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# Inverse/genetic method and its application in identification of mechanical parameters of interface in composite

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**Abstract**

In this paper, an inverse/genetic method for interfacial parameter identification is developed. The interfacial parameter identification process can be converted into an inverse approximation problem using the method which includes finite element method and genetic algorithms for searching solution. Based on the interfacial failure information obtained from experiment, the inverse approximation procedure identifying interfacial parameters is constructed by taking the advantages of genetic algorithms over traditional gradient-based search methods. The study indicates that a good prediction with relatively high accuracy of the interfacial parameters of real composite can be achieved with the proposed method. It seems that the proposed method is promising in solving a wide range of parameter identification problems in robust way.



*Keywords:* Mechanical parameters of interface; Inverse/genetic method; Hybrid analysis; Finite element method

## 1. Introduction

With modern manufacturing technology, various multiphase composites with special properties have continuously been presented to meet the growing demand for practical industries and engineering. Consequently, it becomes important to investigate material properties of these composites to provide information for understanding, and then designing structures containing the multiphase composites. In particular, studies on interfacial property of multiphase composites have attracted a quite number of researchers in this field. Not only do the interfaces in composites connect reinforcement and matrix, they transfer some mechanical parameters as well. The failure of a composite often arises at the interface. Therefore the mechanical behavior of interfaces has a strong influence on the mechanical properties of composites, including their strength and toughness. During the past decades, investigations have been carried out on the mechanical performance of composite interfaces relating to aspects such as strength, damage, debonding, and failure. These studies have produced various interfacial theories and models which have been widely applied in designing and analyzing composite structures [1–7]. These interfacial theories are usually based on certain postulations or simplifications, and thus they might have some limitations when applied to real structures such as how to determine the characteristic parameters of the interface in a real composite structure. On the other hand, although deformation fields on the surface of a composite can be measured by existing experimental techniques [8–10], the characteristic interfacial parameters in multiphase materials, such as the mechanical and physical characteristic parameters of interfaces between the strength-reinforced phase and the toughness-reinforced phase cannot be directly determined by means of experimental measurement. Therefore, for an actual multiphase composite, how to determine effectively its interfacial parameters through simultaneous use of theoretical models and experiment approach is still an unresolved problem in the field of composite material.

During the past years, parameter identification techniques have got wide application in predicting materials properties of composites. This method combines ingeniously mathematical analysis with measurable mechanical parameters and has been used to determine material parameters which are difficult to obtain directly by means of traditional experimental measurement. For

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example, the identification of material constants of a fiber-reinforced composite by ultrasonic velocity measurements was studied in [11,12]. Using the displacement response of structures under dynamic load, the elastic constants of a composite plate and a functionally graded material plate were determined by a combined method of GA and non-linear least square method [13,14]. Based on the non-uniform two-dimensional displacement field generated from numerical experiments, Springmann and Kuna [15] presented an optimization procedure to identify material parameters for inelastic deformation laws using gradient-based method. However most of the previous works in this field focus on the study of identification techniques and the parameters identified are primary macro- and linear parameters of materials. To our knowledge, there is very little work discussing the identification of complex or non-linear mechanical parameters of an actual multiphase composite when the influence of interfacial phase is taken into account.

An inverse/genetic method for interfacial parameter identification is proposed in this paper. This method can be easily used to solve inverse problems of complex material parameter identification by taking the advantages of genetic algorithms (GAs). Based on hybrid analysis, we studied the interfacial property of a real multiphase composite by using the proposed method for verifying the effectiveness of the method. Experimental data are used as the initial data for finite element calculation and the identification procedure. Based on the interfacial joint model developed, the strength and stiffness parameters of a real microstructural area produced from an actual metal matrix composite $Al/Al_2O_3$ are analyzed and identified. The strength and stiffness parameters in the normal and tangential direction of the interface in the microstructural area are quantitatively estimated. The study shows that the novel inverse/genetic method is feasible and promising in identifying complex properties of multiphase composite materials.

## 2. Inverse problem solving of interfacial parameter identification

### 2.1. Feature of inverse/genetic method

To illustrate the main feature of inverse/genetic algorithm and difference between inverse and forward problem, let us consider a general solid mechanics problem:

$$\mathbf{Y} = \mathbf{H}(\mathbf{X}, \mathbf{R}, \mathbf{C}, \mathbf{\Phi})\mathbf{X} \tag{1}$$

where $\mathbf{Y}$ is a vector of output parameters representing the response, $\mathbf{X}$ is a vector of input parameters such as external loads, $\mathbf{R}$ stands for a vector of material property parameters, $\mathbf{C}$ is a vector of parameterized boundary conditions, $\mathbf{\Phi}$ is a vector of model-related coefficients. $\mathbf{H}(\mathbf{X}, \mathbf{R}, \mathbf{C}, \mathbf{\Phi})$ is a characteristic matrix representing the transfer process from input to output. According to the type of information being sought in the solution procedure from Eq. (1), we have two major solution procedures known as forward problem and inverse problem [16,17], respectively. The former is to find out the vector $\mathbf{Y}$ from the given input vector $\mathbf{X}$ and the established matrix $\mathbf{H}$ (derived from given vectors of $\mathbf{R}$, $\mathbf{C}$, $\mathbf{\Phi}$). The latter is usually divided into two types of problems. The first one is to determine the unknown input vector $\mathbf{X}$ from the observed output vector $\mathbf{Y}$ and the established matrix $\mathbf{H}$. This type of inverse problem is often called source or cause identification problems. The second one is to identify the parameter vectors of $\mathbf{R}$, $\mathbf{C}$, $\mathbf{\Phi}$ from the known input vector $\mathbf{X}$ and the observed output vector $\mathbf{Y}$. This type of problem is often called parameter identification problem. Obviously, the interfacial parameter identification to be treated in this paper belongs to the second inverse problem above, which refers to the determination of unknown interfacial parameters of a material. Typically, this method to be used is to find an optimal solution from possible solution space of interfacial parameters, based on which the outputs of the structure calculated from the corresponding forward problem can best match the actual results. It should be mentioned that the interfacial parameter identification problem here is more complicated than other parameter identification problems as it is difficult to measure responses of the interface behavior in an actual material.

