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A systematic method for identifying contradiction of casting process

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1. Introduction

The theory of inventive problem solving (TRIZ), one of the most important innovation theories, has long recognized that the essence of solving problem is to eliminate the contradictions existing in technical systems, and has provided some tools to identify and remove these contradictions [1]. Among these tools, the substance field model (S-Field model), an analytical tool used for identifying contradiction, consists of two substances and one field [2]. It is noted that the model contains a small number of components and remains a simple structure. Consequently, the S-Field model can be only used for identifying the contradiction of simple problem or the basic lowest level problem in a complex technical system. Therefore, TRIZ still needs to be fur-ther improved and developed due to the inadequacy in some functions and operability aspects [3, 4]. For this issue, a few researches have made some progress [5-9]. However, all results of the above researches only suit the applications in product conceptual design. A good conceptual design that maintains the independent function requirements (FRs), should be uncoupled or decoupled so that we can deal with the design parameters which correspond to a given function requirement, without con-sidering other function requirements. Contrarily, for a coupled design in which there exists no less than one contradiction, we must consider the effect of a decision on other FRs [10]. Therefore, the contradiction problems in conceptual design are a type of single factor technical problem, i.e. the change of one element affects one or more causes.

Casting process optimization aims at removing or weakening the effect of defects on casting quality so as to obtain high efficiency and low cost. In general, the casting defects, either in microscale or in microscale, result from the multiple micro factors in which the effect intensity of one micro factor is not identical to others [11, 12]. In this case, the casting process optimization is to solve a complex problem possessing multiple micro factors, i.e. two or more micro factors simultaneously affect single cause of problem. Moreover, every micro factor may serve as a subproblem. In this situation, the afore-mentioned methods for identifying contradictions are not helpful. With respect to casting technical problem, it is necessary to break the complex casting process problem down into several subproblems through the systems approach. After the decomposition of the engineering problem, the contradictions in subproblems could be identified by using S-Field model and related knowledge.

The systems approach is a scientific analysis method with three capabilities including optimization, simulation and restoration [13]. Applying this method to analysis of casting process problem, the elements in the technical system, as well as their role and interrelation, can be effectively clarified. Furthermore, it is helpful to the decomposition of casting technical system and the identification of contradictions.

Motivated by this idea, we propose a method based on systems thinking for solving casting process problem. Furthermore, the validation of the method presented in this paper is demonstrated by optimizing casting process of the intake manifold.

The remainder of this paper is organized as following: in section 2, we provide the systematic method for identifying contradictions within casting process problem. A case study is carried out in section 3. Section 4 presents discussion on the features of proposed method. The paper concludes with section 5.

2. The method

As mentioned above, the specific problem in terms of TRIZ is the subproblem in casting technical system rather than the engineering problem. Therefore, it is necessary to systematically analyze and decompose the engineering problem before identifying contradictions. Moreover, the analysis in essence is a process of recognizing problem, thereby, the scientific analysis should proceed some steps including describing phenomena, defining problem, ascertaining causes, identifying and evaluating factors, and searching for solution. For these reasons, the systematic method for identifying contradictions of casting process problem is proposed in Fig. 1.

The procedures of the systematic method are outlined below.

- describe the castings defect;
- ascertain the root cause;
- analyze and identify the factors in all levels.

Analyze the basic lowest level subproblems using S-Field model, and identify the contradictions.

Define the standard problems. Here, the castings defects appear as practical engineering problems while the basic subproblems which result from the factors in the lowest level, are the specific problems of TRIZ.

By this method, the contradictions and standard problems are obtained. Next, we could strictly follow the general algorithm of TRIZ to search for possible solutions through making use of solving tools of TRIZ such as 40 Invention Principle or 76 Standard Solution for S-Field model. On this base, the final solution could be developed. It is important to emphasize that the decomposition of problem is the heart of the proposed method.

