論文内容要旨（和文）

平成20年度入学　博士後期課程

専攻名　　物質生産工学　専攻

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論　文　題　目　　片状黒鉛鋳鉄の被削性に及ぼす各種要因の研究

本論文は，片状黒鉛鋳鉄の被削性を左右する各種要因の解明するため，化学的及び物理的に解析したものであり，各章の概要は次のようである．

第１章では鋳造及び鋳鉄の歴史，鋳鉄の種類及び用途，また本論文で扱う片状黒鉛鋳鉄の特性及び工学的価値について述べた．金属の凝固及び組織を考察する上で欠かすことのできない平衡状態図についてもFe-C二元系及びFe-C-Si三元系の状態図について解説した．鋳鉄を機械要素として扱う上で必要不可欠な工程である接種処理について，その目的と効果について述べた．鋳鉄の被削性に少なからず影響があると思われる溶解工程について，旧来のキュポラによる溶解と電気炉による溶解，それぞれの特徴と違いを比較しながら述べ，また鋳鉄の生産工程概略を量産鋳物を例として簡単に説明した．次に現状鋳物製品の設計において欠かすことのできないツールであり，本論文第４章・第５章でも使用している鋳造湯流れ凝固シミュレーション（CAE）の利用について説明した．第１章の最後に本論文の目的でもある被削性についてその評価方法，被削性の向上がもたらす経営的・社会的メリット，および被削性に関する研究の現状を述べた．本論文では「なぞの切削性」と呼ばれる鋳鉄の被削性を多角的に捉えメカニズムを解明し鋳物部品製造のプロセスにおける生産性向上を目的とした．

第２章では片状黒鉛鋳鉄の成分と被削性について実験・考察した．鋳鉄には５元素と呼ばれるC,Si,Mn,P,SのほかCr,Sn,等様々な元素が含まれている．被削性に関しては，特に硬質物質を形成する炭化物・酸化物等が注目されそれらの物質を晶出・析出させるため過剰に合金物質を添加し，その結果において鋳鉄の被削性が論じられてきた例も少なくない．本章ではそれらの合金成分を実用範囲内で添加・増減し被削性試験を実施した．結果は多変量解析により統計処理しC,Si及びMnにて有意となった．特にC及びSiに関しては１％水準にて有意であり本実験の条件下においては，C，Siが増加すると被削性が低下すると考えられる．鋳鉄中のC%の増加は黒鉛として晶出する炭素以外にも鋳鉄基地中に固溶するカーボン分が増え，それらが炭化物を形成し被削性の低下を招いていると考察した．鋳鉄中のSiはフェライト中のFe元素と置換し，シリコフェライトを形成する．このシリコフェライトは格子定数がフェライトのそれより小さいため，格子の歪を作り出し転位線を増加させる．この転位線がフェライトを硬化させ被削性の低下を招いている．

第３章では第２章の実験結果をうけ，切削速度・ワーク及びツールの温度それらの被削性への影響

を探った．一般には切削速度を上げると刃具磨耗が増大すると言われているが，本章の実験では切削スピードを上げると刃先磨耗が減少するという結果を得た．同時に刃具・ワーク共に温度上昇も少なくなっており，刃具磨耗に対しては切削速度より刃先温度が大きく寄与していると考えられる．熱電対による刃先温度の詳細な測定結果より，切削速度が速くなると刃先とワークの接触時間が相対的に短くなり刃先温度上昇が抑えられていた．切削速度を上げても刃先温度上昇を抑えることにより，刃具磨耗を減少させ生産性を大きく向上させることができる．

第４章・第５章では鋳鉄の凝固と被削性に関し論ずる．先ず第４章では鋳鉄の冷却曲線測定時に見られる急冷現象の発生部位，発生タイミングを鋳造凝固シミュレーションにより探った．熱電対による実測の場合石英管を介し測定するため，凝固時の温度をダイレクトに測定できない．そのためシミュレーションにて各ポイントの冷却曲線を計算させた．計算結果より本来最徐冷部である最終凝固部付近において共晶凝固終了時に急冷が発生していた．本部位は逆チル不良の発生部位と一致し，本急冷が被削性を悪化させる逆チル不良の主原因と推定する．

第５章ではシミュレーションの各パラメータの変更とFe-C-Si三元系平衡状態図の採用により正確なシミュレーション結果を得た．シミュレーションの結果より，最終凝固部の急冷現象は共晶反応中固液共存状態より起こっていた．最終凝固部の組織観察結果にても，徐冷組織であるA型黒鉛と急冷組織であるD型黒鉛が斑状に存在しており，シミュレーションによる結果を裏付けていた．最終凝固部のチル組織はもとよりD型黒鉛＋パーライト組織は非常に硬く切削性の悪化を招く．製品内部に最終凝固部がこないように方案設計することも被削性の向上につながる．

第６章では総括をおこなった．すなわち以上の結果より被削性に及ぼす要因は多岐に亘り，一つ一つの要因を紐解くことにより「切削性のなぞ」を解明することができた．製品受注時より被削性を考慮した材料設計，方案設計，工程設計を行なうことにより生産性の非常に高い環境性能に優れた鋳物素材を作り出すことができる．被削性の向上により品質はもとより，トータルコストにおいても中国及び新興国の鋳物に対し充分に対抗できる鋳物が造れると確信する．

論文内容要旨（英文）

平成２０年度入学　博士後期課程

専攻名　　物質生産工学　専攻

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論 文 題 目　Study on machinability of flake graphite cast iron and its contributing factors

