Chapter 4
Blank Materials

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Abstract All sheet metal forming operations start with the blank material. The final part properties are dependent on the incoming material properties and how they could be changed during the process. To engineer the final part, it is essential to understand the incoming blank material. This chapter discusses the most common 22MnB5 steel, and other steel grades already in use or proposed to be used in hot stamping processes. Incoming blank could be uncoated or coated. Coatings can affect the final properties due to scale formation, decarburization and by the presence of microcracks. In the last decade, tailored blanks have been used in a number of automotive applications. The last section of this chapter summarizes Tailor Rolled, Patchwork, Tailor Welded blanks, and their combinations.

4.1 22MnB5

Currently, most of the production and research is being done using 22MnB5 grade (Material number 1.5528). This is a low-carbon steel, with manganese and boron alloying. The chemical composition of 22MnB5 is given in Table 4.1. As delivered, the steel has a yield strength of approximately 400 MPa, UTS around 600 MPa and approximately 22% total elongation. After quenching, the material's yield strength exceeds 1000 MPa and UTS reaches 1500 MPa. The total elongation of the final part is typically over 5% [1–3] (Fig. 4.1).

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Table 4.1 Chemical composition of 22MnB5 [4–6]

	C	Mn	B	Cr	Si	Al	Ti	N
Minimum	0.19	1.10	0.0008	0.10	0.00	0.02	0.015	0.000
Nominal	0.22	1.18	0.0020	0.16	0.22	0.03	0.040	0.005
Maximum	0.25	1.40	0.0050	0.35	0.40	0.08	0.050	0.010

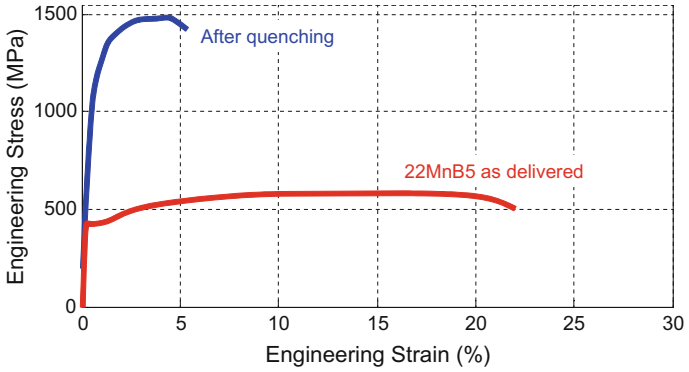

Fig. 4.1 Engineering stress–strain curves of 22MnB5, in as-delivered conditions and after quenching (re-created after [2])

This alloy has been commercialized by several names, including but not limited to:

- Ultralume by AK Steel, available as uncoated or Al/Si coated [7].
- USIBOR 1500 by ArcelorMittal, typically AlSi-coated steel produced and patented by ArcelorMittal. Zn-coated versions are also available by the name USIBOR 1500 GI or GA [8, 9].
- BR 1500 HS: by BaoSteel [10],
- BTR 165: uncoated steel by Benteler [11],
- SQ 1500: (Sumi-quench) by Nippon-Sumitomo [12],
- Hot Press Forming (HPF) 1470 by posco, available uncoated, AlSi coated or Zn (GI) coated [13, 14]
- Docol 1500 PHS: uncoated steel by SSAB, earlier named as Docol 1500 Bor [15, 16]
- MBW1500: Mangan-Bor-Stähl zum Warmumformung, literally meaning manganese-boron steel for hot form hardening, produced by ThyssenKrupp. Available uncoated or AlSi coated (MBW1500+AS) [17]. There was a ZnNi-coated version [18] which was later discontinued [19, 20].
- phs-ultraform 1500: Zn-coated steel by voestalpine [21]
- WHT1500HF: uncoated steel by Wisco [22].[1]

[1] Steel companies are listed alphabetically.

4.2 Higher Strength Steels (>1700 MPa)

Mn-B alloyed steels have been long available in hot-rolled (i.e., thick blanks) and uncoated conditions for agriculture and construction machinery industries [23]. Chemical compositions of several standard Mn-B and Mn-B-Cr alloyed steels that have higher carbon than 22MnB5 are tabulated in Table 4.2 [1, 6].

