Coating technologies for hot forging dies which fulfill the specific requirements of the forging industry provide new opportunities to design effective forging dies, while simultaneously improving the quality of the manufactured parts.

The investigations of the behaviour of silicide-coated forging dies gave practical results on the use of the tested coated surfaces.

The experimental forging part was a rotary, cup-formed workpiece with flash. The tool system consisted of an upper tool with a mandrel with a 10 degree draft angle, and a lower tool with a 5 degree draft angle without
ejector. Both upper and lower tool were tested with various surface coatings: titanium-aluminium (2.8 mum thickness), chromium-disilicide (1.6 mum) and titanium-carbide/titanium-silicide (3.0 mum).

During the forging process, visible material abrasion took place. Especially at the radii an average material abrasion of more than 20 mum depth could be observed. At these spots, the surface coating was partially destroyed. Different results in the behaviour of the coated surfaces were obtained depending on forging temperatures and tool wear. The abrasion was determined by 3D measurement of the surface contours and macroscopic photographs before and after the forging process.

Keywords: surface engineering, hot forging, coated dies

INTRODUCTION

At present, physical vapour deposition (PVD) and chemical vapour deposition (CVD) techniques are used to a great extent to deposit hard material coatings on cutting and forming tools for the purpose of wear protection. Cathodic arc evaporation is used as the dominant deposition method. The coatings’ oxidation temperature is limited to approx. 800 °C. During forging of steel materials, the thermal stresses of the active components are considerably higher than the temperature resistance of the metal carbides, metal nitrides and metal carbonitrides that have until now been deposited as hard material coating. Nevertheless, metal disilicides (CrSi\(_2\) or MoSi\(_2\)) whose oxidation resistance is about 1700 °C, is not known to be used as thin coatings to protect tools and die inserts at high working and contact temperatures.

After CVD coating, the dies must be subjected to a vacuum heat treatment to achieve the required strength, this is due to the high coating temperatures in the thermally activated CVD procedure of depositing thin silicide coatings.

Arc evaporation, which is commonly used for die coating, was used for the production of silicide coatings and tested in practice die forging.

APPLIED COATING EQUIPMENT

ARC VAPORISATION OF PURE METALS IN SILICEOUS ATMOSPHERE

In reactive arc evaporation a source for the metallic coating component (titanium) was applied and tetramethylsilan (TMS) Si(CH\(_3\))\(_4\) was used as
Practical Tests of Coated Hot Forging Dies

TMS is available in liquid form and is injected into the vacuum chamber with a vaporizer. A considerable addition of carbon into the coatings is to be expected due to the chemical composition of tetramethylsilan. No disadvantageous influences, rather the formation of carbides or the so-called Nowotny phases which may contribute to stabilising the silicide phases, were expected (see also "Filtered cathodic vacuum arc deposition" [1]).

Input volume and inlet position of the reactive gas were varied with respect to the substrate in comprehensive studies to control the Si content inside the coating. The Ti content was varied upon substrate distance, the wave angle, the evaporation rate (reduced arc current), and a diaphragm was introduced between the target and the substrate. In this way, it was possible to vary the Si content in the coating from 4 to 40 at%. Minimal carbon content was about 20 at%.

The hardness of the coatings’ main part ranges from 20400 to 26500 MPa and thus reaches hardness values of TiN. X-ray diffractometry showed an amorphous structure of the coatings, as well as of the TiC-phase. It was also possible to detect graphite-similar carbon with the XPS analysis (see "Deposition of silicide coatings" [2]). In the practice tests, the coating was named as TMS.

**CRSI COMPACT TARGET PVD-COATING**

Immediately using a metal silicide target is another way to deposit silicides. The investigations were extended to compact targets whereby tests were carried out with a CrSi-target due to the sufficient ignition characteristics of chromium. This target was manufactured by isostatical hot pressing (GFE Nürnberg, FRG) with 33% at% Cr and 67 at% Si which corresponds to the CrSi$_2$ in the following test series.

The arc was ignited without any problem. A stable circular path with high spot velocity was achieved by the selection of an adequate magnet.

The deposited coating microhardness HU ranged from 15.000 N/mm$^2$ to 25.000 N/mm$^2$, at a coating thickness from 1.1 to 1.6 mum. The layer growth rate was about 0.2 mum/min at a target- to- sample distance of approx. 240 mm.

As shown in the X-ray diffractometry studies, the coatings have one phase and consisted of hexagonal CrSi$_2$. The grain size was estimated to 25 nm.
Thus, a crystalline \( \text{CrSi}_2 \) was produced with a PVD procedure without subsequent tempering.

