be estimated by two straight lines and a slope of log W* is the log Nf curve for period lo4 to lo3. Third set of experiment carried on specimen made of Inconel 718, a nickel based super alloy. Specimen simultaneously experience tension, torsion, tension and torsion. The analytical result from test plotted on graph. Only data obtained with a proportional cyclic load were selected for analysis from all three sets of experiments. It is clear that the parameter W* is independent of the load regime and can correlate the fatigue data obtained under various load conditions. From these analysis author shows that strain energy parameter W* is able to normalize data on fatigue stress with a zero average obtained under different loading condition for medium carbon steels and nickel based steels. Ellyin and K. Golos (4) proposed a multiaxial fatigue damage criterion based on the strain energy density. The proposed criterion is sensitive to hydrostatic pressure includes the effect of mean stress. Materials constants can be estimated based on two simple test results such a uniaxial tensile test and torsion fatigue test. Thus, in order to formulate criteria for input energy, it is necessary to estimate the elastic and plastic components from strain energy during loading and unloading. The material assumes is initially isotropic and homogeneous.

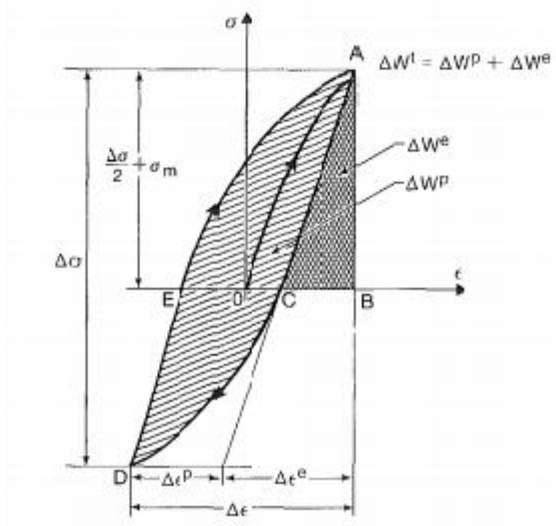

Fig 2: Elastic-Plastic strain energy densities for uniaxial cyclic loading case.

The detail description is provided in (5). The master curve in the multiaxial case is defined as a unique curve that contains the upper branch (load) of the hysteresis chain for the amplitude of various deformations. Throughout an analysis of master curve in a further studies author develops a relation between Strain energy density, Δwt plotted against the fatigue life, Nf. Similarly as per studies and analysis on different experiments, author develops an analytical model. In order to compare the proposed reference forecast with experimental results, it is necessary to required data on stress-strain curve of proper axes from which E and n values can obtained. Most important point of this theory is that damage caused by cyclic loading is a function of mechanically introducing energy into materials. In additional, the effect of average stress is also included, but not used in comparison with experimental data . F. Ellyin (5) introduced a concept of total energy density for multiaxial states of stress. In addition, in each division author carried out studied of specific load conditions, leading to uniaxial and multiaxial stresses. The studies lead to common understanding of phenomenon of fatigue failure, so that general theories can offer on an certain aspects. Author mentioned contribution of various studies in this paper. They can divide into three categories. Criteria based on stress, strain based or energy based criteria. Fig 3 shows graph strain energy density, Δwt plotted against the fatigue life, Nf for various types of tests. Material used is low carbons steel which are used in construction of modern pressure vessel. Experimental data show the relationship between the total strain energy and fracture cycle. Material used is low carbons steel which are used in construction of modern pressure vessel. Experimental data are presented to show the relationship between the total strain energy and fracture cycle.

$$\sigma_{ij} = S_{ij} + \frac{1}{3}\sigma_{kk}\delta_{ij} \qquad \text{..……….(1)}$$

Above Equation(1) shows if fatigue damage is associated with the density of plastic energy deformation, the influence of hydrostatic pressure cannot be taken into account since kkp=0 because the volume does not change during plastic flow process.The proposed criterion is sensitive to hydrostatic pressure and is consistent with concept of cracking and subsequent multiplication.