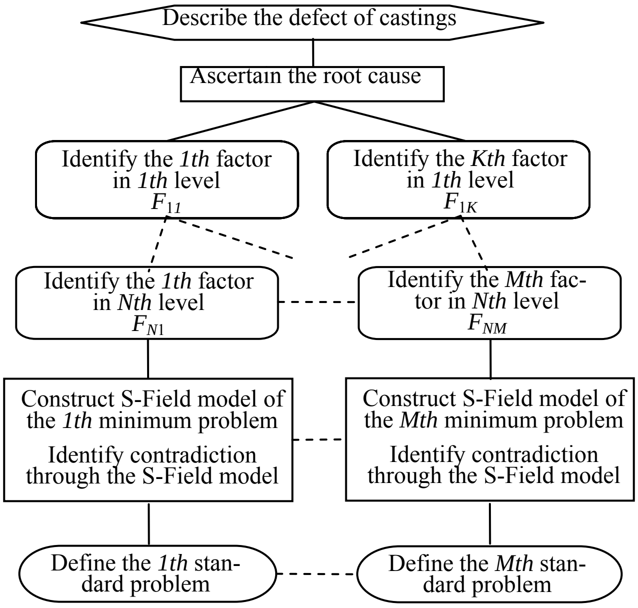


Fig. 1 Flow chart of the systematic method

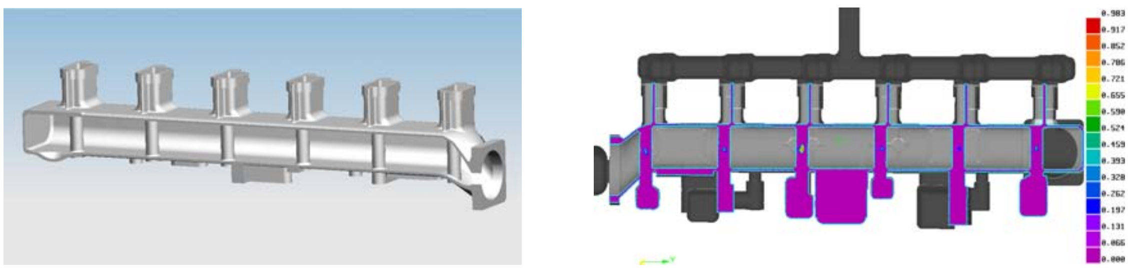
3. Casting process optimization of intake manifold

As described before, the casting process optimization is divided into two stages, i.e. problem analysis and contradictions identification, and problem solving and process optimization. First, using the proposed method, the contradictions within a complex technical problem are identified while the corresponding standard problems are defined. Finally, the desired casting process that can improve the quality and efficiency of casting, is obtained by utilizing the solving tools of TRIZ and the knowledge in related domain.

3.1. Problem analysis and contradictions identification

1-) Description of casting defect.

The intake manifold that is made of magnesium alloy AZ91D, consists of one air passage and six outlets. There six cylindrical rods of 24 mm in diameter evenly locate in the air passage of 4 mm in thickness, as shown in Fig. 2, a. Because the manifold is used for transfer-ring compressed air of 0.6 MPa, some mechanical properties such as the strength, the pressure resistance and the leakage resistance, are need. Due to the pressure of compressed gas, it is also required that no shrinkage pores and no serious porosities form in castings. In addition, the intake manifold was produced by the permanent mould which consisted of metal parts and a rein sand core. Moreover, the joint face of the permanent mould was parallel to the centre lines of the six cylindrical rods. However, some serious shrinkage pores had formed in the centres of these cylindrical rods as shown in Fig. 2, b which came from the numerical experiment. In the numerical experiment, the initial and boundary conditions had been defined according to the actual production conditions while the thermo-physical properties, including AZ91D and the permanent mould, had been selected from the database module of the simulation software.



a b

Fig. 2 Structure and shrinkage pores prediction of the intake manifold produced by permanent casting: a - structure of the intake manifold castings; b - prediction of shrinkage pores in the castings

2) Ascertainment of root cause.

During solidification, the molten metal experiences volume reduction due to the phase change. Therefore, the region that is just solidifying and shrinking, needs access to sufficient amounts of feeding metal at higher temperature so as to obtain castings possessing uniform density. Contrarily, shrinkage pores will emerge in this region. Meanwhile, the melt will represent an in-sufficient feeding capacity. In other words, the insufficient feeding capacity is the root cause that results in occurrence of shrinkage pores.

3) Analysis and identification of factors.

There many factors affecting the feeding capacity of melt are shown in Fig 3. These factors, i.e. solidification mode, feeding pressure and solidification order, respectively, are the elements in the first level.

In the mould filled by liquid metal, the region at low temperature solidifies sooner than the high temperature area. Therefore, a progressive solidification exists from the low temperature section to the high temperature section.

Furthermore, the strong feeding capability can be obtained only by ensuring that the casting section keeps increasing toward the feeding metal. From this point of view, the solidification order directly relate to the temperature profile which is influenced by the heat capacity and the heat-transfer capability. In addition, various solidification modes that depend on the composition of alloy, lead to different feeding capacities. The feeding pressure that derives from gravity of molten metal, has relations with running and feeding system. As a result, the composition, the running and feeding system, and the heat capacity and the heat-transfer capability, are identified as the factors in the second level. However, because of the well filling and the complete shape of manifold, but the appearance of shrinkage pores, the heat capacity and the heat-transfer capability are seen as the chief factors resulting in two basic subproblems.

