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論 文 内 容 要 旨

Improvement of automobile fuel efficiency is the important national problem because of the global warming and the increase of oil prices. One of the methods to improve the fuel efficiency is the change of power train (e.g. electric vehicles), but this requires very long time for development. Then, the improvement method realizable in relatively short time is the reduction of body weight. For the body-weight reduction, there are two methods: the weight reduction design and the material selection. However, the weight reduction design has already been implemented to the maximum, and therefore, the body-weight reduction depends on the material selection. Against this background, Fiber Reinforced Plastic (FRP) is expected to contribute the reduction. The fiber reinforced composites are applied to aircraft structures, but in this field, their formability and cost are not taken seriously. On the other hand, these features are important in the automotive manufacturing, therefore discontinuous FRP is mainly used. However, the strength of discontinuous FRP is much lower (about 25 percent) than that of continuous FRP, and therefore the application of the discontinuous FRP is extremely limited. Then, it is important to develop the discontinuous FRP whose strength is as high as that of continuous FRP.

In conventional FRP, the target of the previous researches is limited to composites of continuous fibers and thermosetting resin or of short fibers and thermoplastic resin. However, in the researches, these two composites are treated separately, mainly because the composite of the medium-long fibers between continuous and short ones is difficult to be molded, and there is no uniform theory. Then, it is significantly important in the materials development to construct the theory dealing with all fiber length.

The purpose of this doctoral thesis is to clarify the change of strength characteristics of composites depending on the fiber length with the analyses combining the micromechanics model and the unit cell simulation. In addition to that, this thesis proposes the next-generation FRP for automotives basing on the results.

This thesis consists of five chapters.

The first chapter is the introduction of this thesis, describes the background and clarifies the purpose of this thesis through the review of previous researches about the strength prediction of FRP.

The second chapter describes our new material for compression molding of discontinuous FRP and its tensile strength properties. As mentioned above, discontinuous FRP are used in many engineering fields due to their excellent formability into complex shapes. Injection molding and compression molding are the general production methods of these plastics. In particular, compression molding can produce composites that have mechanical properties superior to those of other moldings, because it facilities a high fiber volume fraction (Vf) and in composites. With general compression molding, glass mat thermoplastic (GMT) composed of randomly oriented glass fibers and thermoplastics resin is used in many engineering applications. Products with complex shapes, such as bumper beams, can be fabricated by using GMT. However, the strength of GMT is much lower than that of continuous fiber-reinforced plastics. Therefore, GMT cannot be applied to structural components. Then, this chapter proposes a press sheet consisting of discontinuous carbon fibers and thermoplastic resin as a new molding material with high formability and strength characteristics. This press sheet enables carbon fibers to be dispersed and in-plane randomly oriented in thermoplastic resin, and shows isotropic in-plane mechanical property. These features contribute to its superior formability. A complex-shaped component, such as a rib structure, is easily fabricated. Even in those rib structures, a small matrix-rich region and good fiber dispersion are maintained. This indicated the components made of the sheet have superior shape stability. And the most important feature of this sheet is the improvement of strength, which is the problem in previous discontinuous FRP, by adjusting the fiber length. In this chapter, this feature is focused, and its effect is estimated by tensile tests for obtaining the important information to optimize the fiber length and orientation from perspective of strength and formability. In addition, the experimental results are verified and compared with those of micromechanics analysis to research failure modes. This analysis predicts the strength and stiffness by introducing a fiber failure criteria determined by the Duva-Curtin model into an inclusion model based on the Mori-Tanaka theory. The computational results using the actual values of fiber length and orientation distribution obtained from the experiments represent a tendency similar to the experimental ones that the strength increases and converges on a certain value with the increase in fiber length. The computational and experimental results of strength agreed when the fiber was longer than about 3mm, and this indicates that the composites were fractured by fiber breakage. These results are significant because the effect of fiber length on strength has been suggested without practice so far, but is clearly proven with the new material developed by the author et al. And these give the basic information for the future development of material.

