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VROČE UTOPNO KOVANJE OJNIC IZ Al KOMPOZITA

HOT FORGING OF AN Al MMC CONNECTING ROD ON AN INDUSTRIAL SCALE

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In this work, a production procedure already practised on an industrial scale for the forging of aluminum alloys was applied for the closed-die hot forging of Al MMC Al-6061/Al_2O_3/10p (supplier: Duralcan Co., USA). The production line consists mainly of a cutting, a forging, a hot trimming, and a heat treatment area.

The effectiveness of the production line was demonstrated by producing 1160 samples of connecting rods. The temperature of the forged bars was 500±10°C, the upper and lower temperatures of the forging die were about 325°C and 320°C, respectively. The forging operation was applied on a screw press with a capacity of 10 MN in order to achieve higher productivity.

The forging trial performed demonstrated on an industrial scale that Al MMC, consisting of equiaxial particulate reinforcement having an average particle size of less than 10 µm, can be hot forged under a strain rate of 3 s^{-1} without damage to the ceramic phase and the generation of other microstructural failures.

Dimensional inspection of the forgings confirmed that the tolerances specified in DIN 1749 were achieved with absolute certainty.

Key words: automotive components, microstructural features, closed-die hot forging, aluminum matrix composites.

Vroče utopno kovanje ojnic iz kompozita z matrico na osnovi aluminijeve zlitine 6061, diskontinuirano ojačane z 10 vol. % Al_2O_3 delcev (proizvajalec: Duralcan Co., USA) smo izvajali na način, ki ga v industrijskem merilu že vrsto let uspešno uporabljajo za kovanje aluminijevih zlitin. Osnovne proizvodne faze tega postopka so: rezanje vložkov za utopno kovanje, utopno vroče kovanje, obrezovanje brade na povišani temperaturi ter toplotna obdelava kovanih izdelkov.

O učinkovitosti predlaganega proizvodnega postopka za vroče utopno kovanje kompozitov na osnovi aluminija smo se želeli prepričati v industrijskem merilu, in sicer z izdelavo 1160 vzorcev ojnic. Vložke za utopno kovanje smo pred kovanjem predgrevali na temperaturo 500±10°C v zračni atmosferi. Za predgrevanje smo uporabljali plinsko ogrevano tunelsko peč s premičnim transportnim trakom iz jeklene mreže.

Kovaški utop smo segrevali s plinskim gorilnikom, in sicer tako, da je znašala temperatura spodnjega dela utopa 320°C, temperatura zgornjega dela utopa pa največ 325°C. Kovali smo na 10 MN vretenasti stiskalnici s hitrostjo deformacije 0,3 s^{-1}. Preizkusi kovanja so pokazali, da je vroče kovanje kompozitov na osnovi aluminija, diskontinuirano ojačanih s keramičnimi delci, v industrijskem merilu popolnoma izvedljivo že z manjšimi dopolnitvami obstoječe tehnologije vročega kovanja aluminijevih zlitin. Naše raziskave so pokazale, da uporaba večjih hitrosti deformacije (npr. 0,3 s^{-1}), ki zagotavljajo potrebno produktivnost, ne vpliva na poškodbe keramične ojačitvene faze, pod pogojem, da so keramični delci čim bolj kroglične oblike in so manjši od 10µm.

Preverjanje dimenzij izdelanih ojnic je potrdilo, da so odstopanja znotraj toleranc, ki jih predpisuje DIN 1749.

Ključne besede: vroče utopno kovanje, Al kompoziti, hitrost deformacije, avtomobilske komponente, mikrostruktune značilnosti.

1 INTRODUCTION

It is generally accepted that, in comparison with thixoforming, squeeze casting, vacuum-assisted high pressure die casting, conventional high pressure die casting and other metalworking processes, the hot forging process can ensure the best mechanical properties. Only by hot forging can quality requirements be achieved with absolute certainty, even with quality control reduced to just visual inspection of chemically etched parts. This is why forgings are almost always used where only the best, reproducible, statistically guaranteed and repeatable performances are daily requested. Some typical examples are aeronautical parts, components for military application, automotive and other high demanding parts with high safety demands, etc.

Because hot forging is also one of the most expensive metal forming technologies, it becomes competitive only when it does not lend itself to high-volume production and when is applied to forming of high added value metallic systems such as discontinuously reinforced metal matrix composites based chiefly on aluminum.

Various forging trials performed in the last decade [1-6] have demonstrated that discontinuous metal-matrix composites based on existing wrought aluminum alloys in the 2xxx, 6xxx, and 7xxx series can be successfully forged in all types of forging process, including high-definition and precision closed-die forgings.

The common elements in the manufacturing of any aluminum alloy and Al MMC forging include preparation of the forging stock, preheating the stock, die heating, lubrication, the forging process, trimming, forming and repair, cleaning, heat treatment, and inspection. The critical aspects of each of these elements are reviewed in [7].

