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Influence of load and reinforcement content on selected tribological properties of Al/SiC/Gr hybrid composites

Sandra Veličković[1], Slavica Miladinović[1], Blaža Stojanović[1], Ružica R. Nikolić[2], Branislav Hadzima[2], Dušan Arsić[1]

[1] University of Kragujevac Faculty of Engineering, Sestre Janjić 6, Kragujevac, Serbia, +381 34 335990, sandrav@kg.ac.rs
[2] University of Žilina, Research Center, Univerzitna 8215/1, 010 26 Žilina, Slovakia

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Abstract
Hybrid materials with the metal matrix are important engineering materials due to their outstanding mechanical and tribological properties. Here are presented selected tribological properties of the hybrid composites with the matrix made of aluminum alloy and reinforced by the silicon carbide and graphite particles. The tribological characteristics of such materials are superior to characteristics of the matrix – the aluminum alloy, as well as to characteristics of the classical metal-matrix composites with a single reinforcing material. Those characteristics depend on the volume fractions of the reinforcing components, sizes of the reinforcing particles, as well as on the fabrication process of the hybrid composites. The considered tribological characteristics are the friction coefficient and the wear rate as functions of the load levels and the volume fractions of the graphite and the SiC particles. The wear rate increases with increase of the load and the Gr particles content and with reduction of the SiC particles content. The friction coefficient increases with the load, as well as with the SiC particles content increase.

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1. Introduction

Metal matrix composites (MMCs) are the materials with the superior properties with respect to the conventional materials. Research of the MMCs is being intensified in the last couple of decades and it is becoming even more actual due to the trend and necessity for producing such materials with even better properties than the currently existing ones. The MMCs consist of at least two phases: matrix and reinforcement. Matrix materials are metals or alloys, while reinforcements are ceramics in the form of particles, whiskers or fibers. When the matrix material is reinforced with two or more different reinforcements, the resulting materials are known as the hybrid metal matrix composites (MMCHs). (ZEREN, A. 2015, ADEOSUN, S.O., OSOBA, L.O., TAIWO, O.O. 2014)

Properties of the hybrid composites, as well as their improvement, depend on the nature of the reinforcements (being built-in into the matrix), their hardness, size of particles, volume fractions, distribution of the reinforcing phases, as well as the manufacturing technique. Performances of the hybrid MMCs are better than those of the conventional ones (ZEREN, A. 2015, BASAVARAJAPPA, S., PAULO DAVIM, J. 2013). Generally, the MMCs are mainly used as substitutes for the conventional materials, in many applications, especially in the aerospace, automobile and recreational industries where the performance requirements are getting more demanding. The MMCHs' application is growing rapidly due to their exceptional properties like the high resistance-to-weight and strength-to-weight ratios, hardness and wear resistance, good creep behavior, small weight, design flexibility etc. (DIXIT, G., KHAN, M. M. 2014, STOJANOVIC, B., IVANOVIĆ, L., 2015, STOJANOVIC, B., GLISOVIC, J. 2016).

One of the most widely used composites are the aluminum based composites (Aluminum Matrix Composites). Aluminum is the second most present metal and with its alloys it is economically competitive in applications of the metal materials due to the low specific (volume) weight, high corrosion resistance and easy processing (BASAVARAJAPPA, S., PAULO DAVIM, J. 2013, BANSAL, S., SAINI, J. S. 2015).

Aluminum hybrid composites are the new generation of metal matrix composites, which are capable to satisfy requirements of engineering applications. Advantages of the AMCs, as compared to conventional alloys, are as follows:

low density, high strength, better stiffness, superior high temperature properties, good damping characteristics, abrasion and wear resistance (BANSAL, S., SAINI, J.S. 2015, SURESH, P., MARIMUTHU, K., RANGANATHAN, S. 2013). Aluminum metal matrix composites are the most frequently applied for manufacturing the engine cylinders, connecting rods, elements of the vehicles' braking system, cardan shafts etc. They are also used for producing the brakes' assemblies, gears, valves, pulleys, turbines, turbo-compressors, pump housings and accompanying equipment (STOJANOVIC, B., IVANOVIĆ, L. 2015, STOJANOVIC, B., GLISOVIC, J. 2016).

