Properties of cold-work tool steel X155CrVMo12-1 produced via spray forming and conventional ingot casting

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Spray forming is a process used for the fabrication of metallic materials in the form of billets, plates or tubes by atomizing a melt in an inert gas atmosphere followed by deposition of the spray onto a moving substrate. Originally developed by an R&D company in Great Britain in the 1970s known as Osprey Metals [1], first applications of the production method were found in the area of non-ferrous metals such as aluminum

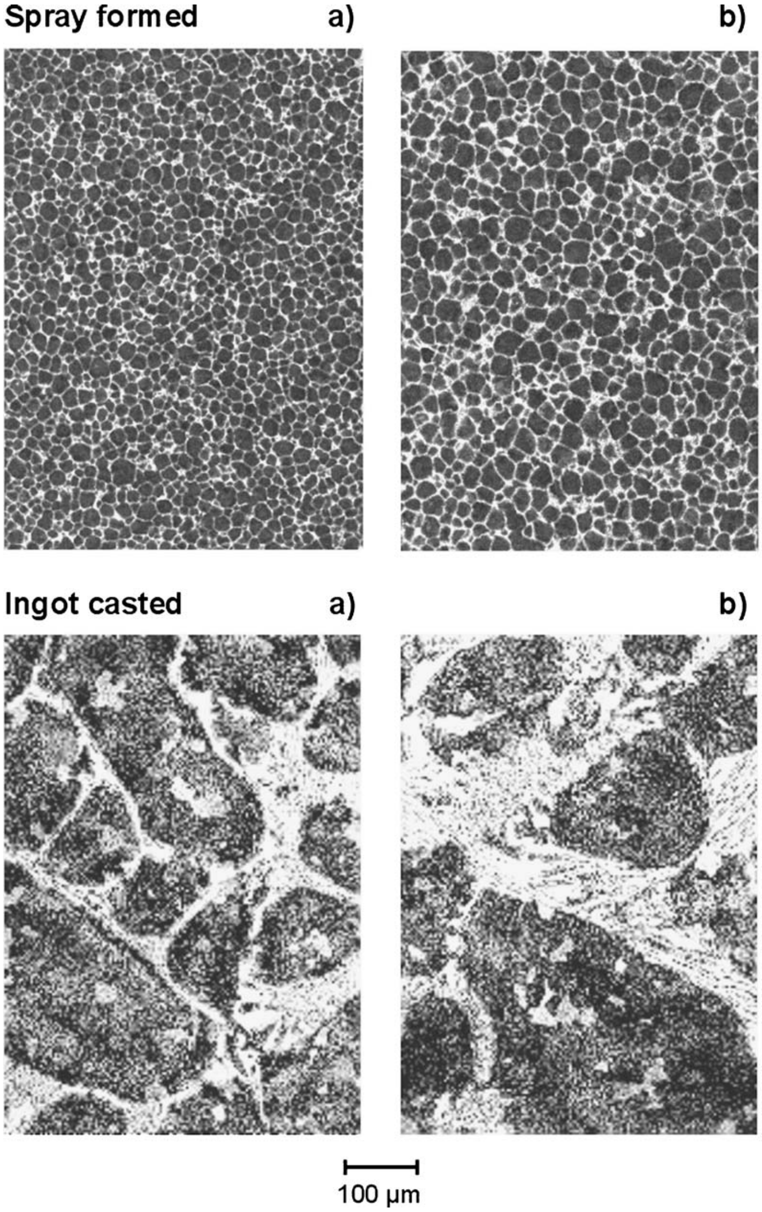

Figure 1 Microstructure in as-spayed and as-cast condition: (a) edge and (b) core.

TABLE I Chemical composition of X155CrVMo12-1

Production process	Chemical composition in Mass (%)										
	C	Si	Mn	P	S	Cr	Mo	Ni	V	AL	N
Spray formed	1.49	0.20	0.25	0.023	0.014	11.62	0.67	0.14	1.02	<0.003	0.085
Ingot casted	1.59	0.36	0.34	0.022	0.003	11.37	0.73	0.17	0.83	0.003	0.017
DIN EN	1.45	0.10	0.20	≤	≤	11.00	0.70	–	0.70	–	–
ISO 4957	1.60	0.60	0.60	0.030	0.030	13.00	1.00		1.00		

[2, 3] and copper alloys [4, 5]. Later, researchers tried to utilize the advantages of the process such as rapid solidification and as a consequence thereof minimization of segregations in the small-scale experimental production of carbon and high alloyed steels. Fundamental work to extend the technology of spray forming steels on an industrial scale has been carried out by the Danish Steel Works Ltd. since the late 1980s [6] resulting in the design and set-up of a vertical billet spray forming plant with a maximum melt capacity of 4000 kg at Dan Spray A/S, Taastrup (Denmark), which is now also used to produce tool steels.