**THE COATINGS IN FORGING TESTS**

Die forging with flash was selected as the method to characterize the performance of the coatings described (see "Testing of hot forging dies" [3]). In this forming process, the die has to withstand high stresses from the forming forces, and temperatures of the forging parts up to 1100 °C.

The whole die was dimensioned for the working space (including the tool set) of the spindle press Eumuco SPKA 2000.

A rotary cup-shaped workpiece with flash was selected as the forging part. The upper tool was fitted with a mandrel with a 10° draft angle, the lower tool without ejector had a draft angle of 5°. Typical wear locations were defined on the mandrel head radius, \( R = 5 \) mm on the male die, and the flash edge radius, \( R = 1 \) mm at the female die.

Figure 1 shows the male die, a forged part and the female die.

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*Figure 1.* Male die, forged workpiece, female die (from the left to the right).
The test plan included the following parameters:

- Coupling spindle press
  Eumuclo SPKA2000, 20,000 kN
  forging force

- Heating up of the samples
  in a batch-type furnace (electrically heated)
  Furnace temperature 1.120°C
  Sample material 16MnCr5

- Lubricant
  Hycogen 87/13H (Fuchs Lubritec GmbH, FRG)

- Die coatings
  coating of both upper and lower tool

- Variant №0
  uncoated

- Variant №1
  Titanium-aluminium nitride coating (2.8 µm)

- Variant №2
  Chromium disilicide coating (1.6 µm)

- Variant №3
  TMS coating (3.0 µm)

The shaping procedure during forging was subject to FE analysis (see Annex 1). In this simulation, the locations of maximal deformation were forecasted and thus the worst-case wear positions were defined.

Maximal wear was found on the male die on the mandrel head radius including the transition area to the mandrel wall (to different lengths), as well as on the lower tool in the region of the flash edge radius and on the bottom radius. In the following discussion, the evaluations are related to these wear locations.

The male die surface temperature after forging, in the case of adhering parts, is considerable. The male die surface temperature is the result of the heat transfer during the up to 10 seconds of the adherence of the part to the mandrel. Immediately after removing the part by means of a tong, surface temperatures of up to 430°C, which dropped down to 120°C after 60 seconds, were measured.
EVALUATION OF THE COATINGS IN FORGING TESTS

The forging part’s easy separation from the mandrel was selected as the subjective feature to represent the behaviour of the coatings during forging. This criterion is extremely important for a continuous forging procedure.

In the tests, TMS coating provided the best results. All parts separated on their own without outside influence. It was even possible to forge without adding lubricant, which can be traced back to the effect of the carbon partially bound in the coating like graphite. For the CrSi$_2$-coating, an increased friction could be detected during forging. It is assumed that the crystalline structure of this coating is the reason for this behaviour. As a result, about 70% of the parts continued to adhere to the mandrel in the upper tool. This percentage even exceeded that of the uncoated tool. When the commonly used hard material coating TiAlN was applied, about 20% of the forging parts adhered to the mandrel.

INDUSTRIAL TEST OF CVD-COATED FORGING DIES

Three coating variants were tested and evaluated (see Fig. 2 and [3]) under test conditions close to industrial conditions. During real use in a forging plant, the tools have to withstand higher stresses due to longer-period thermal influences. An industrial forging part, a hexagon socket screw with 24 mm nut across flats, was taken as test sample. In contrast to the cylindrical body of the first test part, this part required the use of a non-rotary mandrel with several edges and surfaces (see Fig. 2).

The wear criterion for a tool change was determined by the dimensional accuracy of the hexagon socket contour which was checked with a reference gauge.

If particles of the forging part’s material (X 5 Cr Ni 13 4) adhere to the upper tool (material X 32 Cr Mo V 3 3) during forging, then the size of the hexagon socket is increased and the wear criterion is reached within a short time. With each follow-up forging operation, new particles continue to adhere to the upper tool’s surfaces and intensify this effect. Accordingly, the coating has to meet the requirements resulting from high temperatures, high surface pressures, and relative motions between tool- and forging part materials.

The real forging dies were coated with thermally activated CVD at about 1000 °C and afterwards hardened in vacuum. The obtained coating was a
multilayer coating of the composition TiC / TiCN / TiN (from inside to outside), thus it was not a silicide coating. The total coating thickness was about 4 µm.

Whereas the parts adhered at once in the case of uncoated upper tools, at the coated tools no adherence (so-called weld-ons) occurred.

The application of an additional graphite containing lubricant (Hycogen 87/13, Lubritech Fuchs, FRG) sprayed on the tool surfaces resulted, in this specific application, in an increased tool life.

ANNEX 1

FEM ANALYSIS OF THE METAL FLOW DURING FORGING PROCESS

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