Berichte aus dem
Institut für Eisenhüttenkunde

Carsten Drouven

Microstructure Evolution and Phase Transformations in Intermetallic-Strengthened Fe-Al-Mn-Ni-C Alloys

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“Microstructure Evolution and Phase Transformations in Intermetallic-Strengthened Fe-Al-Mn-Ni-C Alloys”

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Abstract

The continuous development of high-strength materials for improved weight saving has promoted research into high-Al alloyed steels, promising a concurrent decrease in materials density and increase in strength by the precipitation of intermetallic phases.

In the present work, novel alloy concepts of intermetallic-strengthened high-Al alloyed steels are developed primarily to investigate the microstructure evolution and the formation of intermetallic phases.

The designed model alloys aim at the concurrent precipitation of diverse intermetallic phases, including B2-type FeAl/NiAl and κ-type $(Fe,Mn)_3AlC$ phases. Concepts are derived to control the intermetallic precipitation. A 'solubility-assisted precipitation'-concept is developed and successfully validated to use favorable elemental partitioning between both matrix phases of a duplex alloy and precipitate intermetallic phases phase-specifically, thus retaining the particle-matrix coherency.

The alloy microstructures are characterized on a mesoscopic level along the processing routes to forged and rolled products. The microstructural evolution during processing and final aging of these alloys is affected by the presence of intermetallic phases and demonstrates complex austenite-ferrite transformations with the emergence of diverse types of ferrite. The emerging phases, such as Widmanstätten ferrite, are studied in detail with respect to their morphology, elemental partitioning and orientation relationships.

Phase transformations involving the intermetallic phase formation are studied by *in-situ* heating experiments and synchrotron X-ray diffraction as well as transmission electron microscopy and atom probe tomography. A novel phase transformation sequence of κ-type $(Fe,Mn)_3AlC$ intermetallic phases is proposed with the formation of an ordered κ-precursor by a continuous disorder-order phase transformation during quenching from elevated temperatures. Subsequent isothermal aging is proposed to induce a phase decomposition of the C-lean κ-precursor into disordered austenite and a C-rich κ-phase. The growth kinetics of the intermetallic phases are governed by the diffusion rates of their constituents and affected by simultaneous occurring phase transformations. The phase transformation sequence of intermetallic phases is proposed to affect their morphology and atomic chemistry.

The room temperature mechanical properties of the high-Al alloyed intermetallic-strengthened steels exhibit high yield strengths in exceedance of 1 GPa. Considering their low density, the alloy systems demonstrate exceptional density-specific mechanical properties.

Zusammenfassung

Die kontinuierlich voranschreitende Weiterentwicklung hochfester Werkstoffe zur Optimierung des Leichtbaupotentials hat zunehmendes Interesse an hochaluminiumhaltigen Stählen, die eine simultane Dichtereduktion des Stahls und Festigkeitssteigerung durch intermetallische Phasen in Aussicht stellen, hervorgerufen.

In dieser Arbeit werden neuartige Legierungskonzepte von intermetallisch-verstärkten Stählen, unter primärer Zielsetzung der Untersuchung der Mikrostrukturentwicklung und des Ausscheidungsverhaltens intermetallischer Phasen, entwickelt.

Die entwickelten Legierungskonzepte zielen auf eine simultane Ausscheidung unterschiedlicher intermetallischer Phasen, einschließlich FeAl/NiAl- und $(Fe,Al)_3AlC$-Phasen, ab. Es werden Konzepte zur Steuerung der intermetallischen Ausscheidungsbildung vorgestellt. Ein experimentell validiertes Konzept umfasst die löslichkeitsgesteuerte, phasenspezifische Ausscheidung intermetallischer Phasen in einer Duplexlegierung mit dem Ziel die Kohärenz zwischen Matrix und intermetallischer Phasen aufrecht zu erhalten.

Die Mikrostrukturen der Legierungen werden entlang der Prozesskette zu Schmiedebauteilen und Walzprodukten erfasst. Die Mikrostrukturentwicklung wird durch die intermetallischen Phasen beeinflusst und weist eine komplexe Austenit-Ferrit-Phasenumwandlung mit der Entstehung verschiedener Ferritphasen auf. Die entstehenden Phasen, bspw. Widmanstätten Ferrit, werden hinsichtlich ihrer Morphologie, Elementverteilung und Orientierungsbeziehung untersucht.

Die Phasenumwandlungen intermetallischer Phasen werden im Rahmen von *in-situ* Heizexperimenten unter Verwendung von hochenergetischer Synchrotrondiffraktometrie sowie unter Zuhilfenahme der Transmissionselektronenmikroskopie und Atomsonde untersucht. Eine neue Phasentransformationssequenz wurde für die κ-$(Fe,Mn)_3AlC$-Phase vorgeschlagen. Darin bildet sich eine Kohlenstoff-arme, metastabilen κ-Phase durch eine kontinuierliche Ordnungsumwandlung beim Abschrecken von hohen Temperaturen. Eine anschließende Ausscheidungshärtung führt zu einer Phasenzersetzung der metastabilen κ-Phase in Austenit und eine Kohlenstoff-reiche κ-Phase. Die Wachstumskinetik der intermetallischen Phasen ist von den Diffusionsraten der jeweiligen Bestandteile abhängig und wird durch simultan stattfindende Phasentransformationen beeinflusst. Die Phasentransformationssequenzen können einen Einfluss auf die Morphologie und atomare Zusammensetzung der intermetallischen Phasen haben.

Die mechanischen Eigenschaften dieser hochaluminiumhaltigen, intermetallisch-verstärkter Stähle bei Raumtemperatur weisen sehr hohe Streckgrenzen mit mehr als 1 GPa auf. Unter Berücksichtigung der geringen Dichte dieser Legierungen ergeben sich bemerkenswerte dichtespezifische mechanische Eigenschaften.

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