Mn-B alloyed steels are typically delivered in soft, ferritic-pearlitic condition. First, they have to be austenitized in an atmosphere controlled furnace. Once quenched, their strength levels are at least doubled, as listed in Table 4.3. Steels with higher carbon level than the most common 22MnB5 typically have higher strength. These grades may save even more weight, with equivalent intrusion resistance [12, 24, 25]. For hot stamping applications, some of the steels listed in Tables 4.2 and 4.3 are slightly modified and commercialized under different names.

Table 4.2 Chemical compositions (wt-%) of higher strength Mn-B and Mn-B-Cr steels (trace amounts of other elements, balance Fe) [1, 4, 6]

Steel	(Mat'l number)	C	Mn	B	Cr
27MnCrB5	(1.7182)	0.25	1.24	0.002	0.34
28MnB5		0.28	1.30	0.005	–
30MnB5	(1.5531)	0.30	1.30	0.005	–
33MnCrB5	(1.7185)	0.33	1.35	0.005	0.45
34MnB5		0.34	1.30	0.005	–
37MnB4	(1.5537)	0.33	0.81	0.001	0.19

Table 4.3 Yield and Ultimate Tensile Strength of several quenchable steels before and after quenching [1, 4, 6]

Steel	As delivered		Quenched	
	Yield stress MPa (ksi)	UTS MPa (ksi)	Yield stress MPa (ksi)	UTS MPa (ksi)
27MnCrB5 (1.7182)	478 (69)	638 (93)	1097 (159)	1611 (234)
28MnB5	420 (61)	620 (90)	1135 (165)	1740 (252)
30MnB5 (1.5531)	510 (61)	700 (90)	1230 (165)	1740 (252)
33MnCrB5 (1.7185)	420 (61)	620 (90)	1290 (187)	1850 (268)
34MnB5	600 (87)	820 (119)	1225 (178)	1919 (278)
37MnB4 (1.5524)	580 (84)	810 (117)	1378 (200)	2040 (296)

For example, ArcelorMittal has been developing a steel grade similar to 34MnB5, commercially named as USIBOR® 2000P, which is currently under customer trials. This grade will be available with AlSi coating [8, 31]. Baosteel is also preparing a 1800 MPa steel [13].

Mazda has become the first vehicle manufacturer to use higher strength boron steels. The CX-5 (SOP 2011) has 1,800 MPa (~260ksi) tensile strength reinforcements in front and rear bumpers, Fig. 4.3. According to Mazda, the new material saved 4.8 kg (~10.6lbs.) per vehicle. The material was supplied by Sumitomo Metals (SumiQuench 1800, SQ1800 as shown in Fig. 4.2, modified 30MnB5) and hot stamped at a facility of Aisin Takaoka, both in Japan [12, 32]. Figure 4.4 shows the comparison of bumper beams with SQ1500 and SQ1800. With the higher strength material, it was possible to save 12.5% weight with equal performance [12].

Posco has already demonstrated HPF 2000 steel in a number of component-based examples, and also in the Renault EOLAB concept car [28, 33]. Since 2016, Posco has also been developing a 1800 MPa grade [14]. SSAB has already commercial-

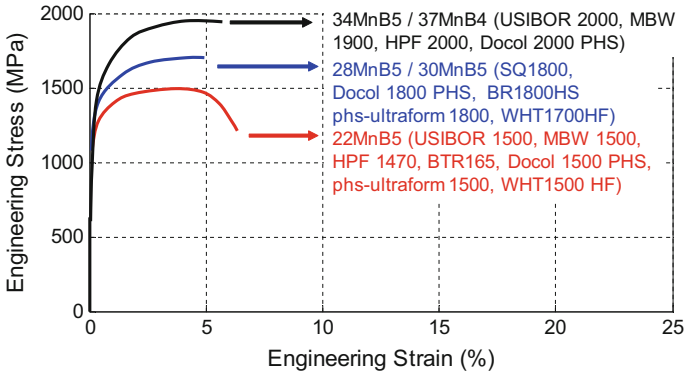

Fig. 4.2 Engineering strain–stress diagram for 22MnB5 and higher strength boron steels (re-created after: [12, 24, 26–30]. Note that some of these grades may not be commercially available