To compare the material properties of tool steels produced via spray forming and conventional production, the above mentioned plant was utilized to produce a spray formed billet of cold-work tool steel X155CrVMo12-1 (AISI D2, 1.2379) with a dimension of Ø 500 × 2000 mm and weight of 2800 kg. The billet was hot-forged at 1180 °C with a deformation ratio φ of 7.5 and the bars with a dimension of Ø 182 mm were subsequently soft-annealed. Also material from conventional ingot casting with an ingot weight of 6000 kg that was hot-rolled to a dimension of Ø 81 mm (deformation ratio $\varphi = 14.1$) and also soft-annealed was used. The chemical composition of both materials (Table I) was within the limits of DIN EN ISO 4957.

The experiment comprised a spectrochemical investigation of the segregation profiles of main alloying elements in the as-sprayed and as-cast condition. Also the microstructure, especially carbide sizes and carbide distribution as well as cleanliness (K1 to K4 according to DIN 50602), was investigated by optical microscopy. Mechanical properties were determined in impact bending tests applying unnotched specimens (size 10 × 10 × 55 mm) as well as bending tests (specimen size Ø 5 × 90 mm). All specimens for mechanical testing were hardened and tempered (heat treatment 1080 °C/30 min/hot bath + 540 °C/3 × 1 hr/air) to reach a hardness of 58 ± 2 HRC.

The solidification process during spray forming is very complex. Small droplets solidify during their flight completely, whereas large droplets are deposited in a semi-or totally liquid state. This creates a layer of some millimetres thickness on top of the substrate consisting of liquid or partially solidified particles. Smaller dendritically or semi-solid particles get smashed when they hit the substrate and melt again. Fragments of particles that do not melt are nuclei for the succeeding rapid solidification. As shown in the microstructure of the spray formed steel investigated, the solidification is not dendritic but mainly globulitic (Fig. 1). The remaining melt enriched with alloying elements forms a close meshed network around the primary grains and thus finally solidifies as a very fine ledeburitic carbide network. The size of the primary grains is relatively constant over the cross-section as well as over the length of the billet. In comparison, the typical as-cast network structure of the same steel is much wider and includes much coarser primary carbides. Towards the core of the ingot, the network becomes wider and the size of the primary carbides increases.

The segregation profiles of the main alloying elements carbon, chromium, molybdenum and vanadium as determined by spectrochemical analysis of samples taken from the bottom of the billet and the ingot and are shown in Fig. 2. The as-cast material shows a clear decrease in the amount of alloy element towards the core of the ingot. In contrast, the distribution of elements in the as-sprayed condition is more uniform and no signs of macroscopic segregation are visible.

Hot forming results in breaking up the carbide network in both materials. In Fig. 3 the fine and homogeneous microstructure of the spray formed and forged material is depicted, showing the even distribution of carbides in the matrix. The average carbide size in the core area ranges from 25 to 30 μm with columnar

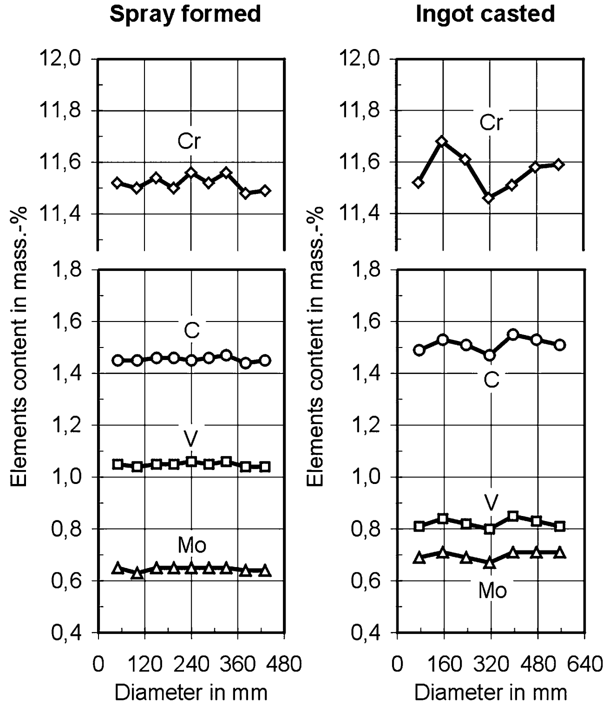

Figure 2 Concentration profiles in the as-sprayed and as-cast condition.

