Development of micro rotary swaging tools of graded tool steel via co-spray forming

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Received 30 September 2015 / Accepted 8 October 2015

Abstract – In order to meet the requirements of micro rotary swaging, the local properties of the tools should be adjusted properly with respect to abrasive and adhesive wear, compressive strength, and toughness. These properties can be optimally combined by using different materials in specific regions of the tools, with a gradual transition in between to reduce critical stresses at the interface during heat treatment and in the rotary swaging process. In this study, a newly developed co-spray forming process was used to produce graded tool material in the form of a flat product. The graded deposit was subsequently hot rolled and heat treated to achieve an optimal microstructure and advanced properties. Micro plunge rotary swaging tools with fine geometrical structures were machined from the hot rolled material. The new forming tools were successfully applied in the micro plunge rotary swaging of wires of stainless steel.

Key words: Spray forming, Graded tool steel, Micro rotary swaging

1. Introduction

The selection of tool materials for micro rotary swaging processes is an important issue. Adapted material properties are required as the tools are loaded differently in the various functional areas. For example, the tool surface should be hard and resistant to wear and the tool body should have sufficient toughness [1, 2]. The varying properties can be optimally combined by using adapted materials in the specific regions of the tools. The combination of materials can be achieved by the use of a gradual transition in between to reduce critical stresses at the interface during heat treatment and in the swaging process. Such graded materials have much lower tendency to delaminate than surface-coated materials.

On the other hand, tool materials for micro rotary swaging should be precisely machinable by micro-machining because the required geometrical structures of the tool surfaces are significantly smaller than 1 mm in more than one dimension [2]. To meet this requirement, the tool materials should exhibit fine and homogenous microstructures since the precision machining of the tool structures may be disturbed by large carbides or significant segregation [3].

A newly developed co-spray forming process is supposed to produce such graded tool materials [4]. In this process,

two melts of different tool steels are co-sprayed and deposited on a flat substrate, resulting in a graded flat product when the two sprays partially overlap. By means of combining two tool steels in a single deposit, different microstructure and properties can be combined [5, 6]. In addition, a fine and homogeneous microstructure can be achieved in the spray-formed materials due to rapid solidification [7, 8].

In this study, a flat deposit of graded tool steel (HS6-5-3C/X110CrMoV8-2) was produced by this novel co-spray forming process. The graded deposit was subsequently hot rolled and heat treated to achieve optimal microstructure and material properties. Micro plunge rotary swaging tools were machined from the graded steel and tested in the deformation of wires of stainless steel 1.4301 (AISI 304).

2. Production of tool material

A high speed steel HS6-5-3C (AISI M3:2) was applied in the tool surface area and a cold working steel X110CrMoV8-2 in the tool body. A large number of carbides in HS6-5-3C are responsible for high hardness and excellent wear resistance. X110CrMoV8-2 shows significantly higher toughness compared to the high speed steel. The co-spray forming of the graded steel was carried out on the spray forming facility SK1+ at the University of Bremen (see Figure 1). The steels

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Figure 1. Co-spray forming of a graded steel deposit (X110CrMoV8-2/HS6-5-3C).

were melted in separate crucibles, and atomized by means of nitrogen gas jets generated by two free-fall gas atomizers. A flat ceramic substrate, moving from left to right, was used to collect the atomized droplets. HS6-5-3C was first spray-deposited on the substrate to form the lower layer of the deposit, followed by the deposition of X110CrMoV8-2 and the forming of the upper layer of the deposit. Since the two spray cones overlapped partially, a gradient zone was generated between the two layers. The superheating temperature of both melts was 180 °C. The pouring nozzle diameter was 4.5 mm for HS6-5-3C and 6.5 mm for X110CrMoV8-2. The melt mass flow rates were 0.22 kg/s and 0.47 kg/s, respectively. The gas atomizers scanned in the transverse direction of the substrate. The scanning angle of the atomizers was kept at 10.5°, and the scanning frequency at 5 Hz. The atomization gas pressure was 0.2 MPa for the HS6-5-3C melt and 0.5 MPa for the X110CrMoV8-2 melt, corresponding to a gas mass flow rate of 0.17 kg/s and 0.33 kg/s, respectively. The substrate was preheated to 600 °C and moved at a translational speed of 6 mm/s. The vertical spray distance from the atomizers to the substrate was 580 mm. The central distance between the atomizers was 340 mm. A distance of 156 mm between the axes of the two sprays at the substrate surface was determined as the tilting angles of both atomizers were 9°. The spray-formed deposit was in the form of a flat product, with the dimensions of 250 mm width, 500–600 mm length, and 55–60 mm thickness.