2. Technology of MMCH production

2.1. The reinforcement types

Factors that determine properties of composites are the type of the reinforcement, the volume fraction(s) of the reinforcement(s), size(s) of the reinforcing particles, microstructure, homogeneity and isotropy of the system.

Reinforcements used in aluminum matrix composites (AMCs) are graphite (Gr), silicon carbide (SiC), titanium carbide (TiC), tungsten carbide (WC), boron carbide (B4C), alumina (Al2O3), fly ash, zircon (Zr), silicon nitride (Si3N4), titanium diboride (TiB2). Addition of hard reinforcements, such as silicon carbide, alumina, titanium carbide, improves hardness, strength and wear resistance of the composites, with respect to the matrix alloy (NAVEED, M., ANWAR, KHAN, A.R. 2015). Reinforcements commonly used in aluminum matrix composites have been extended to include organic wastes such as the rice husk ash, coconut shell ash, palm oil fuel ash and the sugar cane bagasse (LANCASTER, L., LUNG, M.H., SUJAN, D. 2013).

The AMCs reinforced with the SiC particulates are known for higher modulus, strength and wear resistance compared to conventional alloys. Addition of the SiC particulates increases both mechanical strength and wear resistance of an Al alloy. The SiC particles have the high yield strength and their modulus of elasticity is very high, whereas the base alloy has the low yield strength and good plasticity (BASAVARAJAPPA, S., PAULO DAVIM, J. 2013, NAVEED, M., ANWAR KHAN, A.R. 2015). Thus in machining of the composites, while the matrix deforms plastically, the SiC particles may only deform elastically or break. The use of SiC and Gr in aluminum matrix composites yields better tribological properties over composites with a single reinforcement (SURESH, P. ET AL. 2013, ZAKAULLA, M., ANWAR KHAN, A. R. 2015)

Composites with combined reinforcement of Al, SiC and Gr are known as the Al-SiC-Gr hybrid composites. The final properties of the hybrid metal matrix composites depend on the matrix and ceramic reinforcements, the bonding of the ceramic reinforcements, the size and distribution of ceramic reinforcements and the graphite particulates in the aluminum matrix.

2.2. The MMCHs fabrication methods

Tribological properties of the Al/SiC/Gr composite materials are strongly affected, among other factors, by the manufacturing process. The fabrication process influences the microstructure, distribution of reinforcement particles and bonds between the matrix and the reinforcement. Fabrication of the MMCs has several challenges like porosity formation, poor wettability and improper distribution of reinforcement.

The basic processes of the aluminum matrix composites fabrication, at industrial level, can be classified into two groups: (i) processing in the solid state and (ii) processing in the liquid state.

Solid state fabrication of Metal Matrix Composites is the process, in which Metal Matrix Composites are formed as a result of bonding of the matrix metal and the dispersed phase due to mutual diffusion occurring between them in solid states at elevated temperature and under pressure. The low temperature of solid state fabrication process (as compared to Liquid state fabrication of Metal Matrix Composites) depresses undesirable reactions on the boundary between the matrix and dispersed (reinforcing) phases.

The fabrication processes in the solid state include the powder metallurgy technology, diffusion metallization and the vapor deposition technology.

The diffusion bonding is a solid state fabrication method, in which a matrix in form of foils and a dispersed phase in form of long fibers are stacked in a particular order and then pressed at elevated temperature.

Sintering fabrication of Metal Matrix Composites is a process, in which a powder of a matrix metal is mixed with a powder of the dispersed phase in form of particles or short fibers for subsequent compacting and sintering in solid state (sometimes with some presence of liquid).

Fabrication processing in the liquid state include stir-casting, compo-casting, squeeze casting, spray casting and reactive – in situ process. *Liquid state fabrication of Metal Matrix Composites* assumes incorporation of dispersed phase into a molten matrix metal, followed by its solidification. To provide the high level mechanical properties of the composite, good interfacial bonding (wetting) between the dispersed phase and the liquid matrix should be obtained.

Selection of the fabrication process depends on numerous factors, like the type and level of reinforcement load, desired degree of micro-structural integrity etc. (STOJANOVIC, B. 2013, SURESHA, S., SRIDHARA, B.K. 2012, RAVINDRAN, P. ET AL. 2013).