When solving inverse problem involved identification of material parameters, one converts the inverse problem into an optimization problem and then solves the optimization problem using various numerical approaches among which GAs have distinctive advantages in treating such problems. GAs are stochastic global search technique based on a simulation of Darwin's nature evolution theory. The research on GAs can be traced back to Holland's work. In 1975, Holland [18] established a theoretical foundation for contemporary developments of GAs. Since then, the GAs have become increasingly popular an efficient numerical tool in many research fields [19]. The previous studies showed that GAs are promising in dealing with large, discrete, nonlinear and poorly understood optimization problem, where expert knowledge is scarce or difficult to model. One important feature of GAs is that they work on a population of points in the search space for each generation, and thus they are not sensitive to the selection of initial points. GAs can work well in many complex search problems for which the gradient-based search technique might not apply. Furthermore, GAs can be operated based on objective function information only, which enables GAs to apply for those complicated problems in which auxiliary knowledge such as derivative are difficult or impossible to obtain. The inverse problem of interfacial parameter identification treated in this paper is a multiparameter, discrete optimization problem as well as lack of expert knowledge. Such a complicated problem seems difficult to solve by using traditional gradient-based methods. This is the reason why we choose GAs rather than others in treating the inverse problem.

### 2.2. Inverse/genetic scheme of interfacial parameter identification problem

The interfacial parameter identification problem considered in this paper is to seek such an interfacial parameter vector in the solution space that the deformation and failure information in interfacial regions obtained from the numerical simulation based on the interfacial parameter vector is in a good agreement with or converger to the related experimental results. GAs here can be regarded as an evolutionary inverse problem solving method. The general idea of the evolutionary inverse problem solving of interfacial parameter identification is depicted in Fig. 1. FE-calculation, which involves the undetermined interfacial parameters is used as the forward analysis in this paper. An individual corresponds to an interfacial parameter vector in solution space. While in genetic space it consists of an array of gene values, its ‘chromosome’. These two representations of individual can be transformed mutually in certain coding way. The algorithm starts with a set of initial individuals, called a population, which represent candidate solutions of the identification problem. This population then evolves gradually into different populations for several interactions (generations). Finally, the algorithm returns the fittest individual of the population as the solution to the present problem. In each iteration (or generation), the algorithm evaluates, selects, and recombines the members of the population to produce offspring and form succeeding (or new) populations. Evaluation of each individual is based on a fitness measure. In the fitness measure, an objective/fitness function, which can measure the difference for any individual between the numerically obtained interfacial deformation and failure information in the FE-simulation and the relevant experimental results, is used to evaluate the fitness of individuals. The fitness measure is used by the selection operator to select relatively fitter individuals in the population. Crossover and mutation, the recombination operators, imitate sexual reproduction. Mutation introduces new feature in the population. Crossover is the main recombination operator. It allows information exchange between candidate solutions. This process is repeated until a stop criterion is met. The number of interactions is frequently used as the termination criterion.

## 3. Inverse/genetic algorithm: application in interfacial parameter identification

### 3.1. Interface element

The interface elements play an important role in the construction of the inverse/genetic method capable of identifying interfacial parameters. For this, a non-continuum four-node interface element based on the cohesive model [3,5,7] is adopted in our work to simulate the mechanical performance of the interface under consideration. The element is a two-dimensional element with

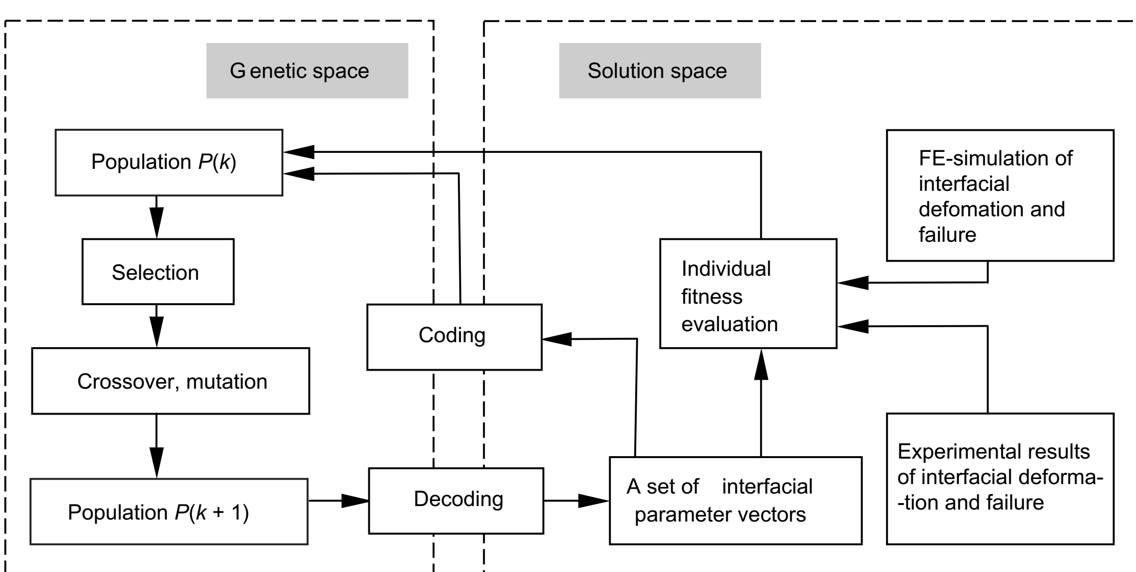


Fig. 1. Inverse/genetic scheme of interfacial parameter identification problem.