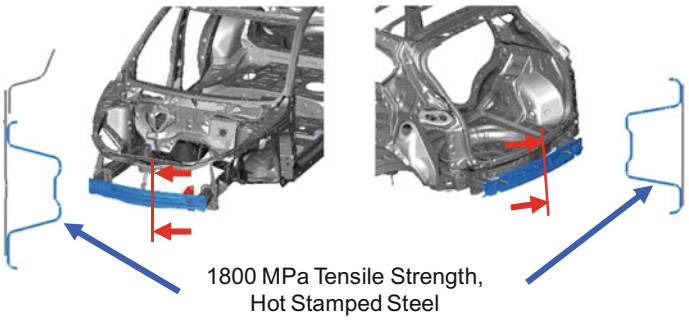

Fig. 4.3 Bumper beam reinforcements of Mazda CX-5 (SOP 2011) are the first automotive applications of higher strength boron steels [32]

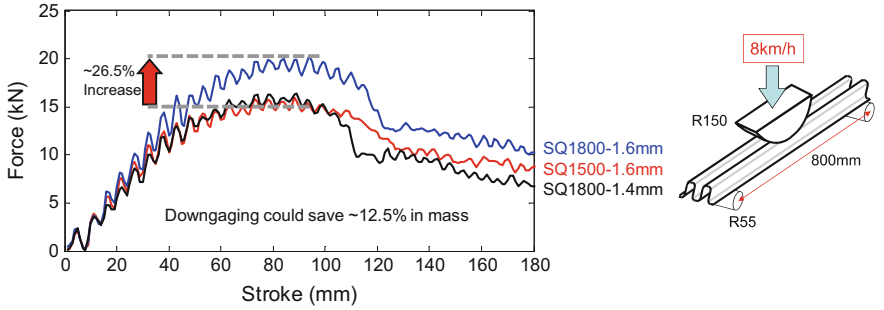

Fig. 4.4 Comparison of bumper beams with SQ1500 and SQ1800 (re-created after [12])

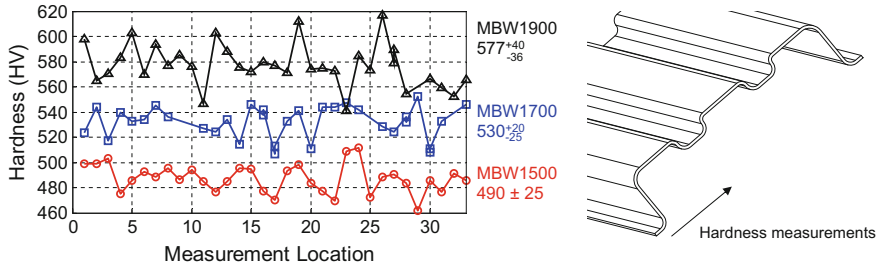

Fig. 4.5 Hardness distribution of an impact beam using ThyssenKrupp Mn-B steels (re-created after [18, 26])

ized uncoated Docol PHS 1800 (∼30MnB5) and is preparing Docol PHS 2000 [34]. ThyssenKrupp has demonstrated that an MBW® 1900 B-pillar with correct properties can save 22% weight compared to DP600 and yet costs 9% less than the original dual-phase design [35]. Ford had also demonstrated that by using MBW1900 instead of 22MnB5, a further 15% weight could be saved [24]. Another grade in development by ThyssenKrupp was MBW® 1700 (28MnB5). Figure 4.2 shows MBW® 1900 (34MnB5) tensile data, compared with MBW® 1700 (28MnB5) and MBW® 1500 (22MnB5), with commercial names from other suppliers as well [27]. Voestalpine has already commercialized phs-ultraform 2000 [36].

Table 4.4 summarizes commercially available and under development steel grades, designed for hot stamping applications.

Vickers Hardness (HV) values for conventional 22MnB5 steel are in the order of 450–500 HV after quenching. 37MnB4, on the other hand, has a Vickers Hardness of 600–610 HV [4]. Similarly, Overrath et al. [26] found ∼490 HV for MBW® 1500, ∼530 HV for MBW® 1700 and ∼580 HV for MBW® 1900, as shown in Fig. 4.5. ThyssenKrupp has commercialized MBW® 1900 in 2013 [42]. MBW 1700 has not been commercialized yet [43].