Review of available literature shows that the most used methods for fabrication of the Al/SiC/Gr composites are the powder metallurgy, stir-casting, compo-casting and in-situ powder metallurgy.

The stir-casting method is one of the economic and commonly used methods in the liquid metallurgy. The stir-casting is a liquid state method for composite materials fabrication, in which the dispersed phase (ceramic particles, short fibers) is mixed with a molten matrix metal by mechanical stirring. It is the simplest and the most cost effective method of liquid state fabrication. The liquid composite material is then cast by conventional casting methods and may also be processed by conventional metal forming technologies. The main features of the stir-casting are: (i) content of the dispersed phase is limited (usually not more than 30 vol. %) and (ii) distribution of the dispersed phase throughout the matrix is not perfectly homogeneous. In the processing of composites' fabrication, the stirring time between matrix and reinforcement is considered as an important factor.

Another variation of the casting fabrication process is the compo-casting. The process differs from the stir-casting by the fact that the ceramic particles are being infiltrated into the alloy in the semi-solid state. Preparation of the semi-solidified melt consists of cooling the matrix melt down to the working temperature, which is then maintained until the beginning and during the infiltration process. Prior to it, the mixing was performed isothermally, at the defined mixer's rate, in order to disintegrate the dendritic structure that was created during the melt cooling and to alleviate the infiltration process (SURESHA, S., SRIDHARA, B.K. 2010a,b). Discontinuous fibers are dispersed in a liquid alloy, then stirred solidification is followed by re-melting and forced filtering into the porous ceramic matrix. In that way up to 70% of the excess melt can be removed what allows obtaining a high volume fraction of fibers having the random planar alignment.

3. Influence of the load and the volume share of reinforcement particles on tribological behavior of the MMCHs

Infiltration of the reinforcement particles into the metal matrix affects the tribological and mechanical properties of composite materials. Depending on various requirements of the industry, the volume shares percentages of SiC and Gr are being combined, as well as sizes of the reinforcing particles.

Wear is the progressive loss of material due to relative motion between a surface and the contacting substance or substances. Wear may be classified as adhesive wear, abrasion wear, surface fatigue wear and tribo-chemical, fretting, erosion and cavitation wear.

Generally, the friction and wear properties of composites also depend on the shape and distribution of hard or soft particles filled in the matrix. Hard particles increase the strength and wear resistance of composites, but decrease their ductility, whereas the soft particles acting as lubricant decrease the coefficient of friction (RADHIKA, N. ET AL. 2012, VENCL, A., BOBIC, I., STOJANOVIC, B. 2014).

In addition, the composites' fabrication methods also influence their tribological properties.

From review of the available references on Al/SiC/Gr hybrid composites, it can be concluded that in the beginning of their application the larger volume share of SiC particles was used, with respect to composites manufacturing in the previous period. That was the reason why the fabrication, as well as machining of those composites, was more difficult. The cause for that was increased hardness of such composites, (dictated by the SiC volume share). Therefore, in the past few years the content of SiC particles was gradually decreased and it did not exceed 10 wt.%, while the minimal amount was 3 wt.%. That improved both manufacturing and processing (machining) of the hybrid composites with the Al matrix.

Tribological behavior of the Al/SiC/Gr MMCs was studied in order to obtain the best properties of the composite materials with minimal number of experiments, what was achieved by application of the Taguchi method. Many authors were, during the analysis of experiment, applying the Analysis of Variance (ANOVA), as well. The ANOVA was used for the purpose of identifying which of the considered parameters significantly affect the performance measures. By application of that analysis, one can determine the dominating factor(s), with respect to the others, and the percentage contribution of that/those particular independent variable(s). The Response Surface Methodology (RSM) was also used for analysis of obtained results. The RSM represents a collection of experimental strategies, mathematical methods, and statistical inferences that enable a researcher to make efficient empirical examination of the considered problem.

