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MANUFACTURE OF SiC REINFORCED STEELS BY SPRAY FORMING

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ABSTRACT

Silicon carbide powders were added to the metal spray during spray forming of two different steels. For this purpose, a specially designed device was used which allows for the controlled injection of powder particles directly into the atomisation zone where they mix with the metal droplets. After deposition, the resulting billets were characterised both by micrography, hardness measurements and wear resistance tests.

INTRODUCTION

Spray forming is a process which allows for preparing metals and alloys with properties such as low oxide content, fine grain size, or a high content of metastable alloy phases. This combination of properties cannot be achieved by conventional casting methods [1]. One feature makes the spray process appear particularly attractive: the possibility for modifying the properties of the sprayed deposit by injecting powders such as oxides, carbides, borides, nitrides or pure metals into the spray cone. The powders are allowed to react with or to be wetted by the liquid metal droplets and to be incorporated into the metal as it is deposited onto the substrate. Metal matrix composites (MMCs) can be made by adding inert powders such as carbides or oxides. Known examples of such spray formed MMCs are SiC in aluminium [2], graphite in copper [3], or alumina in steel [3].

For making MMCs it is crucial to disperse the powders uniformly in the metal matrix in order to ensure a good contact between particles and liquid metal during the deposition process and therefore to achieve a good bonding between particles and metal. Much care has therefore been taken to develop an injection device which allows for an effective and reliable distribution of particles [4].

We report on the injection of silicon carbide into two different steels. The resulting microstructure and some mechanical properties are discussed.

EXPERIMENTAL PROCEDURE

The powder was injected into the spray cone through a specially designed ring of nozzles as described in Ref. [4]. A twin screw feeder was used for transporting the powders from a powder hopper into a mixing chamber at rates between 0 and 600 ml per minute from which it was transported to the actual injection nozzle in the spray chamber by a stream of nitrogen gas. The powder was injected into the region between the atomising gas and the primary gas stream, which stabilises the atomisation process. This way a very intense contact between the ceramic particles and the metal droplets is ensured.

In a first series of experiments the two steels were spray formed by using “standard” parameters established for spraying without particle injection: in these tests the metal outlet of the tundish had a diameter of 5 mm. With a constant height of the metal column of 250 mm this yielded an average metal flow of 300 g/s. The substrate was rotated at 1.8 Hz at a distance to the atomiser of 500 mm and was lowered at a rate of 0.85 mm/s as soon at the deposit reached a height of about 50 mm. The first experiments yielded quite porous billets mainly due to cracking in the cooling phase. Moreover, strong metallurgical reactions between the silicon carbide particles and one of the steels (C35) could be observed. The reason for this was found to be a too high melt temperature and too low atomisation pressures. An adjustment of these parameters lead to macroscopically dense billets. However, some residual porosity could still be found in the microscopic images. The latest experiments were therefore carried out at even lower superheats (120°C) which is actually the limit because an even lower temperature would increase the

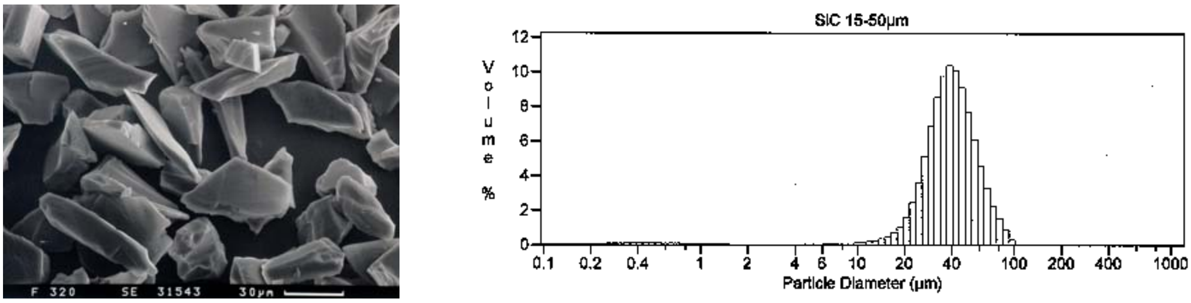

Figure 1: Particle morphology and size distributions of the SiC powder used

danger of premature solidification in the metal outlet.

Materials

Steels

Two commercially available steels were used for the experiments: an unalloyed steel containing 0.35% carbon (German designation: C35, USA: SAE 1034) and a ferritic stainless steel containing 0.2% carbon and 13% chromium (German designation: X20Cr13, USA: SAE 51420). The first steel was chosen because it is an inexpensive material which might have a good application potential as particle reinforced material. The stainless steel is frequently used in machine construction where its processing, e.g. by grinding and polishing, gives rise to a large volume of waste material. This waste is collected and could be recycled in the spray forming process thus leading both to an upgrading of the material and to new application fields.