Based on processing maps determined by dynamic material modelling of compressive flow stress for non-reinforced and particle reinforced aluminum alloys [4-5] it was confirmed that the forging conditions for the composite materials should be essentially the same as those for non-reinforced aluminum alloys. Moreover, it was demonstrated that in both hydraulic and mechanical presses, the forging behaviour of the composite material was very similar to that of the non-reinforced material, the major difference being that the composite material had a greater tendency to tear in the flash area, [2].

A broad range of applied strain rates were reported in literature, ranging from very fast (for example, >10 s^{-1} on equipment such as mechanical and screw presses) to relatively slow (for example, <0.1 s^{-1} on equipment such as hydraulic presses) [2].

Despite the excellent forgeability of Al MMCs, a number of barriers must be overcome to ensure widespread introduction of Al MMCs forgings in medium and high-volume industrial production. These barriers can be classified as either connected with the composite material or with the forging procedure.

It is well known that the further commercialization of MMCs is strongly related to substantial lowering of the cost of the composite material, as well as the improved formability and machinability of the final components, and the availability of an adequate recycling technique capable of converting the scrap composite back into high-quality, cost-effective composite with almost the same value-added portion.

The closed-die forging procedure of Al MMCs is also limited by several barriers. One is based on possible damage to the ceramic reinforcement if in appropriate deformation or strain rates are applied. Also, reinforcing additions to existing aluminum alloys modify the deformation behaviour and increase flow stress. Further, because these materials are more abrasive, forging and trimming die lives are shorter than is typical of work with the parent alloys. Finally, if flash - typical of traditional closed-die forging - consisting of 30-50 vol % of the composite material involved in forging, cannot be reused by recycling, the associated cost penalties will depreciate the main attractiveness of forging.

Regarding the great advantage of hot forging as an industrial method of forming, the main purpose of this work was to investigate if the same procedure and the same production equipment used for industrial forging of aluminum alloys could be applied for quality and cost-effective hot forging of Al MMCs. Special attention was also paid to verify whether forging under a high strain rate on equipment such as a screw press could be applied without causing damage to the ceramic reinforcement.

The convenience of the investigated production technique was demonstrated by producing 1160 samples of hot forged Al MMC connecting rods.

2 EXPERIMENTAL PROCEDURES

The particle-reinforced aluminum alloy matrix composite used in the present work was Al-6061/Al_2O_3/10p supplied by Duralcan Co., USA (Duralcan designation:W6A.10A). It was produced by mixing 10 vol. % of Al_2O_3 particles, having an average size of 7μm, into molten AA 6061 aluminum alloy. After casting, billets were pre-homogenized at 570°C for 4 h and cooled at 200°C/h. They were then hot extruded into 35 mm diameter rod.

A connecting rod (**Figure 1**) for an automotive application was selected for hot forging. The same procedure and the same production line extensively used for industrial forging of aluminum alloys were selected for preparing the Al MMC components, in this way providing industrial scale of work.

Each extruded rod in Al-6061/Al_2O_3/10p having a diameter of 35 mm and a length of 5 m, was cut on conventional saws using blades with carbide-tipped teeth (speeds <70m/min combined with medium-heavy pressures) to obtain bars with length 170 ± 1 mm.

A closed die with two cavities prepared by convenient HSM (High Speed Milling) technology was used for forging trial.

After cutting, the bars were heated at 500±10°C for 2 h prior to forging. The average upper and lower temperatures of the forging die were about 325°C and 320°C, respectively; these values were continuously monitored throughout the trials by embedded

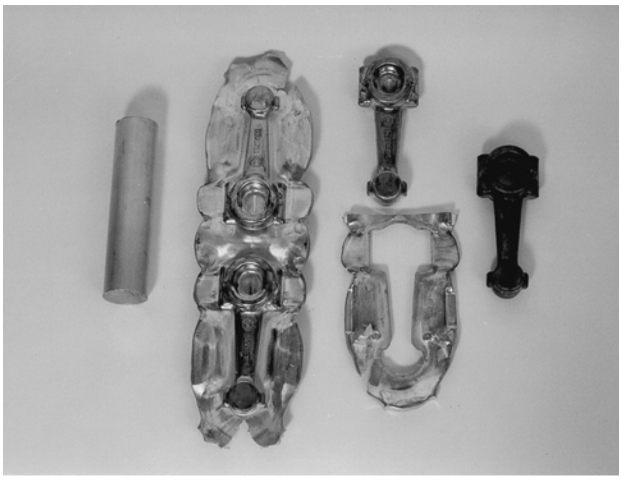

Figure 1: Typical forming steps in production of connecting rod are presented starting from a cut forging bar, a forged specie with flash, a trimmed product and a heat treated connecting rod