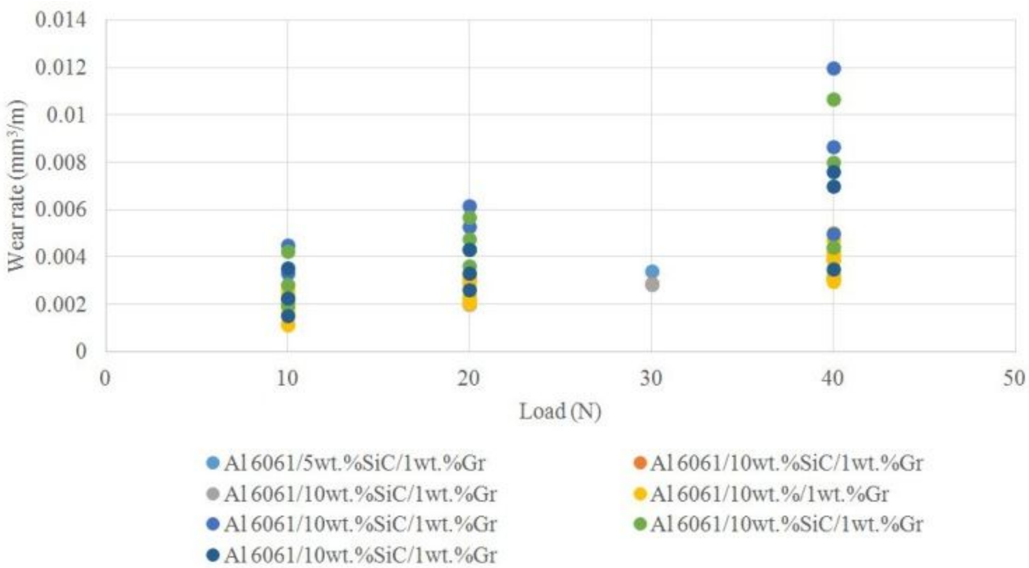

Fig. 1. The effect of load on the wear rate of the Al/SiC/Gr composites with different weight percentage of SiC particles and fixed 1 wt.% Gr

Source: (ZAKAULLA, M., ANWAR KHAN, A.R., MUKUNDA, P.G. 2013, ŞAHIN, S., ET AL. 2014).

Tribological behavior of specimens made of the Al/SiC/Gr composites were studied by conducting the dry sliding wear test, mainly on the pin-on- disc tribometer. The wear test parameters were within the following intervals: load between 10 N to 60 N, sliding speed from 1 m/s to 3 m/s, the sliding distance up to 1000 m. The size of the reinforcement particles varied from nm for SiC to mm for Gr.

The effect of load on the wear rate of the Al/SiC/Gr composites, with different weight percentage of SiC particles, in the presence of graphite, are shown in Figures 1 and 2.

Based on the diagrams in Figures 1 and 2, one can conclude that the wear rate increases with the load increase. Increase of the SiC reinforcing particles volume share in the hybrid composite, on the other hand, causes reducing of the wear rate, since the hardness of the composite material is increased. The sliding speed increase, for the same experimental conditions (the same load and the sliding distance), causes decrease of the wear rate.

The effect of load on coefficient of friction of the Al/SiC/Gr composites, with different weight percentage of SiC particles, in the presence of graphite, is shown in Figure 3.

From diagram in Figure 3 one, can notice that the friction coefficient increases with the load increase, as well as with the SiC particles volume share increase. The sliding distance has the same effect, as well, while the sliding speed increase causes decrease of the friction coefficient of the composite material.

The effect of load on the wear rate of the Al/SiC/Gr composites, with different weight percentage of Gr particles, is shown in Figure 4.