Powders

Silicon carbide is an interesting alternative to other common ceramics such as tungsten carbide because it is even harder than WC and because it is available in many different grain sizes at comparatively low costs. SiC is dissolved in liquid steel at high temperatures but the short exposure to heat during spray forming should not affect it too much.

SiC powders of various sizes were taken into consideration. The powders were characterised by means of microscopy and by technological powder flow tests. The powder with the best flow properties was then selected for spray forming. Figure 1 shows a micrograph and a particle size distribution of the SiC particles used in the experiments. Obviously, the main fraction of the angular-shaped particles is about 40 µm in size. Powders of this size were found to have sufficiently good flow properties for particle injection [4].

Results

Microstructure of MMCs

In first experiments the injection of silicon carbide caused an exothermal reaction in the C15 steel. However, the carbide particles are still visible in the billet and even seem to have bonded with the metal (see Figure 2). In a second experiment the reaction was suppressed by choosing a lower melt temperature. This lead to an improved macrostructure with still a good bonding between steel and SiC. In spraying the ferritic steel no metallurgical reactions were observed.

Spray forming experiments with various injection rates of SiC were carried out. The highest powder injection rate applied corresponded to 1.6 kg powder for 35 kg steel. This mass ratio of 1:21 corresponds to a volume ratio of about 1:8.

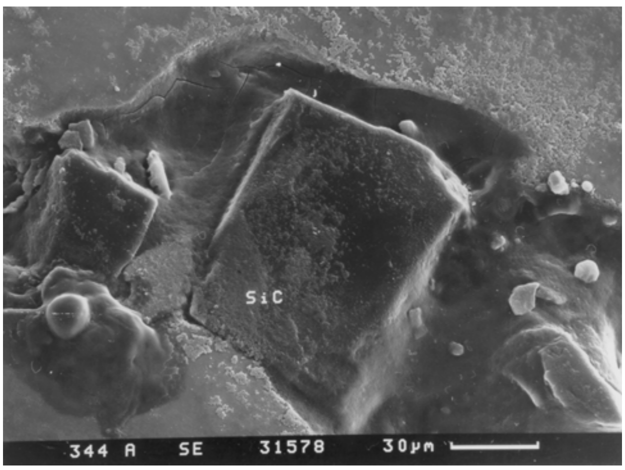

Figure 2: Steel C35 with embedded SiC particles.

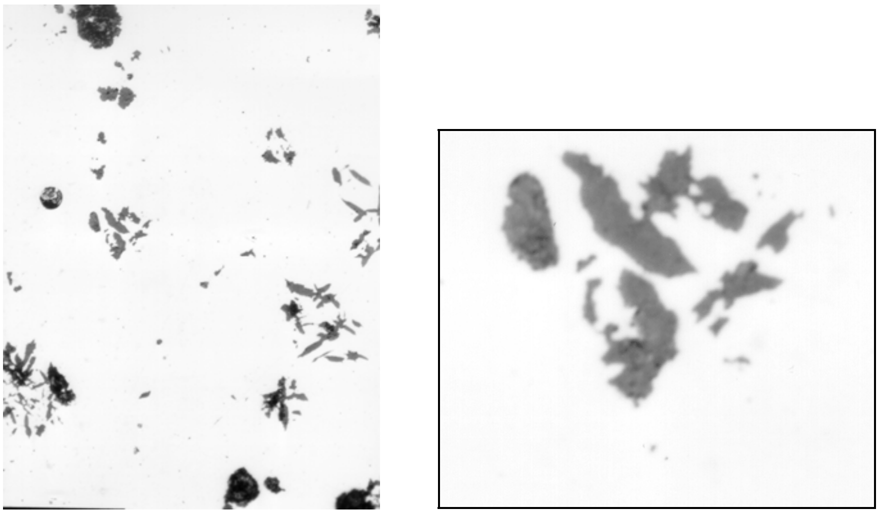

Figure 3: SiC particles embedded in C35 steel (volume content about 4%)

Assuming an equal deposition efficiency for steel and SiC one would therefore expect to find a volume fraction of SiC around 12.5% in the steel. However, the maximum contents which could be found were below about 6%, indicating that much of the ceramic powder is lost as overspray probably due to the density difference between steel (7.8 g/cm^3) and SiC (3.1 g/cm^3).