The third chapter discusses the failure mode of composites manufactured from the press sheet in more detail by experiments and model analysis. The strength characteristics and the formability of discontinuous FRP are in a trade-off relationship through the fiber length, that is, the increase of fiber length increases the strength and decreases the formability. Therefore, for making both the formability and the strength high enough, it is necessary to select the appropriate fiber length after judging the failure mode that affects the strength characteristics of composites. Then, in this chapter, the fracture mode of composites was experimentally investigated by measuring the residual fiber length in tensile-fractured specimens. When fiber length was short, the residual fiber length distributions were almost consistent with those in the virgin material. On the other hand, the residual fiber length became shorter than that in the virgin material when fiber length was long. This strongly indicated that failure mode changed from matrix fracture to fiber breakage as increasing fiber length. Moreover, the computational model and the micromechanics model considering both fiber breakage and matrix damage is proposed to discuss the failure mode of composites dependent on the fiber orientation and length. The validity of these analytical methods is verified by comparing the computational results of tensile strength with the experimental ones of strength in composites made of the press sheet. The computational model uses the layer-wise method that treats a composite with fiber orientation distribution as a laminate of unidirectional sheets with various orientation angles. This method can be applied to short fiber reinforced plastic with an arbitrary orientation distribution by using the unit cell simulation of unidirectional composite that utilizes probabilistic fiber strength for fiber breakage and continuum damage mechanics for matrix fracture. At first, we applied LWM to composites manufactured from the press sheet and analyzed stress-strains under in-plane fiber orientation distribution by changing fiber length. As a result, the predicted stress-strains and the fiber length at which the failure mode changes from matrix fracture to fiber breakage are almost agreed well with those of experiments. Moreover, we applied LWM to the composites which have in-plane localized fiber orientation in order to test the validation of LWM. The fiber orientation was introduced into the LWM by approximating the experiment fiber orientation distribution with polynomial and substituting it into fiber orientation ratio in LWM. Then the predicted tensile strength agreed well with the experiment results; thus, the present model can predict composite strength even if the fiber orientation is non-uniform. The LWM based on unit cell simulation has the advantage of precisely addressing matrix damage. However, the LWM is not convenient because it requires too much simulation time. Then, a new micromechanics analysis applying a stress criterion calculated from the global load sharing model for fiber breakage and using the continuum damage mechanics for matrix fracture is proposed as a simpler and easier method. In the model, the failure mode of composites can be judged by introducing these failure criteria into a stress analysis of an inclusion model based on the Mori-Tanaka theory. This method can give the results almost equal to those of the layer-wise method by adjusting parameters of matrix hardening and fracture characteristics in Mori-Tanaka's averaged stress field. LWM and MM can quantitatively estimate the fracture modes and strength that depend on fiber length and orientation. This makes it possible to discuss what the best fiber length is for keeping the high strength and increasing the formability, and can contribute to the material design for optimizing both the strength and the formability. Finally, we compared these models with a rule of mixture utilizing the fiber orientation factor and the failure criterion of fiber breakage proposed in previous research, and examined the limitation of the rule of mixture. As a result, it was clarified that the rule of mixture overestimates tensile strength when fibers are short (i.e., matrix damage is the dominant fracture mode of composite) since it considers only fiber breakage. Moreover, the difference in strength between rule of mixture and MM becomes larger with an increase in the amount of fibers that are oriented along the direction vertical to the loading direction. However, the rule of mixture provides results comparable to those of MM, which does not consider the localization of matrix damage when fiber length is sufficiently long and the fibers are highly oriented along the loading direction. Thus, the rule of mixture with fiber orientation factor is partially useful for qualitatively predicting composite strength with fiber orientation distribution, although accuracy depends on fiber orientation distribution.