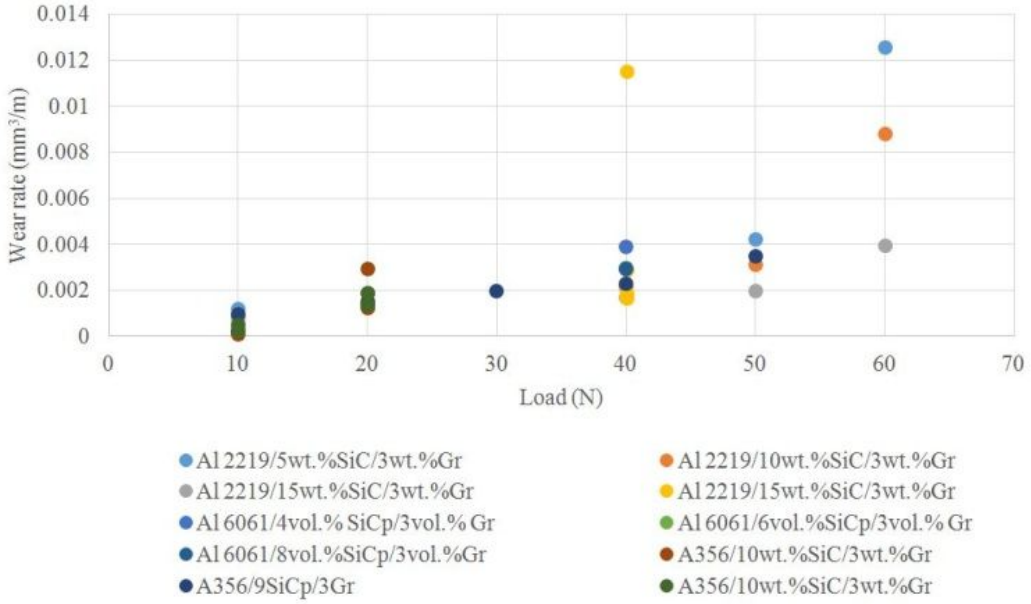

Fig. 2. The effect of load on the wear rate of the Al/SiC/Gr composites with different weight percentage of SiC particles and fixed 3 wt.%Gr or 3 vol.%Gr

Source: (BASAVARAJAPPA, S., DAVIM J.P. 2013, DEVARAJU, A. KUMAR, A., KOTIVEERACHARI, B. 2013, STOJANOVIC, B. ET AL. 2015, VISWANATHA, B.M. ET AL. 2016).

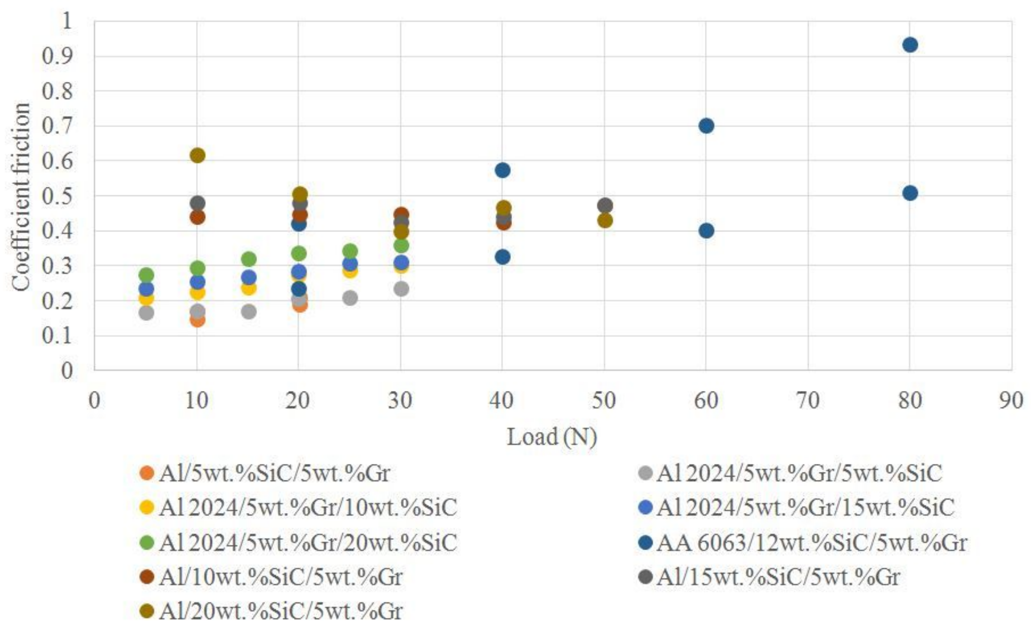

Fig. 3. The effect of load on coefficient of friction of the Al/SiC/Gr compo-sites with different weight percentage of SiC particles and fixed content 5 wt.%Gr

Source: (STOJANOVIĆ, B. ET AL 2016, PAVITHRAN, B. ET AL. 2015, VARGHESE, A.N., PRADEEP, P.V. 2014).