The spray-formed deposit was soft annealed to reduce hardness and avoid cracking. It was heated at a rate of 50 K/h to 840 °C and held at 840 °C for 4 h, followed by a controlled cooling at a rate of 20 K/h to 500 °C and a subsequent uncontrolled furnace cooling to RT. Samples were taken from the deposit for chemical composition testing, porosity measurement and metallographic study.

Figure 2. Main element distributions of the graded deposit (X110CrMoV8-2/HS6-5-3C, after soft annealing).

The spray-formed graded deposit was subsequently hot rolled on a lab rolling mill at the University of Bremen to eliminate porosity and break up the carbide network. Rolling samples with a thickness of 44–49 mm, a width of 32 mm and a length of 200 mm were machined from the graded deposit. The samples were preheated in a furnace to 1100 °C and rolled in three passes to a final thickness of approximately 24 mm. For each rolling pass, the true strain and the strain rate of the sample were about 0.2–0.3 and 1 s^{-1} , respectively. The total strain of the sample was 0.6–0.7.

Microscopic samples and semi-finished tools were machined from the hot rolled material. They were hardened and tempered prior to final grinding or milling: (1) they were austenitized in a vacuum furnace at 1080 °C for 20 min, followed by gas quenching with 6 bar nitrogen; (2) they were subsequently tempered three times at 550 °C for 2 h and cooled in air. The hardness of the X110CrMoV8-2 was about 65 HRC and about 66 HRC for the HS6-5-3C.

2.1. Element distributions in the graded deposit

The chemical composition of the graded deposit was analyzed by spark optical emission spectroscopy (S-OES, ARL3460). The sample was ground at intervals and the S-OES measurement was conducted at the newly ground surfaces (starting from the base of the sample). In this way, the element distributions in the thickness of the graded deposit were determined. The distributions of the alloying elements C, Cr, Mo, W and V in the spray-formed deposit are presented in Figure 2. The gradient zone starts at the position about 15 mm from the base of the deposit, and it ends at the position about 20 mm from the base of the deposit. It has been proved that the slope of the gradient of the elements in the deposit strongly depends on the distance between the spray axes [4, 5]. Partial overlapping of the spray cones occurred when both spray cones were tilted by 9°, and the droplets of the two different steels mixed in the overlapped spray as well as in the mushy layer of the deposit. Further homogenization of the composition in the gradient zone might take place since some of the elements might diffuse over a short distance at high temperature due to the concentration difference between the steels.

Figure 3. Porosity of the graded deposit: (a) X110CrMoV8-2; (b) X110CrMoV8-2+HS6-5-3C; and (c) HS6-5-3C.

2.2. Material characterisation of the graded deposit

Figure 3 shows the porosity of the graded deposit. Small pores are seen in the deposit, particularly in the gradient zone. The irregular shape of the pores in the gradient zone indicates relatively cold spray condition. During the spray forming of

Figure 4. Polished microsections of the graded deposit: (a) X110CrMoV8-2; (b) X110CrMoV8-2+HS6-5-3C; and (c) HS6-5-3C.

multilayer materials, a porous zone is frequently formed at the interface between the layers of the deposits [9, 10]. When the first layer is spray-formed, the upper surface of the layer often shows high amount of porosity since the surface temperature is relatively low and the solidification shrinkage as well

Figure 5. Element distribution across the thickness of the graded tool steel (X110CrMoV8-2/HS6-5-3C) after hot rolling.

as the interstices between the droplet fragments and solid particles in the surface area cannot be refilled by sufficient liquid phase. If the second spray is close to the first spray, an overlapping of the sprays contributes to higher mass input and enthalpy input to the interfacial area of the deposit. This helps reduce the porosity in this area.

The graded deposit after soft annealing is mainly composed of ferrite and carbides. Some relatively long and continuous carbide structures (carbide network) are located at the prior austenite grain boundary (it is more clearly seen after etching [5]). The carbides in the interior of the prior austenite grains in the upper layer (X110CrMoV8-2) of the deposit are very fine. In the lower layer (HS6-5-3C) of the deposit, some granular carbide particles (V-rich MC type) are observed. In the gradient zone a mixed microstructure can be seen (Figure 4).