four nodes and zero initial thickness (Fig. 2). As shown in the figure, before deformation node 1 coincides with node 4, while node 2 coincides with node 3. Each node has two displacement degrees of freedom, which are the translations in the $t$-direction and $n$-direction. The spring-like interaction of any two plane continuum elements linked by an interface element can be modeled by this special interface element. The relationships between stress and displacement jump of an interface element are shown in Fig. 3, where $\sigma_t$ and $\sigma_n$ are the tangential and normal stresses respectively. With increasing interfacial displacement jump from zero, the stress across the interface increases along with an increase in the interfacial displacement jump. Both are zero at the start and the interface initially behaves 'elastically'. The curve experiences a platform when the stress reaches its maximum (in this stage, damage evolves at the interfacial region), and then it decreases rapidly to zero (at this point, the interface cannot transfer any force and interfacial failure occurs). Such interfacial constitutive relationships enable us to simulate the mechanisms of interfacial deformation, damage and failure by using the proposed interface element.

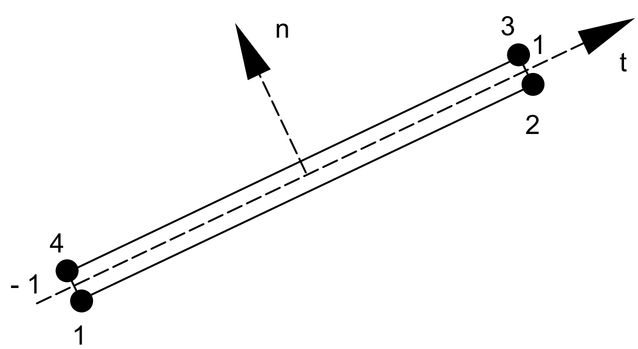


Fig. 2. Local coordinates of an interface element.

The relation between stress and displacement jump within the interface element is determined by the interfacial constitutive curves (Fig. 3) which characterize interfacial behaviors. In the calculation with the curves in Fig. 3, the height and span of these constitutive curves, which are represented by $\sigma_{\mathrm{Tmax}}$, $\sigma_{\mathrm{Nmax}}$, $\delta_{\mathrm{T}}$ and $\delta_{\mathrm{N}}$, can change independently. Thus the mechanical properties of interface can be characterized by the four parameters of interface element, namely $\sigma_{\mathrm{Tmax}}$, $\delta_{\mathrm{T}}$, $\sigma_{\mathrm{Nmax}}$ and $\delta_{\mathrm{N}}$, which are the interfacial strength limit in the tangential direction, the interfacial separation limit in the tangential direction, the interfacial strength limit in the normal direction and the interfacial separation limit in the normal direction respectively. Different interfacial parameters may lead to different interfacial failure results in FE-simulations.

### *3.2. Main steps of the application of inverse/genetic method in interfacial parameter identification of composites*

#### *3.2.1. Encoding and decoding interfacial parameter vector*

For the parameter identification problem considered in this paper, the solution to be searched is the vector of interfacial parameter $r(\sigma_{\mathrm{Tmax}}, \delta_{\mathrm{T}}, \sigma_{\mathrm{Nmax}}, \delta_{\mathrm{N}})$, namely interfacial shear/tensile strength and stiffness. They are all in numerical form. We can use binary string to encode the candidate solution of the interfacial parameter vector. Typically, a binary code in the genetic space is used to represent the interfacial parameter vector in the solution space. The binary string here is called chromosome and every bit of a chromosome has the value of either 0 or 1 only. In order to improve the ability of the GA in local search, the four interfacial parameters are coded according to the Gray coding scheme (an anamorphosis of binary coding) in this work. The representation of the solution for the true interfacial

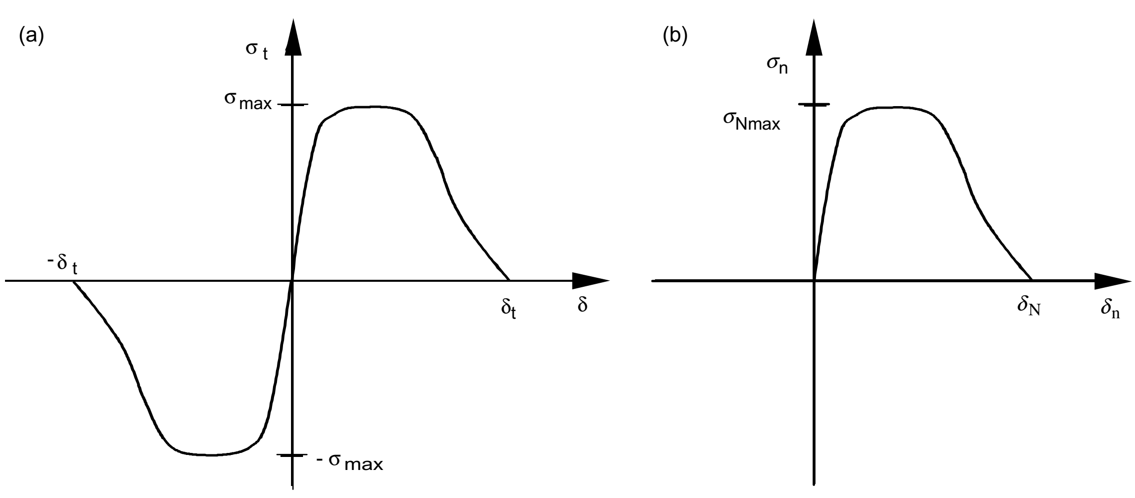


Fig. 3. Stress–displacement jump curves for the interface element: (a) tangential direction, and (b) normal direction.