4) Analysis of subproblems and identification of contradictions.

As the above description, the basic subproblems can be presented as the following specific problems of TRIZ.

- Specific Problem 1. Unreasonable distribution of heat causes the irrational temperature profile and solidification order.
- Specific Problem 2. Difference of heat-transfer capability at interface including mould/casting and core/casting, causes the irrational temperature profile and solidification order.

In order to obtain a deeper understanding on the above specific problems, the S-Field models of TRIZ are respectively designed as shown in Fig. 4.

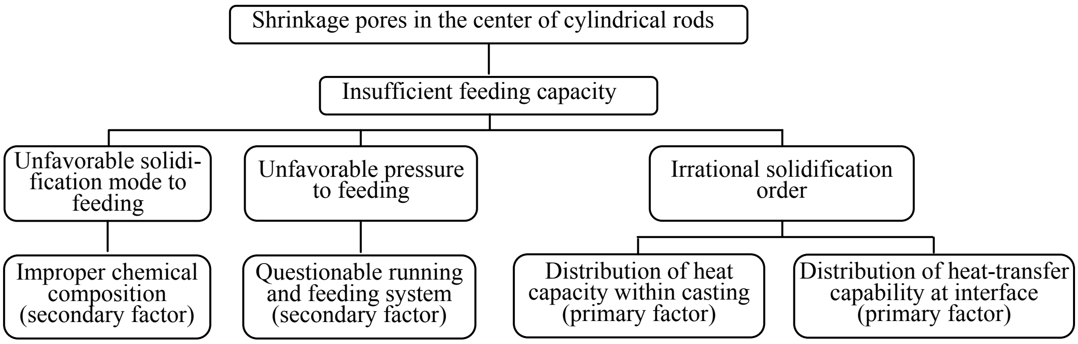
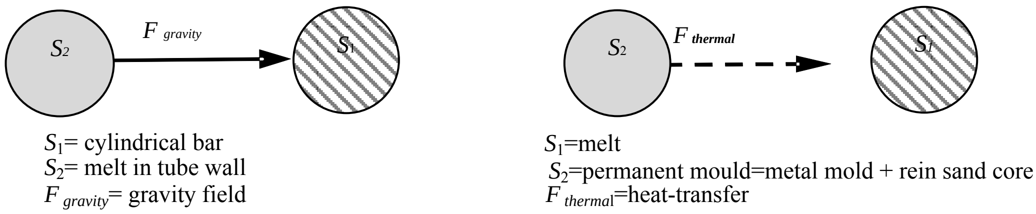


Fig. 3 Systematically analyzing flow chart used for shrinkage pores in the manifold castings



a b

Fig. 4 Substance-Field model of specific problems: a - S-Field model of specific problem 1; b - S-Field model of specific problem 2

In the model of the specific problem 1 as in Fig. 4, a, the substance 2 (S_2, the melt in section of tube wall) feeds on the substance 1 (S_1, cylindrical rods) under the effect of field ($F_{gravity}$, gravity field). However, the molten metal in the wall solidifies earlier than that in cylindrical rods due to the thinner wall thickness, which weakens or removes the effect of gravity on the rods as well as the feeding capacity. In short, this S-Field model is the system with complete architecture, weaker impact and unapparent conflict.

Similarly, as the illustration of Fig. 4, b the substance 2 (S_2, permanent mould) absorbs the amounts of heat from substance 1 (S_1, melt) by means of field ($F_{thermal}$, heat-transfer) which is insufficient action currently, so as to decrease the temperature of melt and to form the manifold castings. For the purpose of blanking and loosing core, the permanent mould is made of metallic parts and rein sand core. Since the difference of heat-transfer capability between the rein sand core and metallic parts results in the undesired temperature profile and solidification order, the cylindrical rods solidify slower and later than the tube walls. As a result, the shrinkage pores emerge in the central area of cylindrical rods. By selecting from the engineering parameters of TRIZ, the parameter (i.e. quantity of objects, numbered 26) denoting the feature of permanent mould as well as the parameter (i.e. sensitivity to harmful effect, numbered 30) denoting the reduced feeding capacity, the contradiction in specific problem 2 can be defined as: quantity of objects (No.26) becomes better (quantity of objects in-creases), sensitivity to harmful effect (No.30) becomes worse (harmful effect is strengthened).

5) Definition of standard problems.

Depending on the above analysis, two specific problems presented before can be translated into the following standard problems respectively.