2.3. Element distributions in the hot rolled material

The distributions of the main chemical elements in the hot rolled material were analyzed by means of electron probe microanalysis (model: JEOL JXA-8200). A typical element distribution (vanadium) across the thickness of the hot rolled steel is shown in Figure 5. The blue bar is the mapping of the element (about 1 mm width). The measurement interval is 11 μm in both directions. The curve on the right side was obtained by calculating the mean values of the element content from the mapping of the element. A picture of a macro-etched sample is combined with the element distribution in the figure. The material of the upper part is X110CrMoV8-2 (0.5 wt.% V), and the material of the lower part is HS6-5-3C (3 wt.% V). The gradient zone is in the range of 8–10 mm from the base of the hot rolled sample.

2.4. Microstructure of the hot rolled graded steel

Representative microstructures of the hot rolled steel (after hardening and tempering) are shown in Figures 6 and 7 (optical microscopy, Model: Axiophot, ZEISS). The etchant Nital

Figure 6. Polished microsections of the graded tool steel processed by co-spray forming, hot rolling, hardening and tempering: (a) X110CrMoV8-2; (b) X110CrMoV8-2+HS6-5-3C; and (c) HS6-5-3C.

(3% alcoholic HNO_3 at RT) was used to reveal the microstructure of the samples. The porosity in the spray-formed deposit was essentially eliminated by the hot rolling, although the deformation ratio was rather low. The hot rolled material

Figure 7. Microstructure of the graded tool steel processed by co-spray forming, hot rolling, hardening and tempering: (a) X110CrMoV8-2; (b) X110CrMoV8-2+HS6-5-3C; and (c) HS6-5-3C.

showed a relatively fine and homogeneous microstructure. The carbide network of the deposit was also broken up to some extent due to hot rolling. There are remarkably more and larger carbides in the lower layer (HS6-5-3C) than in the upper layer

Figure 8. Micro plunge rotary swaging tools of graded tool steel (X110CrMoV8-2/HS6-5-3C): (a) set of swaging tools; and (b) micro swaging tool with indicated different functional areas.

(X110CrMoV8-2) of the graded steel. A gradual transition of the microstructure is obviously seen in the graded steel.

3. Machining of micro rotary swaging tools

A set of micro plunge rotary swaging tools, for deforming wires to a diameter of 0.8 mm, were manufactured in the hardened state by micro milling. The tool surface consisted of HS6-5-3C, the tool body of X110CrMoV8-2, with the gradient zone in between (see Figure 8). The machining was carried out on a DMG Sauer Ultrasonic 20 linear machine tool. The machining operation comprised multiple, consecutive roughing and finishing steps. CAD/CAM-programming was used for tool path generation. Hard coated tungsten carbide ball-end mills of 1.0 mm for roughing and 0.5 mm diameter for finishing were applied. Material allowance for the finishing cut was 10 µm. The depth of cut and the width of cut for finishing were set to $a_p = 5 \mu\text{m}$ and $a_e = 5 \mu\text{m}$, respectively. The spindle speed and the feed velocity were kept constant at $n = 40,000 \text{ min}^{-1}$ and $v_f = 1,000 \text{ mm/min}$.

Figure 9. (a) Assembly of rotary swaging head and (b) principle of plunge rotary swaging.

Figure 10. Tool surfaces of the micro plunge rotary swaging tools (forming zone $\varnothing = 0.8$ mm).

4. Micro rotary swaging of steel wires

Rotary swaging is an incremental forming process for tubes, bars and wires. Forming takes place in the rotary swaging head (Figure 9a) by a quick oscillating movement of the forming tools (1). Due to the rotation of the driven shaft (4) when the base jaws come across a cylinder roller (3) the forming tools are pushed inwards and the workpiece (5) is deformed [11].

There are two main variations of the process: the infeed rotary swaging during which the diameter of the workpiece is reduced over the complete feed length, and the plunge rotary swaging which allows local diameter reductions. In this study, the plunge rotary swaging was applied and Figure 9b shows the

principle of this variation. In plunge rotary swaging, additionally to the oscillating movement, the forming tools achieve a radial displacement towards the workpiece due to the axial displacement of the wedges.