This thesis details chemical and physical analyses of machinability of flake graphite cast iron in order to shed light on the mechanism of its contributing factors. Summaries of each chapter are described as follows:

Chapter 1 presents a series of interpretations and discussions which overview the history of iron casting, types and usages of cast iron and, most of all, characteristics and value engineering of flake graphite cast iron, which is the main object of this thesis. Then, the interpretations shift its focus to Fe-C binary equilibrium diagram and Fe-C-Si ternary equilibrium diagram, both of which are an essential tool to conduct an analysis on solidification and microstructure of cast iron. Aims and effects of inoculation, which is an indispensable process for cast iron to be treated as mechanical parts, are also discussed. The discussion regarding inoculation opens a path to explore the preceding process on iron casting, i.e., smelting process because machinability of cast iron may be affected, at least to some extent, during this process. Smelting process is discussed by comparing conventional cupola smelting and electric furnace smelting. At this point, a whole process of iron casting on a mass-production level has been briefly outlined by the interpretations and discussions presented so far. Next, utilization of a casting simulation system, which has become an indispensable computer-aided engineering (CAE) tool, is interpreted in order to lay the groundwork for Chapter 4 and 5. To conclude Chapter 1, the focus is turned back to machinability. Especially, evaluation method, operational and/or social merits and recent study progress are highlighted. The main theme of this thesis is, therefore, comprised of how to achieve higher casting productivity by analyzing the mechanism of the yet-to-be-defined machinability of cast iron from diversified aspects.

Chapter 2 deals with the relativities between chemical compositions of flake graphite cast iron and its machinability. Cast iron includes a variety of elements not only C, Si, Mn, P, S (commonly referred to as "five elements") but also Cr, Sn, etc. Past studies on machinability were apt to focused on and discussed on the ground of carbides and/or oxides which form hard substances inside the iron, hence excessively adding those alloy-making elements in hope of producing them via crystallization/precipitation process. In this chapter, additions of those alloy-making elements are regulated in an actual use range to see the difference in machinability in accordance with the added amount. The result, which is statistically processed by multivariate analysis, shows significance in C, Si and Mn. Especially, the amount of C and Si shows significance by 1% level, thus bringing forth a conception that machinability deteriorates as the amount of C and Si increases. The reason why the increased carbon percentage in cast iron contributes to deterioration of machinability can be assumed that the increased amount of solid-solute carbon in the matrix structure, which is a by-product of graphite structure in cast iron, forms carbides

that deteriorate machinability. Meanwhile, Si in cast iron replaces Fe, thus forming silico-ferrite. The average lattice constant of silico-ferrite is smaller than that of ferrite. Therefore, lattice shapes are distorted and increases the number of dislocation lines, which can be assumed to harden the ferrite structure and deteriorate machinability.

In Chapter 3, machinability of cast iron is evaluated in relation to machining speed and temperature of the machined object and the machining tool. It is commonly regarded that increasing machining speed can result in more tool wear. However, the experiment in this chapter showed exactly the opposite. The temperature rise both on the machined object and the machining tool was less pronounced than the expected figures in the experiment. Therefore, it can be considered that tool edge temperature affects more to tool wear than machining speed does. In the experiment, tool edge temperature was closely measured by thermocouples. The result indicates that the increased machining speed can relatively shorten the period when the tool edge is contacted to the machined object, mitigating the rise of the temperature. In light of the result mentioned above, it is fair to say that productivity can be significantly improved by expanding tool service life as a consequent of the increased machining speed and mitigated temperature rise.

Chapter 4 and 5 deals with the relativity between machinability and solidification of cast iron. In Chapter 4, rapid cooling phenomena, which are commonly observed on a cooling curve graph, is explored at length by using a casting simulation software to detect the location and the timing of the emergence of rapid cooling. Actual measurement of molten iron shows not direct temperature but approximate values as a result of indirect measuring through a silica tube of a thermocouple. In order to correct this difference, measuring points were designated on a simulation model and then cooling curves for each measuring point were calculated. The result showed that the rapid cooling was observed on the final solidification part during eutectic solidification, where temperature is commonly considered to drop most slowly. The final solidification part of cast iron is apt to have inverse chills, which spoil machinability. It can be assumed that the rapid cooling on the final solidification part is the main cause of inverse chills.

Chapter 5 presents an accurate result of the simulation analyses gained by calibrations of parameters and an introduction of Fe-C-Si ternary equilibrium diagram for temperature measurement. This result indicates that the rapid cooling on the final solidification part occurs amid eutectic reaction where both solid and liquid substances coexist. The result of microstructural analysis endorses the above theory because A-type graphite structure (which is considered to emerge when iron is gradually cooled) and D-type graphite structure (which is considered to emerge when iron is rapidly cooled) coexist in a mottled pattern. Combination of D-type graphite and pearlite structure is hard enough to deteriorates, let alone the chill structure on the final solidification part. Therefore, it can be said that casting patterns should be carefully designed so as not to let the final solidification part sit inside the product.

Chapter 6 offers a summary of what is discussed thus far. Although machinability is affected by many factors, it is possible to fathom the entire mechanism. At least, this thesis helps to do so by unthreading some of the contributing factors one by one. By selecting materials, pattern designs and production process all suitable for machinability at the time of order receipt, it is possible to cast high-quality iron products with higher productivity and smaller impact on environment. Better machinability can realize iron casting which is competitive enough against counterparts from China and other developing countries in terms cost as well as quality.