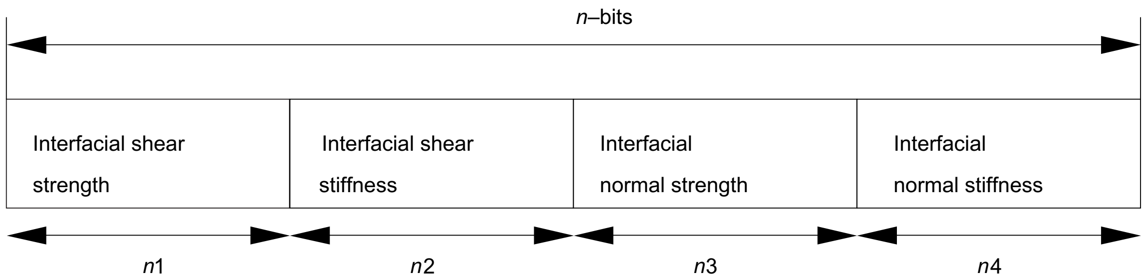


Fig. 4. Representation of interfacial parameter vector.

properties is a bit string of which each substring represents one interfacial parameter as shown in Fig. 4. The length of each substring is determined by the solution accuracy and the interval of corresponding interfacial parameter. For example, if the solution accuracy of the first parameter is set to be 0.01 and the interval is $a$, the length of the substring should then satisfy

$$2^{n1-1} < a \times 100 < 2^{n1} \tag{2}$$

*3.2.2. Initialization*

GA runs based on a population of candidate solutions. Having determined the coding procedure, a fixed number of initial chromosome strings are created at random in the genetic space of interfacial parameter. Each bit of the chromosome string is selected to be 0 or 1 with equiprobability. The fixed number of chromosome strings constitutes the initial population from which GA starts its iterations to search for the optimal solution. Usually, the larger population implies the more solutions operated simultaneously and the better global optimal solution can be obtained. In the meanwhile, owing to the reason that the related forward analysis, i.e., FE-simulation of the interfacial behavior, is time consuming and that the computing time is proportional to the number of population, a larger population requires longer running time per iteration or generation.

*3.2.3. Fitness evaluation*

It is well known that each individual is evaluated using some measure of fitness in GAs. GA begins with computing the fitness values on each individual in the population and then the probability of the individual to be reproduced for the next generation cycle is determined according to its fitness value. In the inverse problem of material parameter identification, the outputs of a structure, which can be directly measured by experiments, are usually the displacement or strain values at some points of the structure. These displacement or strain values can be used to define the fitness function. For example, the fitness function can be defined as the root-mean-square (sometimes called the quadratic mean) of the difference between the actual displacement/strain values and the computed results using the FEM at certain points. For the interfaces with irregular shape existing in real multiphase composites, deformation and failure information in the interfacial region can be obtained from experimental image. However it might not be easy to effectively evaluate the fitness of individuals by directly using the open displacements of the interfaces as the error and noise contained in the displacement data may lead the algorithm to be divergent. The failure region and the failure mode of the interface are identified according to results of the microexperiment in our work. While in the FEM forward calculation, if an interface element has no capacity to transfer shear/tensile stress, shear/tensile failure is said to occur at the interface element. Based on the analysis above, a feasible and easy to use objective function has been constructed as below, with which the difference of an individual between the FE-simulation results and the experimental results can be evaluated.

Suppose there are $s$ interface elements in FE analysis and we denote each of the interface elements with a number $i$ ($i = 1, 2, \dots, s$). Here $s$ is the total number of the interface elements along the interface under consideration. The failure state of each element is characterized by the four variables $n_i$, $t_i$, $\bar{n}_i$ and $\bar{t}_i$ ($i = 1, 2, \dots, s$), where $n_i$ and $t_i$ stand for the failure of the $i$th element in the FE-simulation. Tensile (or shear) failure will occur if $n_i = 0$ (or $t_i = 0$), otherwise $n_i = 1$ (or $t_i = 1$). The values of these two variables are dependent on the parameter $r$, which denotes the interfacial parameter vector ($\sigma_{\mathrm{Tmax}}, \delta_{\mathrm{T}}, \sigma_{\mathrm{Nmax}}, \delta_{\mathrm{N}}$). The actual tensile and shear failure of the $i$th element are expressed by $\bar{n}_i$ and $\bar{t}_i$. We use $\bar{n}_i = 0$ (or $\bar{t}_i = 0$) to show that the tensile (or shear) failure of the $i$th element is experimentally observed, otherwise $\bar{n}_i = 1$ ($\bar{t}_i = 1$). Furthermore, function $\Delta(x_i, \bar{x}_i)$ ($x = n$ or $t$) is used to show whether the failure result from the FE-calculation of the $i$th element coincides with that from the experiment. If $x = \bar{x}$, the value of the function equals 1, otherwise $\Delta(x_i, \bar{x}_i) = 0$. Thus, the objective function can be defined as

$$f(r) = \sum_{i=1}^{s} \left\{ \Delta[n_i(r), \bar{n}_i] + \Delta[t_i(r), \bar{t}_i] \right\} \tag{3}$$

