2004年上海大学博士学位论文 31

高性能预硬型塑料模具钢的计算机合金设计

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Shanghai University Doctoral Dissertation (2004)

Computer Aided Alloy Design of Prehardened Mold Steel for Plastic

Candidate: He Yanlin
Major: Material Science
Supervisor: Prof. Li Lin

Shanghai University Press
• Shanghai •

上 海 大 学

本论文经答辩委员会全体委员审查，确认符合上海大学博士学位论文质量要求。

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答辩委员会对论文的评语

该论文采用“加快材料熟化的方法”，依托工业应用背景，在不增加成本的前提下，有效提高了国产大截面预硬型塑料模具钢的性能，具有较重要的应用价值. 该论文的研究取得了以下创新成果：

本文发现国产与进口大截面预硬型塑料模具钢性能的主要差距是切削加工性能，在此基础上，首次在国内采用国际通用的热力学和动力学计算软件 Thermo-Calc & DICTRA 系统对预硬化钢的成分和热处理工艺进行优化设计，成功研制了可与国外先进钢种相媲美的预硬化钢，并已投入了批量生产，效果良好.

首次在国内应用大型商业化软件计算了炼钢过程中多元多相体系的相平衡关系，根据计算结果分析了钢中非金属夹杂物的析出情况及其影响因素，并在此基础上制定了适当的成分范围，有效降低了预硬化钢中硬脆相氧化物的析出量；此外，利用 DICTRA 程序中 Cell 模型对碳化物转变过程的模拟结果，改进了预硬化钢的热处理工艺，具有一定的指导作用.

首次采用 Thermo-Calc 软件设计了易切削预硬型塑料模具钢，在试验室条件下，将硫、钙含量控制在计算机模拟的成分范围内可使钢中得到所需要的易切削相，在基本不影响其它性能的基础上，切实提高了钢的切削加工性，并且发现微量 S-Ca-Bi 复合加入是制备易切削预硬化钢的可行方案，具有一定的应用价值.

本研究是热力学计算在高性能预硬化钢研制中的一次成功应用，是加速实现国产钢精品化目标的一次有益尝试，为逐步深

化计算技术在新钢种设计中的应用提供了借鉴.

论文反映出作者已较全面地掌握了与课题相关的国内外研究动态，具有较好的基础理论和专业知识水平以及相当强的独立科研能力. 论文立论正确，论据充分，条理性好，层次分明，实验数据可靠. 在答辩过程中，回答问题思路清晰，条理清楚.

答辩委员会表决结果

经答辩委员会表决，全票同意通过何燕霖同学的博士学位论文答辩，建议授予工学博士学位.

答辩委员会主席：**徐祖耀**

2004 年 6 月 10 日

摘　要

预硬型模具钢是制造高品质塑料模具的首选钢种，随着我国模具工业的迅速发展，该钢种具有良好的应用前景. 但是，由于国产钢在性能上的欠缺，进口钢占据了大部分市场份额. 为了改变这一局面，本论文采用了“加快材料熟化的方法”，借助国际通用的热力学和动力学计算软件 Thermo-Calc & DICTRA 对预硬型塑料模具钢的成分和工艺进行优化设计，并依托工业应用的背景，在基本不增加成本的前提下，有效提高了国产钢的性能，使之达到了世界优质同类钢种 ASSAB718 的性能水平，并且在此基础上研制了性能良好、具有一定应用前景的新型易切削钢种.

本文通过对比性测试与研究，发现进口与国产大截面预硬型塑料模具钢的常规力学性能接近，而结合金相观察和 SEM&EDX 分析可以看出国产钢中氧化物夹杂含量较高，以氧化铝为主；而 ASSAB718 钢中以塑性相硫化物夹杂为主，多以硫化锰包裹氧化铝的形式存在；通过低速车削试验和抛光试验，综合检测了刀具后刀面磨损量、切削力及加工试样表面粗糙度等性能指标，结果发现，国产钢与 ASSAB718 钢性能上的主要差距在于切削加工性能. 由于钢中非金属夹杂物是影响切削加工性能的主要因素，硫化物在切削时的变形和减摩作用可以提高切削性能，而高硬度、高熔点的氧化铝夹杂对硬质合金刀具的磨损作用则大大降低了国产钢的切削性能，所以消除或改性钢中氧化物夹杂应成为提高其性能的主要手段.