The graded tools were applied in a rotary swaging machine (Type Felss HE 3/DE) to reduce the diameter of wires of stainless steel 1.4301 (AISI 304) from the initial diameter of 1.0 mm to the final diameter of 0.8 mm. The wires were in a soft annealed state (surface hardness 300 HV0.1). The tool oscillated with a frequency of 100 Hz and the radial displacement was set to 35 µm/s. The total strain of the wires was 0.45. The gradient zone between the two steels (X110CrMoV8-2/HS6-5-3C) did not show signs of fracture or cracking after the test (up to 2500 workpieces).

Figure 11. Topography of the tool surfaces: (a) transition zone and (b) forming zone after micro milling, (c) transition zone and (d) forming zone after micro plunge rotary swaging.

The tool surfaces and the steel wires before and after the rotary swaging were investigated by means of scanning electron microscope (model: CAMSCAN CS44, Elektronen-Optik-Service GmbH). Stereoscopic images were used to retrieve 3D information of the tool surfaces (using MeX software from Alicona). It showed that the tool surfaces were smooth and the fine geometrical structures of the tools were precisely machined by micro milling. Only slight traces of micro milling were observed at the tool surfaces. The excellent micro-machinability of the graded steel was guaranteed due to its relatively fine and homogeneous microstructure.

The tool surfaces before and after micro rotary swaging are shown in Figure 10. By comparing the tool surfaces, it is seen that slight adhesion of the workpiece on the tool surfaces and slight deformation/abrasive wear in the transition zone appeared. The forming zone of the tools was almost unchanged after deforming 2500 workpieces. The topography derived from the surface measurement in SEM with Alicona MeX shows clearly the three-dimensional morphology of the tool surfaces (see Figure 11). The steel wires deformed by the swaging tools are shown in Figure 12. The shape, dimensional accuracy, and surface quality of the deformed wires are satisfactory.

It was noticed that the degree of deformation/abrasive wear at the entrance of the forming zone increased with increasing number of workpieces (Figure 10, upper pictures). The damage could be more serious if the tools are applied to deform more workpieces. This might lead to poor surface roughness, low size and shape accuracy of the workpieces and even complete failure of the deformation (fracture of the workpieces). In order

to reduce deformation/wear of the swaging tools, several strategies can be considered:

1. applying stronger tool materials at the tool surfaces (increasing carbide content and hardness, improving tool properties and performance by means of adaptive heat treatment, etc.);
2. reducing the deformation ratio of the wires;
3. reducing the temperature of the tools by coolant and improving the lubrication of the tools to reduce the friction between the wire and the tools.

5. Summary and outlook

The graded steel (X110CrMoV8-2/HS6-5-3C) was produced by means of co-spray forming and hot rolling, showing a relatively fine and homogeneous microstructure. After hardening and tempering, the hardness of the steels X110CrMoV8-2 and HS6-5-3C was about 65 HRC and 66 HRC, respectively. The as-hardened graded steel could be machined precisely to micro plunge rotary swaging tools with smooth tool surfaces and fine geometrical structures. The new forming tools were successfully applied in the micro plunge rotary swaging of wires of stainless steel. The deformed wires showed satisfactory shape, size and surface quality. Damages of the tools are supposed to be reduced by applying stronger tool materials at the tool surface, reducing deformation ratio

Figure 12. AISI 304 steel wires deformed from $\varnothing = 1$ mm to $\varnothing = 0.8$ mm by micro plunge rotary swaging: (a) workpiece no. 125; (b) workpiece no. 1000; and (c) workpiece no. 2500.

of the workpieces, and reducing the tool temperature and the friction between the wire and the tools. These suggestions are topics for further investigations.

Acknowledgements. The authors gratefully acknowledge the financial support by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) for the Subprojects A4, C2, and C6 within the SFB 747 (Collaborative Research Center) “Mikrokaltumformen – Prozesse, Charakterisierung, Optimierung”.

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Cite this article as: Cui C, Schulz A, Steinbacher M, Moumi E, Kuhfuss B, Böhmermann F & Riemer O: Development of micro rotary swaging tools of graded tool steel via co-spray forming. Manufacturing Rev. 2015, 2, 22.