With the objective function (3), the present inverse problem can be regarded as a problem of finding a point $r^*$ in the four-dimensional space $\mathbf{R}(\sigma_{\mathrm{Tmax}}, \delta_{\mathrm{T}}, \sigma_{\mathrm{Nmax}}, \delta_{\mathrm{N}})$ at which the function $f(r^*)$ reaches its maximum. In other words, the objective function $f(r)$ is maximized such that the corresponding interfacial failure mode obtained from FE-simulation approaches that observed from experiment as much as possible. The solution of the inverse problem can, thus, be stated as

$$r^* = \arg\max_{p \in P} f(r) \tag{4}$$

Consider now the case that failure has already occurred at the interfacial region in experiment, the search for the interfacial parameters can, in this case, limited to the individuals containing failure interface elements in the numerical simulation. Therefore, when evaluating the fitness of individuals, for the individuals without failure interface element in the numerical simulation, the fitness value is determined as follows. We calculate its objective value $f(r)$ from formula (3) at first and then add a proper penalty function to $f(r)$ as its fitness value. While for those individuals with failure interface elements, their fitness values are taken to be equal to their objective values. In this way, the competition for the individuals with failure interface elements will be greatly enhanced and the GA can work more efficiently.

It can be seen from the discussion above that the objective function $f(r)$ employed here is a discrete function for evaluating the fitness of individuals. It is very difficult to obtain its derivative information. Such derivative information is, however, necessary to the gradient-based search method. In contrast, GA can work well with objective function information only. This is one of the major advantages of GA when treating the present inverse problem of interfacial parameter identification.

*3.2.4. Genetic operator*

*3.2.4.1. Selection.* The 'selection' operation here means to select any two individuals for mating among the whole population. The probability of individuals for being selected for reproduction is based on the rank of the fitness of the individuals in the population, because the rank-based scheme is proved to be more robust than the proportional scheme in treating the present problem. The probability value for reproduction of variable $p_i$ corresponding to the $i$th individual in the rank is given by

$$p_i = c(1 - c)^{i-1} \tag{5}$$

where $i$ is the order number of the individual in the rank, $c$ is the probability value for the first individual in the rank. Once the probability values for all the individuals in the population are determined, the selection operation is implemented through the classical 'roulette wheel' methods combined with the 'elite' strategy in our work. During roulette wheel selection, two mates are selected for reproduction based on the probability values determined by Eq. (5). Therefore, the fitter individuals will contribute a greater number of offspring in the succeeding generation. Meanwhile, with the elite strategy, the best individual of the current generation always survives in the next generation.

*3.2.4.2. Crossover and mutation.* The 'crossover' operation is a process to create new individuals (offspring) from existing ones (parents) during reproduction. In this work, 'one-point' crossover is employed as it is simple and easy to implement into computer program. It operates by randomly choosing one crossover point with a probability of $P_c$ from the selected pair of strings. The substrings defined by the chosen point are exchanged afterwards to produce two new individuals. As for the 'mutation' operation, it is to introduce new genetic material (genes) to the chromosomes with a probability of $P_m$. It can, thus, improve the local search ability of GAs, maintain the diversity of the population, and prevent premature convergence. Simple mutation scheme is employed in this work.

## 4. Example and discussion

The feasibility and utility of the proposed inverse/genetic method are illustrated by considering an interfacial parameter identification problem of an actual metal matrix composite. Liu and Fischer experimentally measured the mechanical properties of a metal matrix composite Al(6061)/$Al_2O_3$ on the macro- and microlevels by means of the object grating technique [8,9]. In their work, the edge displacement fields of several microstructural areas ($100 \times 100\ \mu m^2$ was used in their experiment [8,9]), containing $Al_2O_3$ inclusions with different shape and size, were given experimentally. An example of such an area is shown in Fig. 5 (its edge displacements were obtained from their experiment). The material properties are listed in Table 1 and the non-linear stress–strain relation of the matrix Al is shown in Fig. 6, while Fig. 7 depicts the experimental SEM image of the deformed real microstructure. It can be seen from Fig. 7 that the failure of this microstructural area was initiated along the edge of the largest inclusion.

The interfacial failure in the real microstructure is numerically simulated by the well-known finite element software ABAQUS under plane stress condition. The finite element mesh used to analyze the microstructural area (see Fig. 5) is shown in Fig. 8. It is automatically generated by using the CAE program, an interactive preprocessor of the ABAQUS software. The discretized mesh has 7032 plane stress four-node elements. For the sake of simplification, the interface between the largest

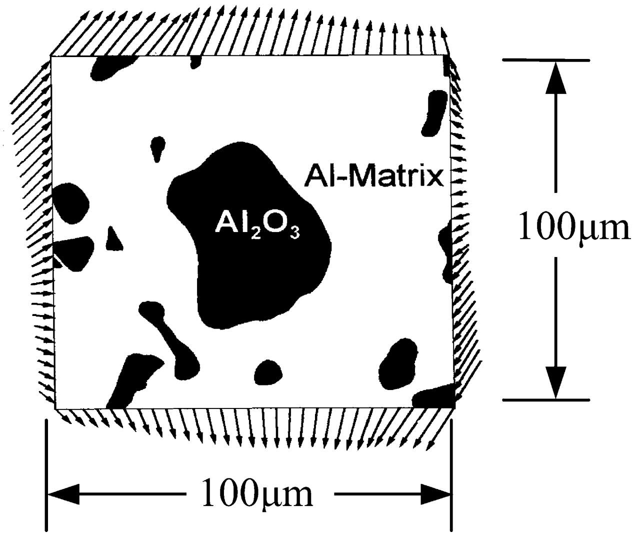


Fig. 5. An undeformed microstructural area with edge displacements obtained experimentally [9].