Thermo-Calc & DICTRA 软件系统中基于 Gaye 模型建立的

SLAG 数据库以及基于 CALPHAD 方法建立的热力学计算系统是计算炼钢过程中多元多相体系相平衡关系的有力工具，根据计算结果可以对炼钢过程中非金属夹杂物的形成过程及其影响因素进行预测. 本文通过对国产钢和 ASSAB718 钢中夹杂物析出类型的预测，指出不合理的成分配比是造成国产钢中氧化铝夹杂物较多的原因，并据此对国产钢的成分进行了优化设计，指出其主要成分碳、锰、硅、铬、镍和钼的质量百分数应分别在 0.36~0.42 wt%，1.35~1.45 wt%，0.2~0.3 wt%，1.8~2.0 wt%，0.8~1.0 wt% 和 0.2~0.4 wt%范围之间. 对调整成分后的国产钢的测试证明，氧化铝夹杂含量显著下降主要代之以硫化锰包裹细微氧化铝质点的复合夹杂物，其切削加工性能得到了明显改善.

鉴于钢中显微组织变化与热处理工艺制定的密切关系，本文运用软件计算并结合 TEM 分析确定了预硬型塑料模具钢中的主要碳化物类型是 M_7C_3 型碳化物，而后运用 DICTRA 程序的“Cell”模型模拟了温度及合金成分对钢中碳化物溶解过程的影响，指出对 M_7C_3 型碳化物而言，通常随着加热温度的升高和保温时间的延长，其溶解量增大，在 1 183K（910℃）时 M_7C_3 型碳化物的溶解量随时间的变化接近在 1 203K（930℃）时的情况；而合金元素 Cr、Mn、Mo 都会对 M_7C_3 型碳化物的溶解产生一定影响. 根据模拟计算的结果，本文采用锻前高温均匀化处理，即 1 200±10℃保温 10 小时，基本消除了大模块组织中存在的偏析现象，从而降低了模块加工表面的粗糙度；此外，采用 910℃正火代替淬火避免了厚度较小的模块发生开裂，并且基本不影响材料的组织和性能.

经过成分调整和锻前高温均匀化处理的国产大截面预硬型塑料模具钢，其基本使用性能，包括切削加工性能、磨抛性能以

及抗腐蚀性能都达到了 ASSAB718 钢的水平，并且可以进行批量生产，效果良好.

在钢中添加硫、钙等易切削元素有助于进一步改善其切削加工性能，但必须控制其含量才能避免有害非金属夹杂物，如钙铝酸盐、硫化钙的形成. 运用 Thermo-Calc 软件计算了不同含量的 S、Ca 等元素对钢中非金属夹杂物析出的影响，发现只有在合理的成分范围内钢中才能形成理想的易切削相，如玻璃质氧化物夹杂 $2CaO•Al_2O_3•SiO_2$(即 C2AS). 在试验室条件下试制了新成分的易切削预硬型塑料模具钢，结合 SEM&EDX 分析，发现在预测的钙、硫范围内，即加入 20~40 ppm 的钙和 0.02wt%的硫，可以获得所需要的易切削相 C2AS；但如果将硫含量提高到 0.04 wt%，则不易获得 C2AS.

与低速切削相比，在高速切削条件下，刀具的损坏严重，寿命缩短，但切削力变小，而且加工表面的质量也有所提高；塑性相硫化物的存在使钢在低速切削条件下性能良好，但在高速切削条件下，只有玻璃质氧化物 C2AS 可在刀具表面形成保护层，有效抑制刀具的磨损，提高切削加工性能；此外，适量添加钙和铋可以改变硫化物的形态、增加粘着强度，从而提高其易切削作用. 易变形相硫化锰的存在造成了钢塑性指标及等向性的降低，而钙对硫化锰的变质作用可减轻这种不利影响，所以综合对力学性能与切削性能的评价，微量 S-Ca-Bi 的复合加入是制备易切削预硬型塑料模具钢的可行方案.

关键词 预硬型塑料模具钢, Thermo-Calc & DICTRA 软件系统, 切削加工性能, 热处理工艺, 易切削相

Abstract

Prehardened mold steel for plastic is the primary for manufacturing high quality plastic mold. With the rapid development of mold industry in our country, this kind of steel exhibits extensive application prospect. However, because of property deficiencies of domestic produced steel, import steels hold major part of market share. In order to change the situation, using "method of accelerated maturation of materials" in this article, the composition and technology of prehardened mold steel for plastic are optimized and designed by Thermo-Calc & DICTRA thermodynamic software package. On the strong background of industrial application, the property of domestic produced steel is effectively improved at the premise of no incremental cost, which reaches to the performance level of the same kind of high quality steel in the world, e.g. ASSAB718 steel. In addition, on the basis of research results mentioned above, the new kind of free machinability steel with high performance and better application is developed.