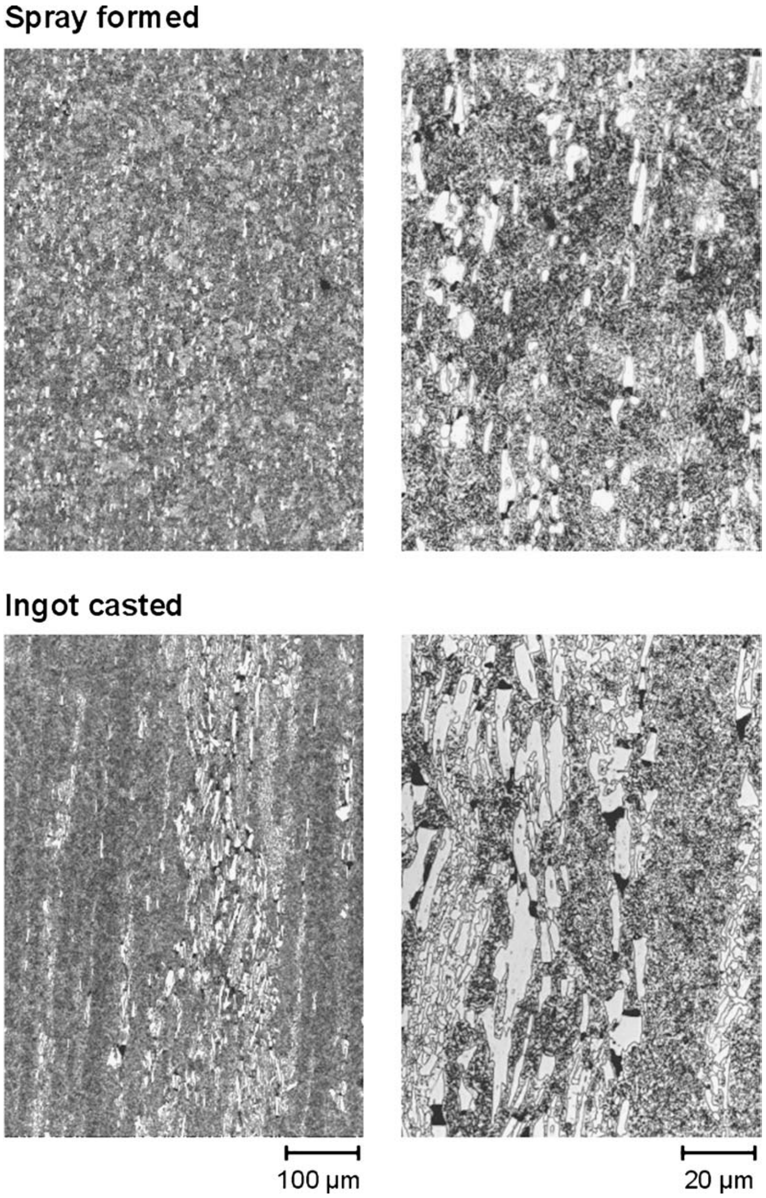

Figure 3 Microstructure after hot-working and soft-annealing (core).

carbides of up to 90 μm lengths. Although the conventional material has been hot-rolled applying a twice as high deformation ratio, the average carbide sizes in the core area (34–50 μm) as well as the lengths of columnar carbides (up to 190 μm) are much larger than in the spray formed material. Also, the spray formed steel X155CrVMo12-1 reveals an excellent cleanliness (K1 = 0.13 for sulfides and 1.41 for oxides) compared to the conventional steel (K4 = 12.7 for oxides).

Besides a high hardness, toughness is one of the important mechanical properties of ledeburitic tool steels. The results of impact bending tests applying unnotched specimens taken from longitudinal direction of the bars are summarized in Fig. 4. At the same hardness level of 58 HRC and despite the fact that the specimens were taken from a bigger dimension of the bars, the spray formed material shows impact bending energies twice as high as that determined for the ingot-cast material. Here clearly, the effects of the much finer and more homogeneous microstructure can be seen.