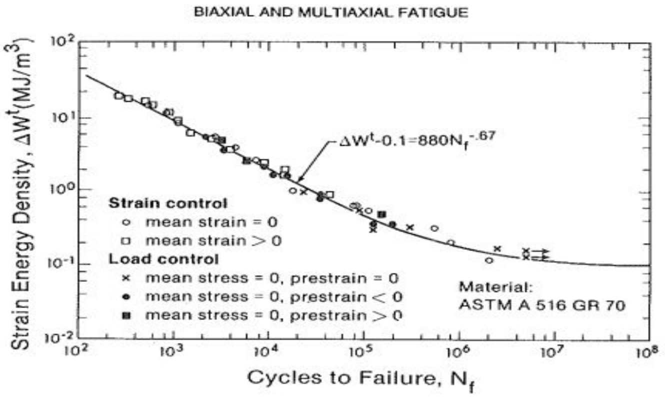

Fig3: Strain energy density, ∆wt plotted against the fatigue life, Nf

Strain energy can be considered as a cumulative measure of the number of fatigue damage per cycle. The purpose of study carried by author shows that authorial energy approach to multiaxial stress states and subsequent studies can lead to a consistent approach. D.Ramesh and M.M.Mayuram (6) perform an experiment on standrad SAE 1040 steel, notched specimen sample in order to predict the life under multiaxial fatigue. The test was conducted with a combination of cyclic bending and torsional loads in a deformed rotary bending machine. Commercially available geometric modeling software was used to determine stresses and strain at notch root. To evaluate life of the sample under combined load condition, stress and strain of notch roots vonmises were taken into account in the life prediction models.

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{2E}(2N_f)^b + \varepsilon_f'(2N_f)^c \quad \text{.........(2)}$$

The Manson-Coffin’s equation gives an empirical representation of the periodic curves of deformation cycle. Equation (2) shows an analytical expression on the line of Manson-Coffin’s which can used for life prediction. Based on the observation, it can argued that, according to the approach of Lohr-Ellipson, the equivalent stress in a multiaxial fatigue load in a critical plane more closely corresponds to experimental observed life and the expected life span.

3. Elastic-Plastic Deformation

As per the study conducted by M.M. Hammouda and co-authors (7) on crack initiation and propagation by analysis of linear elastic fracture mechanics. The two approaches which are employed for the analysis of the notch fatigue problem are linked together with the help of mathematical formulation. In this study total plastic shear deformation at the tip of crack was determined based on the consideration of a long crack of length L propagating in an elastically stressed bulk material at a same speed as that of crack length in a plastic zone of a notched component as shown in fig (4). According to the author, the value of plastic shear deformation at the root of un-cracked notch should be greater than the material threshold value of plastic deformation for an initiated crack to grow and propagate further. It was experimentally found that the fatigue crack growth rates at notches were higher than the one predicted by elastic solutions for short cracks indicating that the single parameter i.e. stress intensity is not capable of prediction of growth rates for very short cracks. But it is claimed that the crack initiation occupies either very small or vast majority of the total life of specimen or the component and under these conditions crack propagation mechanics can be used to calculate lifetimes. Thus, the extent of notch bulk plasticity is a simple function of stress level, cyclic yield stress and notch shape and size.

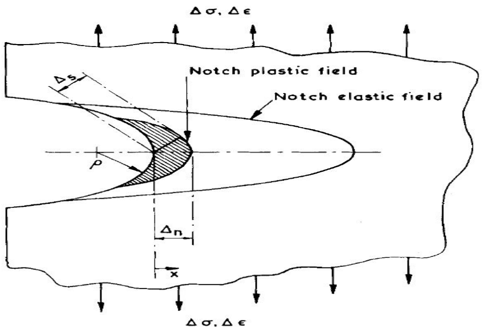

Fig. 4: Elastic and plastic stress strain fields at the root of a notch

S. Usami and co-authors (8) experimented on fatigue limit of material with small cracks under different stress ratios. Fatigue cracks with a length ranging from 0.1 to 3mm were then introduced at the notch roots along with a pulsating compression stress of 0 to 100 Mpa in opposite direction for crack initiation. Further a tension stress in a pulsating manner is applied for crack propagation. Annealing is done in vacuum before actual experimentation. It is inferred that the cyclic plastic deformation accelerates as the value of maximum stress approaches closer to the static yield strength and hence results in decrease of fatigue limit. It is also inferred that the analysis of cyclic elastic plastic phenomenon at crack tips and the damage caused by compressive stress is enough to get a closer numerical value as the theoretical. Yuri Estrin and co-authors (9) reviewed the fatigue behaviour of light alloys with grain sizes reduced to the micron or sub-micron scale by Severe Plastic Deformation (SPD). The analysis is done on the experimental data for high and low cycle fatigue along with fatigue crack growth in SPD manufactured metals and alloys belonging to the different material classes which includes various pure metals and Al, Mg, Ti-based light alloys including particle straightened light metals. Based on the analysis of the parameters that would influence the fatigue behaviour of materials under monotonic loading and concluded that there is subsequent improvement in the performance with the grain size reduction by SPD.