Problems with higher strength materials are (1) their low toughness/energy absorption (i.e., typically even lower elongation than 22MnB5, see Fig. 4.2), (2) delayed

Table 4.4 Chemical compositions, final properties, and commercial availability of >1700 MPa steels specifically designed for hot stamping applications [12, 14, 27, 31, 34, 36–41]

Steel[a]	Chemical Composition (%wt)				Yield	Tensile	Elongation	Bending	Availability		
	C	Mn	B	Nb	(MPa)	(MPa)	(%)	Angle	U/C	AlSi	Zn
USIBOR 2000	0.37	1.4	0.005	–	≥1400	≥1800	≥3	≥45°	–	+	–
BR1800 HS	–	–	–	–	≥1200	≤1800	≥5	–	–	–	–
SQ 1800	0.30	1.8	0.002	0.08	1267	1882	7.6	–	–	+	–
HPF 1800					≥1200	≥1750	≥6	–	*	+	–
HPF 2000					≥1300	≥1900	≥5.5	–	*	–	–
Docol 1800 PHS	0.27–0.33	1–1.35	≤0.005	–	1300	1800	6	–	+	–	–
Docol 2000 PHS	0.36–0.42	1.15–1.45	≤0.005	–	1700	2000	3.7	–	*	–	–
MBW 1700	0.26–0.30	1.15–1.45	≤0.005	–	~1150	≥1700	≥4	–	–	–	–
MBW 1900	0.32–0.38	1.0–1.4	≤0.005	–	≥1200	≥1900	≥4	55–65°	+	–	–
phs-ultraform 2000	0.20–0.36	≤2.0	≤0.005	≤0.01 (incl. Ti)	≥1100	≥1800	≥5	≥45°	–	–	+

*Under development

[a]Steel companies are listed alphabetically

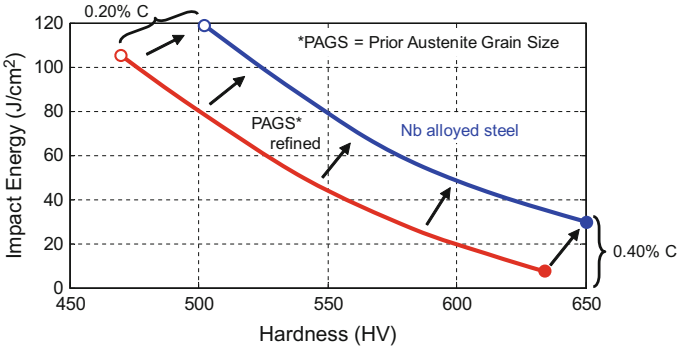

Fig. 4.6 Energy absorbing capacity decreases with increased hardness. If "Prior Austenite Grain Size" (PAGS) can be refined, significant improvements can be achieved [re-created after [41, 42]]

cracking and (3) weldability [12]. Delayed cracking is investigated in Sect. 6.19 and weldability in Chap. 7.

Naderi [4] noted that, during tensile test of 37MnB4 (UTS = 2040 MPa, 296 ksi), all of the hardened tensile samples were cracked out of the gage length. One possible way to improve the toughness (energy absorbing capacity) of higher strength steels is grain refinement. Wang et al. had shown that as the "prior austenite grain size" (PAGS) of a high-strength steel is reduced, both the strength and elongation values are improved. Thus, the toughness is improved [44]. Figure 4.6 shows energy absorption of martensitic steels with hardness between 450–650 HV - in the range of most hot stamping grades. When Nb alloying is introduced, the toughness is increased through PAGS refinement [41].

4.3 Higher Elongation/Energy Absorbing Materials

Since hot-stamped parts are extremely strong, but do not absorb much energy, they are mostly used where intrusion resistance is required. However, lately, there are new materials for hot stamping which have higher elongation (ductility) compared to 22MnB5. Thus, these materials can save weight where energy absorption is required.

These new grades can be investigated in two different strength levels:

(1) 450–600 MPa tensile strength level and >15% total elongation and
(2) 1000–1300 MPa tensile strength level and >5% total elongation.

ArcelorMittal has been developing 4 new materials, as shown in Table 4.5. Figure 4.7 shows the approximate engineering strain–stress diagrams of USIBOR 1500 (22MnB5), DUCTIBOR 1300 and 500. There is also research going on laser welding DUCTIBOR grades to USIBOR grade material to combine intrusion resis-

Table 4.5 Higher elongation hot stamping materials, developed by ArcelorMittal [8, 31, 47]

Product name	Yield strength MPa (ksi)	Tensile strength MPa (ksi)	Elongation (%)	Status
DUCTIBOR 450	340–460 (50–65)	460–610 (65–90)	≥16	Industrial
DUCTIBOR 500	370–470 (55–70)	550–700 (55–100)	≥16	Industrial
DUCTIBOR 1000	≥800 (≥115)	≥1000 (≥145)	≥6	Customer testing
DUCTIBOR 1300	≥950 (≥135)	≥1300 (≥190)	≥5	n/a