Slika 1: Prikazane so vmesne faze preoblikovanja avtomobilske ojnice iz Al kompozita, ojačanega s keramičnimi delci: vložek iz Al kompozita, neobrezan dvojček ojnice s kovaško "brado", obrezana ojnica, del obrezane kovaške "brade", in termično obdelana ojnica

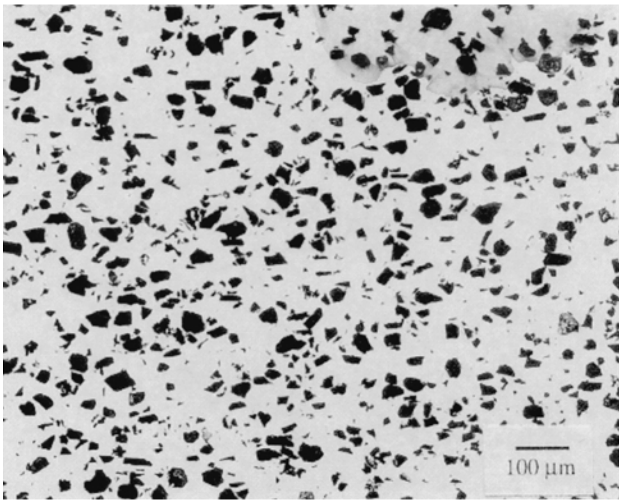

Figure 2: Microstructure of hot forged Al MMC
Slika 2: Mikrostruktura vroče kovanega Al kompozita, ojačanega s keramičnimi delci

thermocouples. The optimum lubrication conditions were found to be a combination of Renite S-28™ sprayed between each operation, and animal grease mixed with lead oxide "painted" onto the dies every third or fourth forging.

The process of forging was performed in one step by closed-die forging. The forgings were obtained on a screw press with a capacity of 1000 t with a deformation rate of 3 s^{-1}.

Forgings were hot trimmed using blades made from HSS steel hardened to 58 to 60 HRC. Hot trimming was accomplished in conjunction with the hot-forging process at a flash temperature around 350-400°C.

Solution annealing and subsequent artificial ageing of the forgings were performed under the same conditions used for the non-reinforced alloy 6061: i. e. 2±0.5 h at 535±5 °C and 8±0.5 h at 170±5 °C, respectively.

The final forgings were subjected to dimensional inspection on a coordinate-measuring machine. Optical microscopy and SEM were also performed in order to determine eventual sources of failure in the forgings.

3 RESULTS AND DISCUSSION

In a forging trial performed in one shift, 1160 pieces of connecting rods were routinely prepared by closed-die forging of MMC.

The measured loss of material during cutting of the extruded rods was 1.5%. Practically, from one extruded rod 5m in length, 29 forging bars with length 170±1 mm were successfully cut. The average width per cut was 2.5 mm. The quality of the cut surface was appropriate.

Non-trimmed forgings typically had a flash consisting of 47 % of the forged bar material.

All forged parts were dimensionally inspected; the findings confirmed that the tolerances specified in DIN 1749 can be achieved with absolute certainty.

No problems arose which could prevent the transformation of these materials by means of the forging process itself. No failures in the microstructure of the forged MMC were observed, **Figure 2**.

Forging die-life could not be verified due to the limited number of forged pieces, but one can consider the same duration which was observed with traditional non-reinforced matrices.

In contrast, trimming die life time seems to be more critical, although trimming trials were performed under hot conditions. Other hardfaced trimming blades should be considered for high volume production of AlMMC forgings.

The productivity of hot forging of MMC is almost the same as the productivity of hot-forging of the non-reinforced matrix, except in cutting, where 10-15% less productivity was obtained.

It was found that the forging behaviour of the composite material is very similar to that of the non-reinforced material. Based on this, one can conclude that the any forging technique applied for non-reinforced aluminum alloys could be successfully used for forging of Al MMCs. The only necessary difference was introduced in cutting and trimming procedures. In cutting, saws using blades with carbide-tipped teeth were necessary. In trimming, instead of cold trimming, hot trimming with additionally hardened and hardfaced trimming blades was found to be a suitable solution.

4 CONCLUSION

Industrial production of Al MMC forgings was successfully performed by closed-die hot forging as practised for aluminum alloys, introducing some necessary adaptations only in the cutting and trimming operation.

These forging trials demonstrated on an industrial level that Al MMC consisting of equiaxial particulate reinforcement having an average particle size less than 10μm can be forged under a strain rate of 3 s^{-1} without damage to the ceramic phase or other microstructural failures.

On that account, slow forming of composite material practised on hydraulic press can be replaced by high rate forging on a screw press, thus allowing better productivity in production of forgings.

The dimensional inspection of forgings confirmed that the tolerances specified in DIN 1749 can be achieved with absolute certainty.

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