In case of light alloys, the high cycle fatigue properties such as endurance limit does not show further enhancements. Furthermore, the ratio of the endurance limit to the ultimate tensile strength is greater than 0.5 for coarse grained metals while in case of UFG alloys it is approximately equal to 0.5. Kalyan Kumar Ray and co-authors (10) studied the deformation in AISI 304LN Stainless Steel with reference to in-situ evolution of deformation induced martensite (DIM). The analysis is done based on the tests carried out on 304LN SS at 223 K to 283 K at an interval of 10 K. The test results indicated that the yield stress, ultimate tensile stress and percentage elongation of specimen at 283 K are higher than that of the specimen tested at 223 K. But, the increase in elongation with the decrease in temperature contradicts the common expectations. Thus, it is inferred that the martensite formed due to the plastic deformation at low temperature increases with further lowering of temperature. With the help of ferritoscope the amount of martensite formation at 223 K and 283 K was found to be 35.0% and 5.3% respectively. Further it is confirmed through X-ray line broadening and TEM analysis that the twinning plays an important role in crack tip deformation behaviour in monotonic fracture toughness specimens whereas in case of cyclic fracture toughness specimens, dislocations and shear bands show predominant effect.

Jan Kanesund and co-author (11), investigate the mechanism of deformation and damage during fatigue of the poly crystalline super alloy IN792 (TMF) .The material used in this study is -precipitation hardened nickel based super alloy IN792. The TMF test can be perform with an arbitrary phase shift between the temperature and the mechanical loading. TMF cycle used in these study, is in (Ψ=00) and out of phase (=1800).All tests are performed at a temperature determine by induction heating and forced air cooling using MTS 810 thermo-mechanical servo-mechanical fatigue system. The minimum temperature used in all TMF tests is 100 ,the maximum temperature is 750 for TMF and 850 or 950 for TMF OP tests. Fig 5 shows Backscatter electron micrograph from an OP TMF 100-8500C test. After testing , the ruptured fatigue specimens were sectioned parallel to the longitudinal axis for micro-structural investigation.

Orientation imaging microscopy (OIM) was performed using an electron back-scattering diffraction (EBSD) system from HKL technology. All the cracks observed in this study have propagated in zones where the material is strongly plastically deformed. This zone forms various types of deformation structures consisting of various type of deformation bonds. In the range from 750 to 850 twins are form in the IP test and TMF OP, and this phenomenon can be observed near the gap.

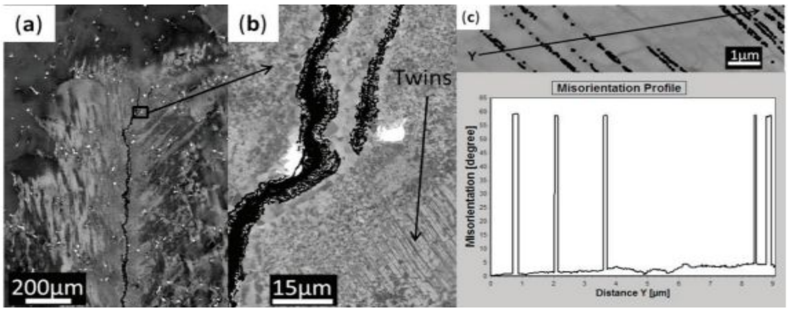

Fig 5: Backscatter electron micrograph from an OP TMF 100-8500C test a) crack appearance and deformation structure b)dislocation structure and twins, c)results from an EBSD analyze which confirm twinning and stress axis in horizontal direction.

Twins were much less likely to be tested at higher temperatures (950). Re crystallization of grain boundaries and recrystallized grains, was observed at a maximum temperature in the range of 850-950. Re crystallization occurred in the deformation zone at 950 .

4. Damage Mechanism

The failure of material due to fatigue occurs in three stages: crack initiation, crack propagation and sudden failure when capacity of residual cross-section falls below applied load. R. Talreja (12) reviewed the basic fatigue damage mechanism in composite. The mechanism of composite fatigue damage is in the same direction depending on the loading mode. The damage mechanism in tensile fatigue may be divided into three types. a]Fibre breakage, inter facial debonding b]Matrix cracking c]Inter facial shear failure Progressive damage depends on the matrix and therefore, Begins with the cracking of the matrix material. Maximum cyclic deformation can only be obtained by testing for endless fatigue, when cracks or cracks do not propagate in the matrix material, determine by the matrix fatigue limit. Based on several experimental data, the author shown to agree with this basic pattern based on the mechanism of fatigue life diagram. The fatigue coefficient is determined in terms of strain and the fatigue limit is for unidirectional, transverse and oblique lamination. Various features of the composites fatigue behaviour emerge when data are plotted in accordance with these diagrams.