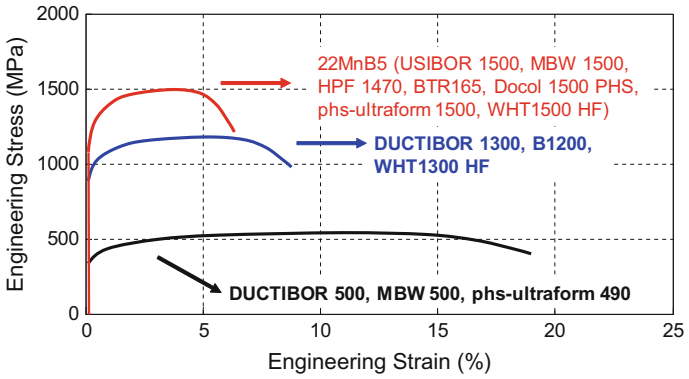

Fig. 4.7 Comparison of 22MnB5 with high elongation grades [8, 10, 43, 49, 52]

tance and energy absorption properties. For details of these studies, see Sect. 8.2.1 [8, 45]. Since 2015, several Fiat models have a rear rail with Ductibor 450 [46].

ThyssenKrupp and voestalpine have also developed 500 MPa (~75 ksi) grades with the commercial names MBW® 500 and phs-ultraform 490, respectively. Production of MBW® 500 started in January 2012. Since 2014, Volvo is using MBW500 steel in the new XC90 in energy absorbing areas [48]. Since then, ThyssenKrupp also developed MBW® 600 [43], voestalpine rolled phs-ultraform 490, which is available with Zn coating, in February 2013 [49].

For crashworthiness, bending angle may be a more important indicator compared to total elongation [50]. Thus, bending angles are also reported in the summary of 450–600 MPa steels is given in Table 4.6.

In 1000–1300 MPa tensile strength grades, BaoSteel has commercialized B1200 steel since 2013. This steel has minimum 900 MPa yield, 1200 MPa tensile strength when quenched properly and can still have 7% uniform elongation [10]. WISCO has also commercially available 1300 MPa grade, WHT 1300 HF [22, 53]. As of 2017, Ductibor 1000 is under customer testing, and there are no updates about Ductibor 1300 [31] (Table 4.7).

Table 4.6 Chemical compositions, final properties, and commercial availability of 450–600 MPa steels [31, 43, 49, 51]

Steel[a]	Chemical Composition (%wt)				Yield (MPa)	Tensile (MPa)	Elongation (%)	Bending Angle	Availability		
	C	Mn	B	Si					U/C	AlSi	Zn
Ductibor 450	≤0.11	≤1.1	≤0.001	≤0.06	≥350	≥460	≥16	≥120°	–	+	*
Ductibor 500	≤0.1	≤1.3	≤0.001	≤0.5	≥400	≥550	≥16	≥120°	–	+	–
MBW® 500	≤0.10	≤1.0	≤0.005	≤0.35	≥400	≥550	≥17	≥140°	–	+	–
MBW® 600	≤0.10	≤2.0	≤0.005	≤0.5	≥450	≥650	≥16	–	–	+	–
phs-ultraform 490	≤0.11	≤1.4	–	≤0.5	≥340	≥460	≥12	≥120°	–	–	+

[a]Steel companies are listed alphabetically

Table 4.7 Chemical compositions, final properties and commercial availability of 1000–1300 MPa steels [22, 31, 54, 55]

Steel[a]	Chemical Composition (%wt)				Yield	Tensile	Elongation	Bending	Availability		
	C	Mn	B	Si	(MPa)	(MPa)	(%)	Angle	U/C	AlSi	Zn
Ductibor 1000	≤0.12	≤2.0	≤0.005	≤0.06	≥800	≥1000	≥6	≥80°	–	+	–
BR1200 HS	0.16–0.20	1.0–1.5	≤0.0030	≤0.40	≥900	≥1200	≥8	–	+	–	–
WHT1300 HF	0.2	1.15	≤0.005	0.24	≥950	≥1300	≥8	–	+	–	–

[a]Steel companies are listed alphabetically

4.4 Other Steels for Hot Stamping

In the last few years, new steels are also considered for hot stamping process. Although these are not in mass production yet, research and development were done on hot stamping of:

(1) Stainless steels,
(2) Medium-Mn steels (including steels with higher Mn content compared to 22MnB5),
(3) Sandwich materials.