With the compared and studied in this article, it is shown that the mechanical property at room temperature between import prehardened mold steel for plastic with large section and domestic produced steel is similar. Combined with microscope and SEM&EDX analyse, it is shown that the content of oxide inclusion in domestic produced steel is higher and mainly composed of

aluminum oxide, but the non-metallic inclusion in ASSAB718 steel is mainly composed of soft phase sulphide inclusion in the form of manganese sulphide with aluminum oxide at the core. The flank wear amount, cutting force and the surface roughness of machining samples are comprehensively tested by turning test at low cutting speed and polishing test, it is shown that the main performance difference between domestic produced steel and ASSAB718 steel is machinability. Because of the key to affect machinability of steel is non-metallic inclusion, machinability of steel can be improved by the deformation and decreasing abrasion effect of sulphide during machining. The machinability of domestic produced steel is markedly decreased by severe abrasion effect of aluminum oxide with high hardness and high melting point on the carbide tool. So it is the main means to improve steel's performance that remove or modify the oxide inclusion in steel.

SLAG database based on Gaye model and thermodynamic computation system based on CALPHAD technique in Thermo-Calc & DICTRA software package are powerful tools for computation equilibrium relation of multicomponent and multiphase system during steelmaking process. According to computational results, the precipitation process and its influencing factors of non-metallic inclusion are predicted. It is shown that the irrational composition ratio is the main factor to result in higher content of aluminum oxide inclusion in domestic produced steel by the estimation of inclusion type precipitated in steel. Then the composition of the steel is optimized, it is shown that the weight percent of alloy elements

carbon, manganese, silicon, chromium, nickel and molybdenum are at the range of 0.36~0.42wt%, 1.35~1.45wt%, 0.2~0.3wt%, 1.8~2.0wt%, 0.8~1.0wt% and 0.2~0.4wt% respectively. The experimental results show that the content of aluminum oxide inclusion is markedly reduced and mainly substituted by MnS with minuscule aluminum oxide particle at the core, the machinability of domestic produced steel after composition regulation is markedly improved.

Due to the close relationship between phase transformation and heat treatment technology establishment, the main type of carbide in prehardened mold steel for plastic is M_7C_3 type by TEM analyse and computed results. Then the effect of temperature and alloy composition on the dissolution of M_7C_3 type carbide in steel is simulated by"Cell"model in DICTRA program. It is shown that generally the dissolution contents of M_7C_3 type carbide are increased with enhanced heating temperature and prolonged keeping temperature time, the relationship between dissolution content of M_7C_3 type carbide and time at the temperature of 1 183K(910℃) is close to that at the temperature of 1 203K(930℃). Alloy elements Cr、Mn、Mo affect the dissolution of M_7C_3 type carbide. According to simulated results, the segregation of elements in large module is basically eliminated by high temperature homogenizing treatment before forging, that is done by keeping 10 hours at the temperature of 1 200±10℃, thus surface roughness of machining steel sample is improved. In addition, the cracking of module with small thickness results from quenching is avoided substituted by 910℃ normalizing,

the microstructure and property of the steel are not basically affected.

The performance of domestic produced steel with large section after composition regulation and homogenization treatment at high temperature before forging, including machinability, polishing properties and anti-corrosion performance, reach to the level of ASSAB718 steel and it can be produced in mass.

It is helpful to improve the machinability of steel with addition of free cutting elements such as sulphur, calcium, etc. But precipitation of harmful non-metallic inclusion, such as calcium aluminates and calcium sulphide, can be avoided only by regulation the content. The effect of elements S, Ca with different contents on the precipitation of non-metallic inclusion is computed by Thermo-Calc software package, it is shown that perfect free cutting phase can form in steel at the proper composition range, such as glassy oxide inclusion $2CaO•Al_2O_3•SiO2$（that is C2AS）. Free machinability prehardened mold steel for plastic with modified composition is tentatively produced. Combined with SEM&EDX analyse, it is shown that free cutting phase C2AS can be obtained by addition 20~40ppm calcium and 0.02 wt% sulphur, but C2AS is not easy to be obtained if the content of sulphur is increased to 0.04wt%, that is agree with the prediction.

Compared with cutting at low speed, it is shown that at high cutting speed, the damage of tool is heavy and tool life is short, but the cutting force becomes small and the surface roughness of machining surface is also improved. The existence of soft phase

sulphide results in better properties of steel at low cutting speed condition, but at high cutting speed condition, only the glassy oxide C2AS is testified to form protective layer at the surface of tool, then the wear of tool is effectively inhibited and the machinability of steel is improved. In addition, the free machinability effect of sulphide phase can be improved by addition of calcium and bismuth because of changing sulphide's shape and increasing the stick strength. The ductility and isotropy of steel are decreased because of the deformation of soft phase sulphide, but the modified effect of calcium on MnS can decrease the disadvantage. With the comprehensive assessment of mechanical properties and machinability, the complex addition of S-Ca-Bi with small content is accessible project for manufacturing free machiability prehardened mold steel for plastic.

Key words prehardened mold steel for plastic, Thermo-Calc & DICTRA software package, machinability, heat treatment technology, free cutting phase

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