- Standard problem 1. Varying of cross section area results in the appearance of harmful effect.
- Standard problem 2. The increase in number of objects enhances the harmful effect.

3.2. Problem solving and process optimization

In this section, we strictly follow the procedures of TRIZ to search for the possible solutions by using solving tools of TRIZ. The commonly used solving tools include Contradiction Matrix, 40 Invention Principle and 76 Standard Solution. 40 Invention Principle are used for solving general contradictions, and each of them is respectively designated as principle 1, principle 2…, and principle 40. Moreover, The 76 Standard Solution are grouped into five large categories, in which those standard solutions are further classified into several little categories. Each of them is designated by a decimal, e.g. class 1.1.3 denotes the third solution that belongs to the first little category of the first large category.

For the standard problem 1 without apparent contradiction, the possible solutions are ascertained from the 76 standard solution as below [14, 15].

• Class 1.1.3 The system cannot be changed, however, it can accept a permanent or temporary external additive to change either S_1 or S_2.

• Class 1.1.6 It is difficult to control the small amounts precisely. It can be achieved by applying and then removing an appendant.

• Class 2.4.7 Arrange objects using natural phenomena.

According to above suggestions, two specific solutions are generated. First, six equal risers are added to the junctions where the cylindrical rods are connected with the tub walls. Second, the cylindrical rods are oriented along the gravity direction by modifying the joint face of casting mould. In this case, the cylindrical rods can easily receive the feeding melt through making full use of self-feeding during solidification.

For standard problem 2, other two specific solutions are found according to the Contradiction Matrix as well as 40 Invention Principle [16].

• Principle 33, homogeneity, suggests: make objects interacting with a given object of the same material.

• Principle 35, parameter change, suggests: change the concentration or consistency, or provide a degree of flexibility.

According to these indications, another specific solution that the mould and the core used for manifold casting are made from resin sand simultaneously, is obtained.

After reviewing these obtained specific solutions, the final solution is developed as following.

• Select the top face of manifold being vertical to cylindrical rod as joint face.

• Prepare the mould and the core using resin sand.

• Add total six risers on the top of the rods, respectively.

• Pour the melt at 680°C into the mould and complete the filling in 12 S or so.

The simulation for the optimized casting process of the manifold has been carried out employing the numerical experiment described in section 3.1. Moreover, the prediction of shrinkage pores in the intake manifold has also been graphically shown in Fig. 5. The result shows that no shrinkage pore or no serious porosity is found in castings, especially in the centres of cylindrical rods, whilst only few concentrated shrinkage pores appear in the risers.

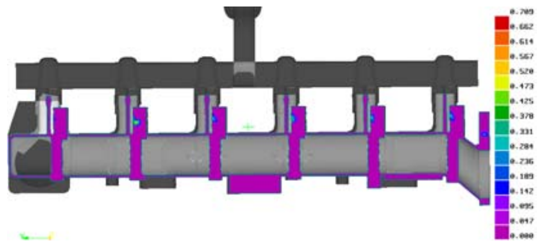


Fig. 5 Simulation and evaluation of shrinkage pores in the intake manifold produced by rein sand casting

4. Discussions

In solving casting process problem, a cause resulting in casting defect is usually influenced by multi-factors, in which one factor interact with others. For in-stance, the distribution of heat capacity within casting cavity, as well as the heat-transfer capability at mould/casting interface, commonly determines the solidification order of melt, and different heat-transfer capabilities lead to different distribution of heat capacity in the same cavity. Therefore, the problem aroused in casting process is a class of complex multifactors problem.

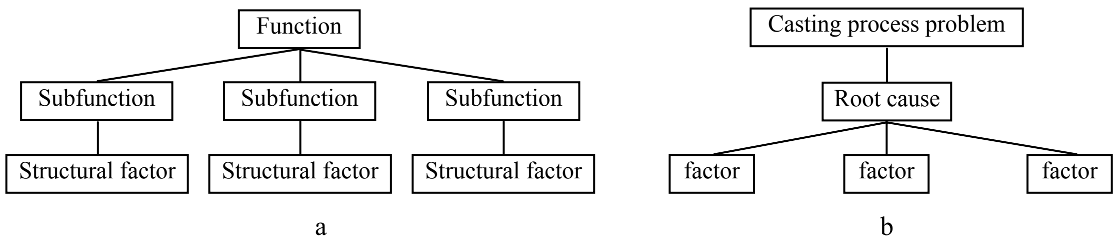


Fig. 6 Flow chart of problem analysis in conceptual designation and casting process optimization: a - flow of analysis in conceptual design; b - flow of analysis in casting process

The conceptual design aims to realize the function of products by designing the product structure. In fact, the function of products can generally be divided into some independent subfunctions which are affected by structure factors such as structure mode or parameters. In questionable design, however, the change of single structure factor may influence on the performance of one or more subfunctions. Thereby, the problem existing in product conceptual design is the type of single-factor problem. The analysis flow of those methods mentioned in the section 1, as shown in Fig. 6, a, shows the divergent corresponding relationships between function and subfunctions as well as the mapping between subfunctions and structure factors. Consequently, these methods for identifying contradiction are unsuitable to casting process problem.