The fourth chapter describes the tensile fatigue fracture characteristics of composites made of the press sheet. As mentioned in the second and third chapters, it is verified that discontinuous FRP can improve its strength to the same level of continuous FRP by using fibers longer than a certain length. Thus, the development of high-strength materials enables discontinuous FRP to be applied into more various structure components like automotive parts in the future. For this use, it is essential to clarify the fatigue characteristics and the fracture mechanisms for reliability assurance and optimum design of the components. However, there are few reports on the fatigue characteristics of the composite with medium-long fiber length. Then, in this chapter, the effect of fiber length on tensile fatigue characteristics of composites made of the press sheet is evaluated by experiments. The results showed that the tensile fatigue strength of composites increases when the fiber length increases, and that it converges on a certain value when the fiber length is longer than a certain length. The endurance ratio (= fatigue limit / tensile strength) also showed a similar tendency, and these results verified that the increase of fiber length essentially improves the resistance of composite to cyclic loading. In addition, observation of fracture surface and evaluation of residual fiber length were performed to clarify the damages and the fracture mechanism of the composites in fatigue loading. Then, the following facts were clarified: the cause of fracture of composites is only the fatigue damage of matrix when the fiber length is short, but on the other hand, it is the accumulation of fiber breakage caused successively in cyclic loading when the fiber length is long. As a result, it was verified that discontinuous FRP can obtain the fatigue fracture characteristics similar to continuous FRP by increasing the fiber length. Thus, it was shown that the composites made of the sheet have high performance against fatigue loading enough to be applied to structural components.

The fifth chapter provides the concluding remarks.

論文審査結果の要旨

自動車の燃費改善を目的とした車体軽量化のため，比強度，比剛性に優れる炭素繊維強化プラスチックを車体に適用する試みがなされている。自動車においては成形性やコストといった面が重視されるため，これらの点に優れる不連続繊維の利用が必要不可欠となる。従来の不連続繊維強化プラスチックは連続繊維強化に比べて強度が極めて低く，その適用可能な構造部位は極めて限られている。このため，連続繊維強化に匹敵する優れた強度特性を有する不連続繊維強化プラスチックの開発が望まれてきた。本研究では，次世代の自動車用繊維強化プラスチックを創出することを目的として，不連続の炭素繊維と熱可塑性樹脂とからなる新規プレス成型用プリプレグを提案した。また，実験およびモデル解析の両面から，本提案の新規プリプレグを利用した複合材料の強度および破壊特性について検証を行った。本論文はこれらの研究成果をまとめたものであり，全編５章からなる。

第１章は序論であり，本研究の背景，目的および構成を述べている。

第２章では，次世代の自動車用材料として，不連続の炭素繊維と熱可塑性樹脂とからなるプレス成型用プリプレグを提案した。本提案の新規プリプレグは，単糸分散した長炭素繊維を熱可塑性樹脂中に平面ランダムに配置することにより作製されており，成形時に高い流動性を保持する。また，成形された複合材料は優れた強度特性を有することを明らかにした。さらに，強度の繊維長依存性を実験的に評価し，繊維破断の破壊則を組み込んだモデル解析により強度予測を行った。その結果，繊維長をある一定以上とした場合に実験と解析結果がほぼ一致した。このことより，提案材料における破壊モードは繊維破断であることが示された。本結果は，強度の繊維長依存性を初めて実証したものであり，材料設計の基礎指針を与える重要な成果である。

第３章では，新規プリプレグからなる複合材料の引張破壊後における残存繊維長を実測し，繊維長を変化させた際の破壊モード遷移を実験にて確認した。さらに，破壊モードと強度の両方を予測可能な数値解析モデルおよびマイクロメカニクスモデルを提案し，実験値との比較からその有効性を検証している。解析結果は幅広い繊維長にて実験結果と一致した。本結果は，新規プリプレグからなる複合材料を幅広い工業分野にて利用するための知見を与える重要な成果である。

第４章では，新規プリプレグからなる複合材料の疲労特性を実験的に評価した。その結果，長繊維化により疲労強度並びに耐久比が改善されることを明らかにした。さらに，疲労破壊後の残存繊維長の評価を通じて繰り返し荷重下における微視的損傷を詳細に検証し，長繊維化により繊維破断が累積する連続繊維強化と同様の破壊プロセスとなることを示した。これは不連続繊維強化プラスチックを構造部材として利用し得ることを示す重要な成果である。

第５章は結論である。

以上要するに本論文は，短繊維から連続繊維に亘る強度および破壊特性の遷移を系統的に検証し，自動車材料を指向する新規材料を創出するものであり，航空宇宙および機械工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。