4.4.1 Stainless Steels

Aperam and Outokumpu have already demonstrated stainless steel grades that can be formed in the current hot stamping lines. Aperam's method is to get almost 100% martensitic structure, whereas Outokumpu recommends duplex (Austenite + Martensite) microstructure after hot forming and quenching [56, 57]. Stainless steels are corrosion resistant by their nature in service conditions. They also do not require a special coating or controlled atmosphere at hot conditions [58].

Aperam has already developed three different steels for hot stamping, one for intrusion resistance applications and two for energy absorbing areas. The chemical compositions and mechanical properties are tabulated in Table 4.8. According to Herbelin, almost 100% martensite can be formed at very low cooling rates (as low as 1 °C/s, as shown in Fig. 4.8), thus parts produced with this steel could be air hardened [58]. The low critical cooling rate allows the part to be formed in a multistep operation (Fig. 4.22) [59].

Outokumpu has shown that Nirosta 1200 PH grade can be hot formed, which would have 1100–1300 MPa yield and 1700–1850 MPa tensile strength, combined with 12–16% total elongation after quenching (see Table 4.8) [56]. The material can save weight both in intrusion resistance components and energy absorbing components, since it can absorb three times the energy 22MnB5 can absorb. Figure 4.9 shows the comparison of Nirosta 1200 PH and 22MnB5. This material is classified as duplex stainless steel, as it contains austenite and martensite.

4.4.2 Medium-Mn Steels

Medium-Mn steels are being developed both for cold and hot stamping applications. There are several advantages of medium-Mn steels over 22MnB5 in hot stamping:

(1) Austenitization temperature is typically lower than 22MnB5 and decreases with increasing Mn content. This could reduce the energy requirement of the furnaces and save energy and cost (see Fig. 4.11) [62, 63].

Table 4.8 Chemical compositions and final properties (after hot stamping and quenching) of stainless steels designed for hot stamping [56–58, 60, 61]

Steel[a]	Chemical Composition (%wt)					Yield	Tensile	Elongation	Bending
	C	Mn	Cr	Ni	Others	(MPa)	(MPa)	(%)	Angle
MaX 1.2	0.10	0.4	12	0	Nb	>800	~1200	>10	>65°
MaX 1.2 HY	0.06	+	11	0.5	Nb	>800	~1200	~10	>95°
MaX 2	0.2–0.25	>0.3	13	0–2	Nb	>1000	~1800	~10	–
H1200 PH	0.43–0.5	<1.0	13.5±1	0	–	1100–1300	1700–1850	12–16	–

[a]Steel companies are listed alphabetically

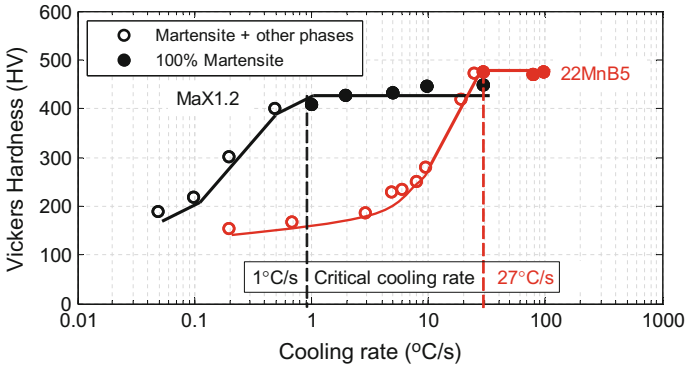

Fig. 4.8 Critical cooling rate comparison of MaX 1.2 and 22MnB5 (re-created after: [58])

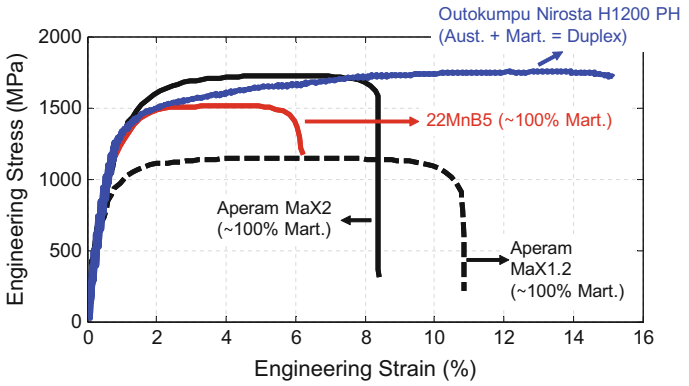

Fig. 4.9 Comparison of 22MnB5 with potential new hot stamping stainless steel grades. All curves shown here are after hot stamping and quenching (re-created after: [56, 58])