Table 1: Fatigue limits for different damage mechanism for epoxy

Limiting strain in fatigue	Damage mechanism
0.006	Matrix cracking
0.001	Transverse fibre debonding
0.0046	Determination caused by debonding in the 90^0 plies

For instance, the strain ranges in which fibre controlled damage is operative against the strain ranges in which matrix and inter facial damage prevail. In addition, the load limit for the mechanism with the lowest energy loss is the fatigue limit, and it is recommended that the data be a property of matrix material. In important result of the fatigue life cycle is the determination of the fatigue strain limits of the composites is shown in table 1, the lowest fatigue performance would be in the loading mode that gives rise to the transverse fibre debonding. The author from these reviews conclude that highest resistance to fatigue is achieved when composite has only unidirectional fibers and the loading is tensile in fibre direction. Thomas Jollivet and co-authors (13) studied damage mechanism on thermoset and thermoplastic composites. Firstly author review various experiments. Further from this experiments author conclude that the process of characterization and exploitation of behaviour law between metallic and composites looks similar, as expected. The main difference from both the material related to damage is that it does not occur at same stage of the material cycle. Further author discussed general damage stages in composites and specific phenomenon due to fatigue loading. When the first damage occurs, low energy power consumption (interface or matrix failure) is required, while last stages (fibre damage) requires a more significant level of energy. The nature and sequence of failure damage mechanism resulting from monotonic or fatigue loading are fairly similar. It was observed that local damage increases due to shear failure and steps of thermosetting micro-bond (TSC). Then further individual fibre fail due to bending (tension and compression). In thermoplastic composites (TPC) , fibres can be fragmented due to lack stiffness of matrix in damaged area. Due to this unstable damage mechanism, its composition is much less compact than loaded one. At the end, authors present fatigue damage examples. Fig 6 shows fatigue fibre breakage process in glass fibre. This shows that in fatigue state, internal fiber is lower than of fibre/matrix interface.

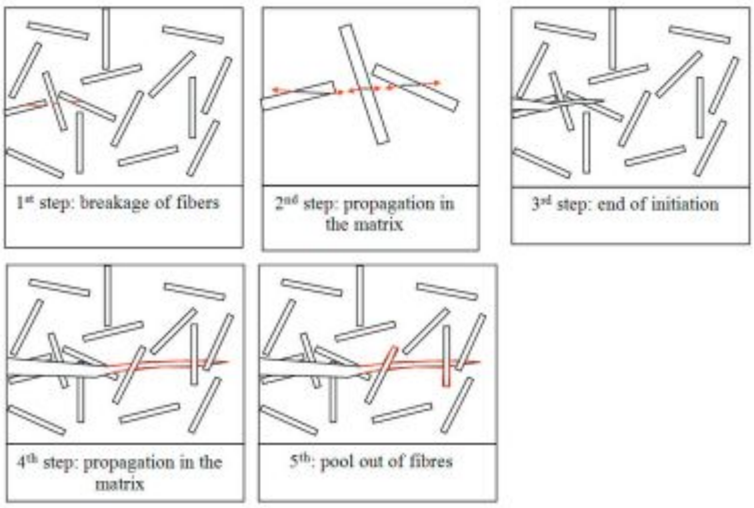

Fig. 6:Steps of fatigue initiation in short glass fibres

It is conclude that in most cases, fatigue failure shows unusally large and smooth translaminar failure (relative to static failure). This study helps to explain the root cause that are often manufacturing defects or very local stress understated by designers.

Conclusion

It is conclude that:

Socie's tensile-type failure model provides good prediction for proportional fatigue. But for non-proportional fatigue such a forecast are dangerous and required further study.

The multiaxial fatigue criterion is based on the cyclic strain energy density of hydrostatically sensitive is a function of imposed triaxial strain conditions, which can used to predict the fatigue life. With use of Lohr-Ellipson approach, expected life (2Nf) is predicted in a multiaxial fatigue loads.

The cyclic plastic deformation accelerates as the value of maximum stress approaches closer to the static yield strength results in decrease of fatigue limit. The fatigue behaviour of materials under monotonic loading concluded that there is subsequent improvement needed in the performance with the grain size reduction by SPD. The martensite formed due to the plastic deformation at low temperature increases with further lowering of temperature.

Highest resistance to fatigue is achieved when composite has only unidirectional fibers and the loading is tensile in fibre direction. In most cases, Fatigue failure shows unusally large and smooth translaminar failure ,relative to static failure.

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