Table 1
Material properties

| | $E$ (GPa) | $v$ | $\sigma_0$ (MPa) | $\sigma_\infty$ (MPa) |
|---|---|---|---|---|
| Matrix-Al | 68.3 | 0.33 | 105.0 | 170.0 |
| Inclusion-$Al_2O_3$ | 380.0 | 0.22 | – | – |

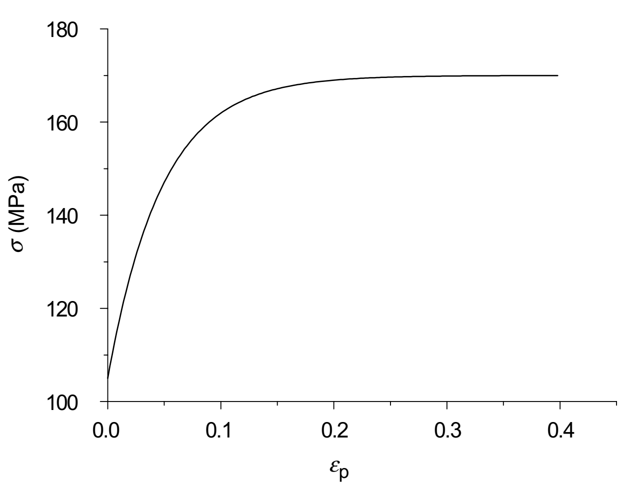


Fig. 6. Plastic stress–strain relation of matrix Al [9].

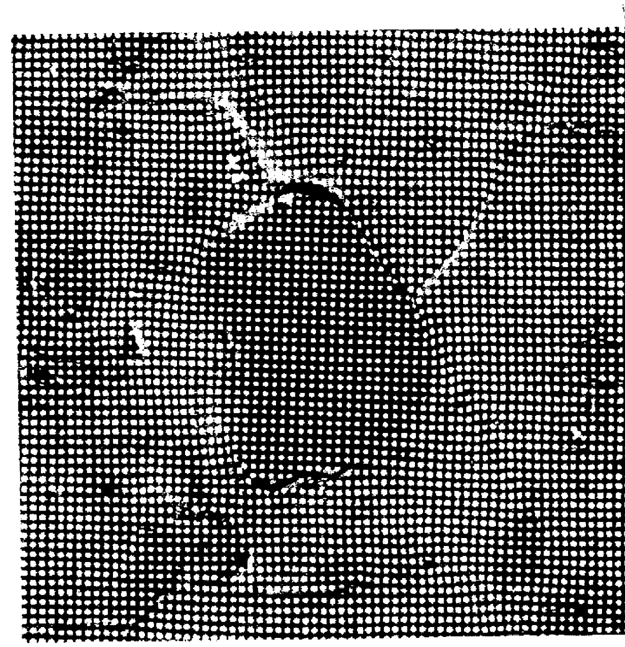

Fig. 7. A bitmap of the deformed microstructural area [9].

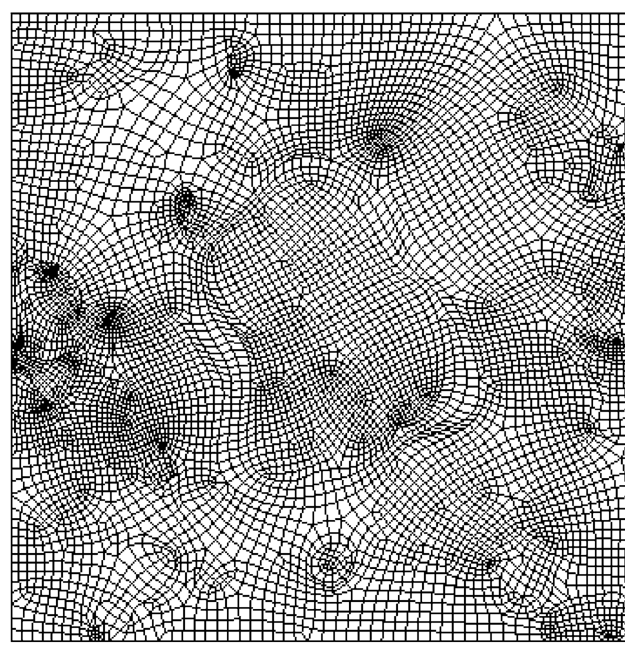

Fig. 8. Computational FEM mesh.