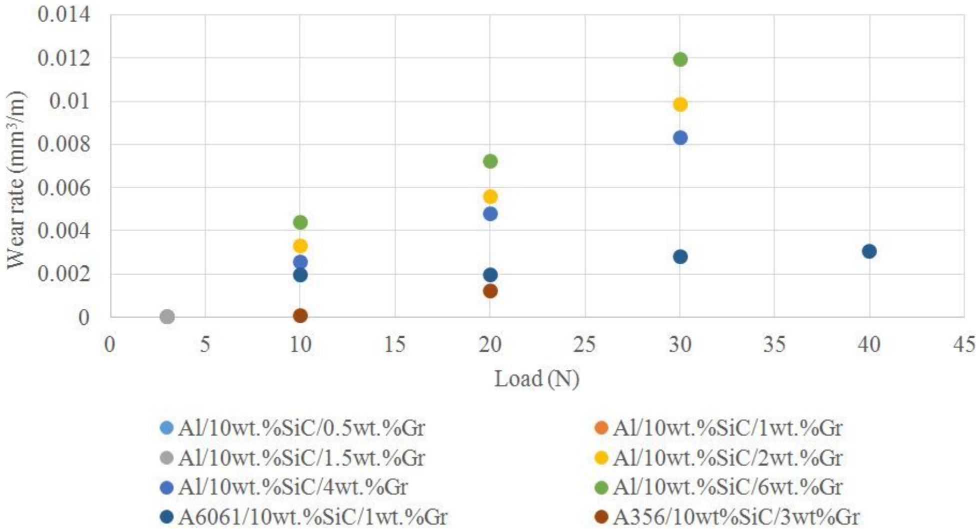

Fig. 4. The effect of load on the wear rate of the Al/SiC/Gr composites with different weight percentage of Gr particles and fixed content 10 wt.%SiC

Source: (ŞAHIN, S., ET AL. 2014, STOJANOVIC, B. ET AL. 2015).

The first three points on diagram in Figure 4 are for the load of 3 N and it cannot be clearly visible what is happening with the wear rate, since the variations of the graphite content are small. The increase of the Gr particles volume share causes increase of the wear rate, with all other experimental conditions kept the same. Generally, based on this diagram, one can notice that for the fixed volume share of 10 wt.% of the SiC particles, the wear rate increases with the Gr volume share increase, as well as with the load increase. The intensified wear occurs due to extrusion of the graphite particles at increased load as the contacts zones between the two surfaces are increased. The increment in wear rate at higher normal loads can be attributed to the larger amount of plastic deformation and hence delamination wear occurs.

4. Conclusions

The hybrid composites generally have better tribological properties than the conventional composites. The ceramic materials as hybrid composites' reinforcement generally increase hardness, tensile strength, toughness, wear resistance and corrosion resistance of the composites, with respect to the same properties of the base aluminum alloy.

What concerns application of the soft reinforcement with the hard reinforcement (SiC) in hybrid composite, such as graphite, it reduces the friction coefficient and increases machinability of the hybrid composite.

With the adequate selection of the process parameters in the hybrid composite fabrication, like the pouring temperature, stirring speed, preheating temperature of reinforcement etc. one can influence the quality of the composite material.

Generally speaking, improvement of properties of the Al/SiC/Gr hybrid composites is strongly dependent on the nature of the reinforcement, its hardness, particles sizes, volume share, uniformity of dispersion within the matrix and the method of hybrid production.

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载荷和强化含量对Al / SiC / Gr复合材料摩擦学性能的影响

關鍵詞
铝合金
混合复合材料
碳化硅
石墨
粒子

摘要

具有金属基体的杂化材料由于其出色的机械和摩擦学性质而成为重要的工程材料。这里介绍了选定的摩擦学性能的混合复合材料的基体由铝合金和增强的碳化硅和石墨颗粒。这种材料的摩擦学特性优于基体的特性 – 铝合金，以及具有单一增强材料的经典金属基复合材料的特性。这些特性取决于增强组分的体积分数，增强颗粒的尺寸以及混合复合材料的制造工艺。所考虑的摩擦学特征是作为负载水平和石墨和SiC颗粒的体积分数的函数的摩擦系数和磨损率。随着载荷和Gr颗粒含量的增加以及SiC颗粒含量的减少，磨损率增加。摩擦系数随着载荷的增加而增加，并且随着SiC颗粒含量的增加。