The global content of particles in a spray formed billet is difficult to determine because local contents obtained from micrographs cannot be extrapolated easily.

The resulting microstructure of one such C35 steel with embedded SiC particles is shown in Figure 3. The SiC particles are needle-shaped and show a tendency to agglomerate in small clusters. Some residual pores can also be seen. Such pores could not be completely eliminated in all the experiments. Probably a mechanical post-treatment, e.g. by rolling, is necessary to obtain completely dense products.

Hardness measurements

Vickers hardness (HV30) was measured for all the samples. Table I lists some of the results. 9 valued were obtained for each sample from which an average was calculated. One sees that in some cases the scatter is very large.

The macroscopical hardness of the spray formed billets compared to the unsprayed starting material is expected to be determined by various factors: the different microstructures of the sprayed and unsprayed steel, the porosity of the billet, and the embedded particles. Especially at low particle contents the influence of the former factor is important. It was found that hardness varied between the different regions of the billets even if the particle content was quite low. The stainless steel, e.g., showed hardness values between HV 300 and 550 in one billet probably caused by an influence of different thermal history of the various parts of the billets (temperature heterogeneities during spraying and exposure to heat during cutting of the samples). Even different billets of the same material show different hardness values owing to slightly different spraying parameters (see Table I, where two values are given for each MMC).

Pores in the materials lead to an unpredictable influence. A hidden pore near the location where hardness is measured can produce unrealistically low values. On the other hand, an accidental par-

Table I: Hardness of various spray formed billets

steel		particle	HV30
Germany	USA	type	(average)
C35	SAE1034	none	184
X20Cr13	SAE 51420	none	256 ± 6
C35	SAE1034	SiC	240 ± 9
			324 ± 40
X20Cr13	SAE 51420	SiC	328 ± 12
			306 ± 16

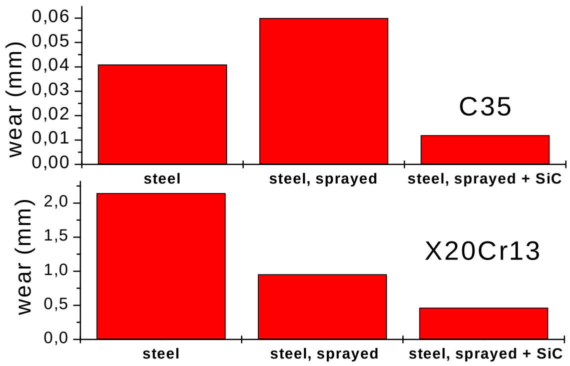

Figure 4: Wear tests on untreated, spray formed and particle-reinforced reinforced steels.

ticle agglomerate near the location of the hardness measurement will yield a too high value. It was therefore concluded that hardness is not a sufficiently suited tool to characterise MMCs.

Characterisation of wear

For a further mechanical characterisation the wear resistance of the sprayed and - as a reference test - of the starting materials was determined. For this, pin-on-disk tests were carried out on different samples. Two tests were conducted for each material. Pins with 8 mm diameter and 15 mm length were cut out of the billets. The disk was a bearing steel (100Cr6 with 1% C and 1.5% Cr) with a hardness of HRC62. The testing load was 0.75 MPa and an emulsion of alumina and water was used as lubricant. The experiments were stopped after a run of 5440 metres except for the stainless steel starting material which had to be stopped after 2240 m owing to strong wear.

The unalloyed steel C35 (SAE 1034) in its untreated state showed a comparatively low wear under the conditions chosen, whereas wear of the stainless steel X20Cr13 (SAE 51420) was so high that the test had to be stopped. The friction coefficient gradually increased from 0.3 to 0.5 for C35 while it fluctuated between 0.3 and 0.9 for X20Cr13. Spray formed C35-billets without particles showed an increased wear, most probably due to some porosity, whereas particle inclusions produced a pronounced decrease of wear, meaning that the hardness increasing effect of the particles overcompensates the increased porosity effect. In contrast, spray forming dramatically increased the wear resistance of the stainless steel for the particle-free and the reinforced state. Here, both the microstructural hardness increase during spray forming and the effect of particle incorporation produce a joint increase by a factor of 10.

SUMMARY

It was shown that silicon carbide can be incorporated into unalloyed and stainless steels in volume fractions up to 6% during spray forming. The distribution of particles was fairly uniform and in some cases a chemical bond between particles and steel was observed. Particle reinforced steels were found to have improved wear properties. What remains to show in the ongoing work is the relation between particle content and particle/steel bonding conditions on one side and wear and other mechanical properties on the other. Moreover, even higher contents of particles will be considered.

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