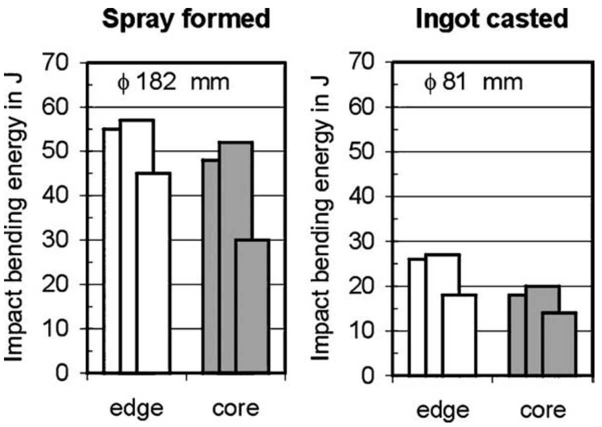

Figure 4 Toughness determined in impact bending test.

Ductility and strength were investigated in static bending tests also applying specimens taken from longitudinal direction of the hot-worked bars. Fig. 5 reveals that the spray formed steel has a bending strength of up

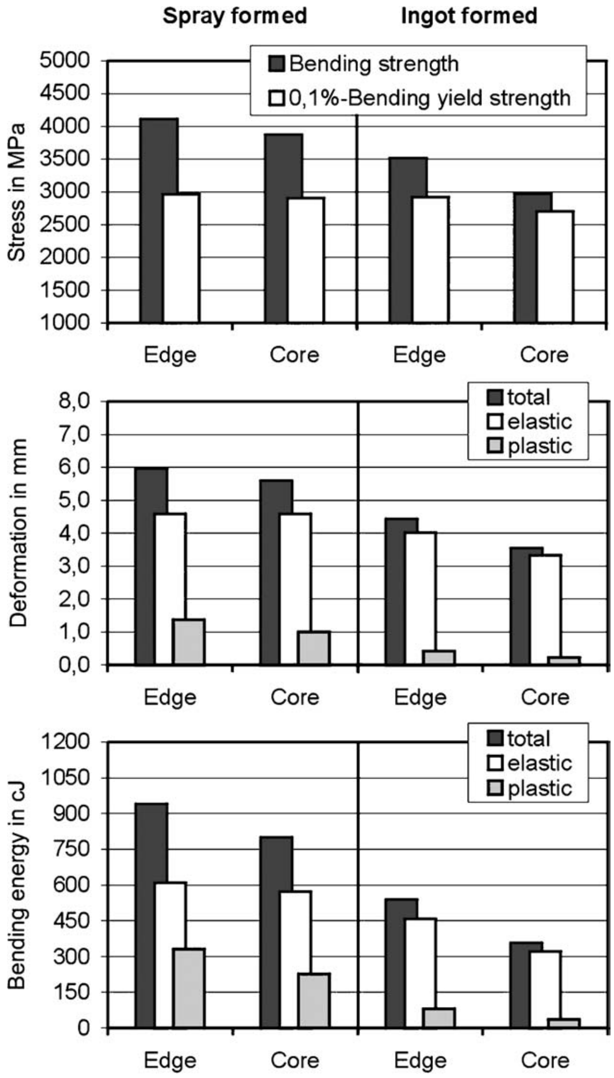

Figure 5 Properties determined in bending test.

to 1000 MPa higher than the ingot-cast steel. The characteristic values for ductility determined in this test, deformation and bending energy, are also higher for the spray formed material. The improvement is related to both the elastic as well as the plastic deformation of the steel.

The ledeburitic cold-work tool steel X155CrVMo12-1 was selected to evaluate the potential of spray forming as a new industrial production technology for tool steels. Summarizing, in comparison to conventional ingot-cast material, the spray formed steel showed a higher homogeneity, lack of segregations and a more uniform microstructure. The carbide sizes were smaller, carbide distribution was more uniform and the degree of purity was excellent. Due to the optimized microstructure, toughness determined in impact bending tests was twice as high. In static bending tests the spray formed material exhibited a bending strength of up to 1000 MPa higher compared to the conventional material. Consequently an improvement of material properties was achieved by application of the new production technology. Due to its enhanced properties, the spray formed ledeburitic cold-work tool steel X155CrVMo12-1 is expected to show improved performance in cold-working applications, where a high hardness, fine carbide size, and high toughness are indispensable. Results of some applications in fields such as precision blanking, stamping, thread rolling, deep-drawing and cold forging will be reported elsewhere.

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