(2) Martensitic transformation can occur at very low cooling rates and thus simple dies could be built for hot forming of these grades, as they could be air hardened. They can also be formed in multistep operations. Martensite start/finish temperatures are also lower than 22MnB5 [64, 65].

(3) Some retained austenite may be present in the final part. Medium-Mn steels, when properly hot stamped, may have high strength and high elongation. For example, tensile strength of 1800 MPa could be achieved with 10% total elongation, similar to the high yield strength medium-Mn steel shown in Fig. 4.10 [62]. Yi et al. achieved 1880 MPa tensile strength with 16% total elongation [66]. Rana et al. studied a number of heat treatment conditions with a 10 wt.% Mn steel and achieved 1330-1450 MPa tensile strength with 16–25% total elongation [67].

Recently, BaoSteel has shown two medium-Mn grades for hot stamping applications. One of these steels was designed for intrusion resistance applications and have high yield strength, in the order of 1000–1050 MPa (~145–150 ksi). As shown in

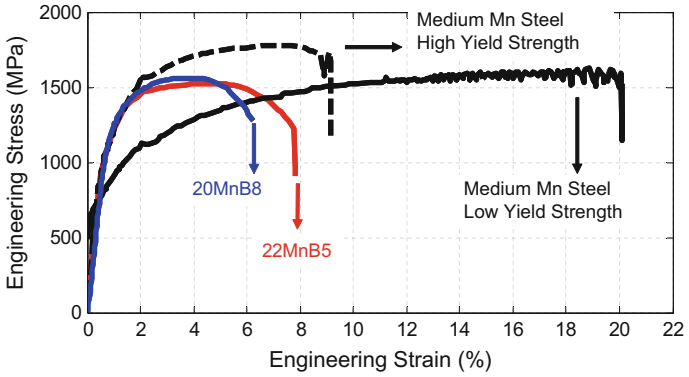

Fig. 4.10 Engineering stress–strain curves of 20MnB8, 22MnB5, and medium-Mn steels (re-created after: [20, 30, 62])

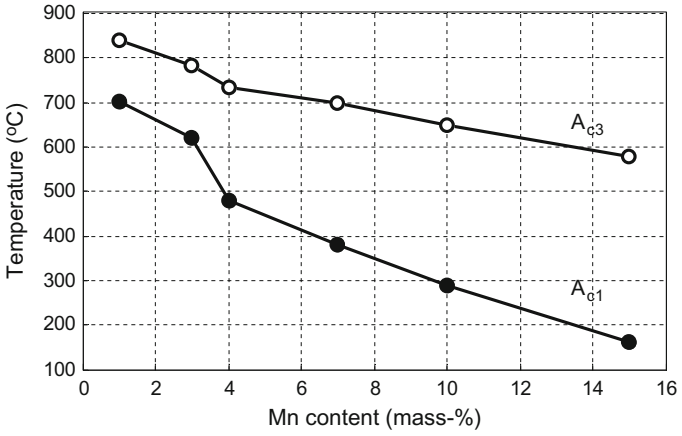

Fig. 4.11 Effect of Mn content on equilibrium transformation temperatures (re-created after: [62])

Fig. 4.10, the low yield strength version has 20% total elongation and approximately 1500 MPa (215 ksi) tensile strength. The chemical compositions were not published yet, but the austenitization temperatures were listed as 750–850 °C (~1350–1600 °F) [30].

Han et al. have calculated the austenitization temperatures using ThermoCalc software [62]. As shown in Fig. 4.11, the furnace temperature can be reduced with increased Mn content. A study funded by the EU for energy efficient hot stamping has shown that a typical industrial furnace consumes 32 m^3/h gas for mass production 22MnB5 at furnace temperature of 930 °C. When the furnace temperature was reduced to 808 °C the consumption went down to 19 m^3/h and at 785 °C it was as low as 17 m^3/h [63]. Thus, a medium-Mn steel may save energy in the life cycle assessment (Table 4.9).