In contrast, the method proposed in this paper focus on the systems thinking, and its flow of analysis as shown in Fig. 6, b illustrates the mapping between casting process problem and cause as well as the diver-gent corresponding relationship between cause and factors. In addition, the performance of this method is similar to that of those methods introduced in section 1 when this method is used for identifying the contradiction in conceptual design. Therefore, the new method can be applied to not only multi-factors problems but also single-factor problems.

Starting from the systems thinking, the new method systematically analyzes the complex multifactors problem of casting process by combining the holistic thinking and analysis thinking. The systematic analysis not only is in conformity with the viewpoint of technical system of TRIZ but also satisfies the requirement of minimization problem of TRIZ. Moreover, be-cause of the steps described in section 2, the analysis flow of the proposed method is in keeping with the law of cognition as well as the habit of thinking. In this case, it is easier to understand and utilize the systematic method for identifying contradiction in multi-factors problem.

The casting process optimization of the intake manifold demonstrates that the identification of contradiction within casting problem and the improvement of casting process can be effectively implemented by integrating the systematic method of identifying contradiction with the solving tools of TRIZ. This is because that the standard solutions provided by the solving tools of TRIZ are the abstractions and the summaries on principles, methods and measures in a broad range of domains, and inspires the specific solutions. Therefore, the integration approach differs from the commonly used optimization methods of casting process that base on experience or numerical simulation, and is characterized by higher va-lidity and efficiency.

The procedure of the systematic method for identifying contradiction, which consists of several steps in order, is convenient for expression by programming language, thereby, the systematic method can be popularized and applied to computer aided innovative design and optimization. On the basis of above discussion, the application of the systematic method enhances the conversion capability from specific problem to standard problem of TRIZ, and improved the feasibility of TRIZ in practice.

5. Conclusions

The systematic method for identifying contradiction of TRIZ, which is proposed in this work, is suitable to the complex multifactors problem of casting process.

The integration of the systematic method and the solving tools of TRIZ enhance the efficiency of cast-ing process optimization.

The proposed method features systematicness, feasibility and programmability.

The proposed method conforms to the general habit of thinking, and is easily accepted and popularized.

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SISTEMINIS KONTRASTŲ NUSTATYMO LIEJIMO PROCESE METODAS

R e z i u m ė

Išradimų problemų sprendimo teorija, viena iš svarbiausių inovacinių teorijų, nepadeda aptikti prieštaravimų. Šią problemą sėkmingai sprendė keletas tyrinėtojų. Deja, jie sutelkė dėmesį į abstrakčius projektus, spręsdami vieno faktoriaus problemas, užuot liejimo proceso optimizavimą traktavę kaip daugiafaktorį uždavinį. Pradedant sistemine analize, šiame darbe teikiamas sisteminis metodas liejimo procese atsirandantiems prieštaravimams aptikti, siūloma nuo specifinių problemų pereiti prie standartinių sprendimų naudojant patobulintą išvardytų problemų sprendimo teoriją. Šis metodas yra patikrintas daug kartų optimizuojant liečių liejimo procesą. Praktika parodė, kad sujungus sisteminį metodą su išradimų problemų sprendimo teorija padidėjo liejimo metodų optimizavimo efektyvumas.

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A SYSTEMATIC METHOD FOR IDENTIFYING CONTRADICTION OF CASTING PROCESS

S u m m a r y

The Theory of Inventive Problem Solving (TRIZ), one of the most important innovation theories, was inadequate to identifying contradiction. Some researchers had been successfully conducted to address the issue. However, these researches focused on conceptual design which was a type of single factor problem, rather than casting process optimization which was a type of multifactors problem. Starting from systems thinking, this work for the first time proposed the systematic method for identifying contradiction of casting process, which enhanced the conversion capability from specific problem to standard problem whilst improved the feasibility of TRIZ. This method was validated by optimizing casting process of the intake manifold. The case study showed that the integration of the systematic method and solving tools of TRIZ increased the efficiency of casting process optimization.

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