inclusion and the matrix is investigated here and there are 112 non-continuum interface elements along the interface (i.e. $s = 112$). The non-continuum interface element mentioned in Section 3.1 is employed and the corresponding formulation of the interface element is implemented into ABAQUS via its user-defined element (UEL) interface. The edge displacements of the real microstructural area obtained from the experiment [8,9] are applied here. Four unknown interfacial parameters to be identified, $\sigma_{\mathrm{Tmax}}$, $\delta_{\mathrm{T}}$, $\sigma_{\mathrm{Nmax}}$, and $\delta_{\mathrm{N}}$, are the interfacial shear strength limit, the interfacial shear separation limit, the interfacial tensile strength limit and the interfacial tensile separation limit respectively. The mechanical parameters of the interface element are identified by the proposed inverse/genetic method based on the interfacial failure information observed in the experiment (see Fig. 7). In our analysis, the interfacial parameters are in the range described as below. The interfacial shear/tensile strength limit is between 0 and 170 MPa, and the interfacial shear/tensile separation limit varies from 0.00 to 2.00 μm. If the computation accuracy of shear and tensile strength parameters is set to be 1, the lengths of substrings corresponding to shear and tensile strength parameters are calculated as 8 bits from formula (2). Likewise, if the computation accuracy of shear and tensile stiffness parameters is set to 0.01, the lengths of substrings corresponding to shear and tensile stiffness parameters are calculated as 7 bits. The probability for reproduction of the fittest individual in every generation is set to be 1.8 times of the average probability of individuals in the same population. When evaluating fitness of the individual $r$, the fitness value is taken to be $[f(r) - 30]$ if no shear failure interface element exists in the FE-simulation. Similarly, the fitness value is obtained subtracting 30 from the objective value $f(r)$ if no tensile failure interface element exists in the FE-simulation for the parameter $r$. As a consequence of this modification, the GA can work more efficiently.

In addition, there are three important parameters which may affect the efficiency of the GA. They are: (1) Population size: in general, the population size affects both the ultimate performance and the efficiency of GAs. A small population may lead to premature convergence and result in suboptimal solution. Conversely, a large population requires more evaluations per generation, which may result in a slow convergence and longer running time. The optimal population size for a given type of problem should be found by numerical experimentation. (2) Crossover rate ($P_c$): the rate at which solutions are subjected to crossover is dependent on the crossover rate $P_c$. The higher the value of $P_c$ is, the quicker the optimal solution can be achieved. A very high value of $P_c$ may, however, lead to premature convergence. In our calculation, $P_c$ is taken to be between 0.5 and 0.95. (3) Mutation probability ($P_m$): the GA might be led to a purely random search algorithm if the value $P_m$ is too lager. Conversely, if $P_m$ is too small, it may cause premature convergence and result in suboptimal solution. Typically, $P_m$ is chosen in the range of 0.001–0.1.

After a series of computational experiments and algorithm performance comparison, the genetic parameters are determined as following: population size = 30, crossover rate = 0.8, mutation rate = 0.05, maximum generation = 100. The fitness curve is shown in Fig. 9 (the fitness has been normalized to the range of 0–1). Finally, the identification values of the four interfacial parameters are: the interfacial strength limit in the tangential direction, $\sigma_{\mathrm{Tmax}} = 48$ MPa, the interfacial separation limit in the tangential direction, $\delta_{\mathrm{T}} = 0.89$ μm, the interfacial strength limit in the normal direction, $\sigma_{\mathrm{Nmax}} = 81$ MPa, and the interfacial separation limit in the normal direction, $\delta_{\mathrm{N}} = 0.72$ μm. The fitness curve in Fig. 9 demonstrates that the proposed GA method is effective and robust in solving the interfacial parameter identification problem of the real microstructure in the actual multiphase composite. It can be seen from the identification results above that the interface between matrix and the largest inclusion is a weakly bonded interface. The interfacial strength is relatively low. The interfacial tensile and shear strengths are much lower than those of the inclusion $Al_2O_3$ and the matrix Al. It is also evident from the identification results above that the stiffness of the interface is lower than that of the matrix Al. That is the reason why the failure is easier to occur at the interface. For the interface property itself, the interfacial shear strength is lower than the interfacial tensile strength. There is, however, not much difference between the interfacial shear stiffness and the interfacial tensile stiffness. The contour plot of equivalent plastic strain (PEEQ) for the microstructural area is shown in Fig. 10(a) using the interfacial parameters obtained from the proposed inverse/genetic method. The interfacial damage in the microstructural area under consideration is taken into account for the results presented in Fig. 10(a). While the contour plot of PEEQ for the microstructural area having the rigid interface is shown in Fig. 10(b). The results, obtained from the numerical simulation for the failure mode of the real microstructure, is observed to be more reasonable than those from the approach in Ref. [9], as comparison with the corresponding experimental results [8,9]. By comparing Fig. 10(a) with (b), we can see that there is apparent difference in the location of the strain concentration and the distribution of the slip bands between the two figures. For example, some new slip bands appear at the tip of the interfacial crack where tensile or shear failure occurs and the density of the slip bands in the microstructural area increases.

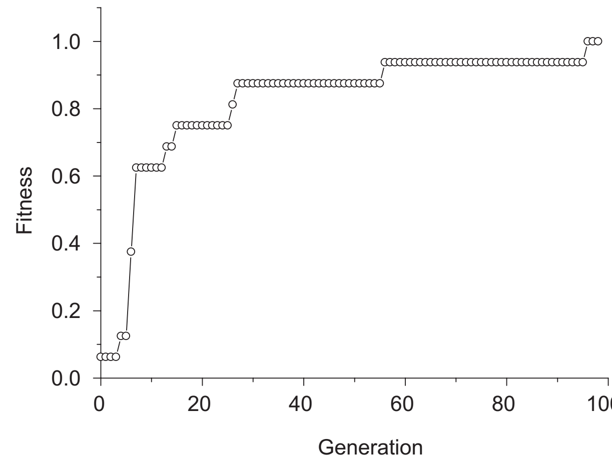


Fig. 9. Fitness curve.

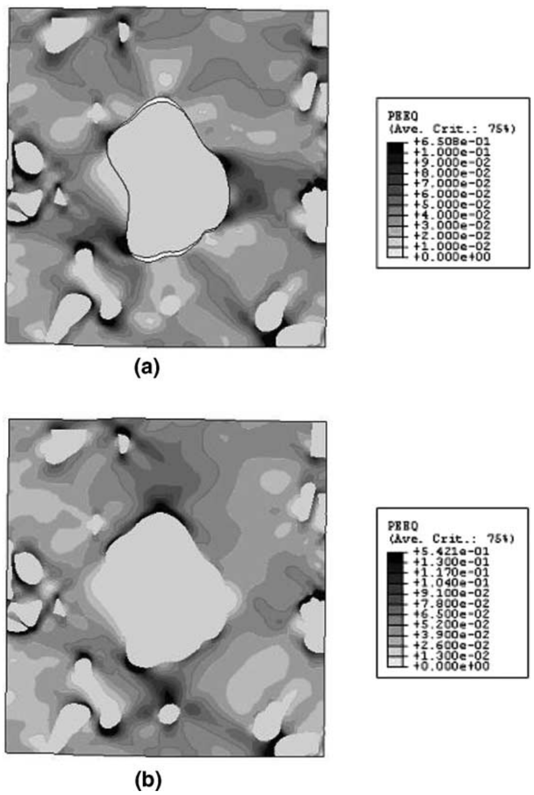


Fig. 10. The contour plots of equivalent plastic strain (PEEQ) for the microstructural area: (a) when the interfacial damage in this area is taken into account, and (b) having the rigid interface.

## 5. Conclusions

An inverse/genetic method for solving mechanical parameter identification problem of interfaces in actual multiphase composites is presented in this paper. Based on hybrid analysis, the proposed method has been used to study interfacial property of a real metal matrix composite. The numerical results have demonstrated that the proposed method can be applied to the interfacial parameter identification of interfacial region in real composites in a simple and useful way according to interfacial fail information. Experimental data of real microstructure have been used as the initial data for finite element calculation and the identification procedure. The tensile and shear mechanical properties of the interface are simultaneously estimated for the real microstructure under mixed-mode fracture. The study also indicates that the proposed method has the potential to solve complex properties identification problems of multiphase composites.

GAs are robust when tackling complex optimization problems owing to its parallel global search feature and that no auxiliary knowledge such as derivative is needed in search process. However, the computational efficiency of the proposed method is relatively low. To improve the performance of the GA, combination strategy should be considered which combines GAs with other local search techniques such as gradient-based method.

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## References

[1] Achenbach JD, Zhu H. Effect of interfacial zone on mechanical behavior and failure of fiber-reinforced composites. J Mech Phys Solids 1989;37(3):381–93.
[2] Allix O, Ladeveze P. Interlaminar interface modelling for the prediction of delamination. Compos Struct 1992;22(4):235–42.
[3] Needleman A. A continuum model for void nucleation by inclusion debonding. J Appl Mech 1987;54(3):525–31.
[4] Needleman A. An analysis of tensile decohesion along an interface. J Mech Phys Solids 1990;38(3):289–324.
[5] Tvergaard V. Effect of fiber debonding in a whisker-reinforced metal. Mater Sci Eng A 1990;125(2):203–13.
[6] Zhou CW, Wang W, Fang DN. Cohesive interface element and interfacial damage analysis of composite. Acta Mech Sin 1999;31(3):372–7 (in Chinese).
[7] Niu XR. Numerical simulation and modeling analysis on fracture behavior of complex interface of dissimilar materials. Master Dissertation, Beijing: Tsinghua University; 2000 (in Chinese).
[8] Liu YL, Fischer G. In situ measurement of local strain in a metal matrix composite by the object grating technique. Scrip Mater 1997;36(10):1187–94.
[9] Fischer G, Soppa E, Schmauder S, Liu YL. Modelling of strain localization in real microstructural areas of the particle reinforced metal-matrix composite Al 6061-10%$Al_2O_3$. In: Proceedings of the Riso International Symposium on Metallurgy and Materials Science, Denmark, 1998, p 261–6.
[10] Barlow CY, Hansen N. Dislocation configurations in metal-matrix composites correlated with numerical predictions. Acta Metall Mater 1995;43(10):3633–48.
[11] Chu YC, Rokhlin SI. Stability of determination of composite moduli from velocity data in planes of symmetry for weak and strong anisotropies. J Acoust Soc Am 1994;95(1):213–25.
[12] Balasubramaniam K, Bao NS. Inversion of composite material elastic constants from ultrasonic bulk wave phase velocity data using genetic algorithms. Compos B: Eng 1998;29(2):171–80.
[13] Liu GR, Han X, Lam KY. A combined genetic algorithm and nonlinear least squares method for material characterization using elastic waves. Comput Methods Appl Mech Eng 2002;191:1909–21.
[14] Liu GR, Ma WB, Han X. An inverse procedure for determination of material constants of composite laminates using elastic waves. Comput Methods Appl Mech Eng 2002;191:3543–54.
[15] Springmann M, Kuna M. Identification of material parameters of the Rousselier model by non-linear optimization. Comput Mater Sci 2003;26:202–9.

[16] Groetsch CW. Inverse problem in the mathematical sciences. Braunschweig: Vieweg; 1993.
[17] Santamarina JC, Fratta D. Introduction to discrete signals and inverse problems in civil engineering. New York: ASCE; 1998.
[18] Holland J. Adaptation in natural and artificial systems. Ann Arbor, MI: University of Michigan Press; 1975.
[19] Goldberg DE. Genetic algorithms in search, optimization and machine learning. Cambridge: Addison-Wesley; 1989.