Table 4.9 Chemical compositions and final properties (after hot stamping and quenching) of medium-Mn steels designed for hot stamping [56–58, 60, 61]

Reference	Chemical Composition (%wt)				Yield (MPa)	Tensile (MPa)	Elongation (%)
	C	Mn	B	Others			
20MnB8 [68]	0.195	1.98	0.003	Ti, Cr,…	>1000	~1500	>8
BaoSteel [30] Low Yield Strength	n/a	n/a	n/a	n/a	690	1620	20.0
BaoSteel [30] High Yield Strength	n/a	n/a	n/a	n/a	1045	1770	9.2
BaoSteel [30] Medium-Mn [62]	0.1–0.2	5–12	0	Ti+V	>900	~1800	~10
Medium-Mn [64]	0.22	4–7	0.0024	Ti	1220	1519	>11.8

Manganese alloying reduces martensite start–finish temperatures (M_s and M_f) and also retards bainite formation. For 20MnB8 (2.0%-wt. Mn), the critical cooling rate is around 20 °C/s (36 °F/s) [68]. In medium-Mn steels (4–7%-wt. Mn), even 10 °C/s (18 °F/s) could be sufficient for 100% martensitic transformation [64].

4.4.3 Steel Composites

ThyssenKrupp has been developing a family steel composites, called TriBond ®, since 2006 [69]. Here, three slabs (one core material and two cladding layers) are surface prepared, stacked on top of each other, and welded around the edges. Initially, TriBond ® was designed for wear-resistant cladding and ductile core materials [69].

In 2014, the original composite was modified for hot stamping. The core material was 22MnB5 and the thinner cladding layers were ductile material (MBW 1500 and MBW 500 respectively), as shown in Fig. 4.12. Coilmaking process was also slightly modified: after hot rolling, the slabs were then cold rolled, annealed, and aluminum coated [70]. As tabulated in Table 4.10, there are currently two planned versions of Tribond with approximately 1200 and 1400 MPa tensile strength (~175 and 205 ksi respectively). Both grades have higher bending angles compared with 22MnB5 after quenching [71].

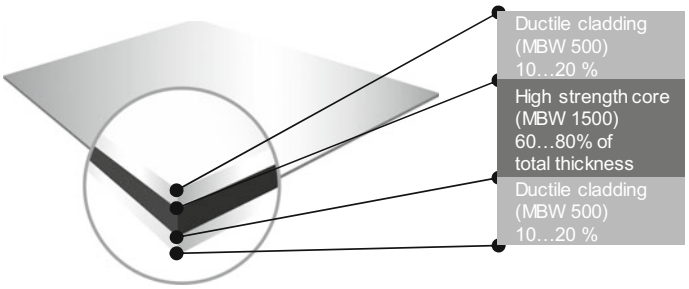

Fig. 4.12 Schematic view of Tribond®grades (re-created after [72])

Table 4.10 Through thickness compositions and final properties of ThyssenKrupp hot forming composites [17, 51, 71]

Steel	Through thickness composition	Yield (MPa)	Tensile (MPa)	Elongation (%)	Bending Angle
MBW 500+AS	100% MBW500	≥400	≥550	≥17	140–155°
MBW 1500+AS	100% MBW1500	≥1000	≥1400	>5	≥55°
TRIBOND®1200+AS	20% MBW500 60% MBW1500 20% MBW500	≥730	≥1100	>5	≥135°
TRIBOND®1400+AS	10% MBW500 80% MBW1500 10% MBW500	≥890	>1300	>5	≥75°

4.5 Coatings

As discussed in Chap. 3, uncoated boron steels suffer from scaling, which adds up another manufacturing step of descaling. Coating the blank does not only solve the scaling problem, but also improves protection against corrosion and reduces the risk of decarburization [21, 73].

If the steel's surface is not coated and exposed to high-temperature atmosphere, oxygen and other oxidizing gases react with the steel. Thus, scale forms on the surface—an oxide layer, typically composed of Fe_3O_4 [74]. The scale must be cleaned by sandblasting after hot forming process [1].

Another phenomenon happening during high-temperature heating is "surface decarburization". If the conditions are favorable for iron (Fe) to oxidize, it may also be possible for carbon (C) to be oxidized as well. If the carbon is oxidized to produce gaseous carbon monoxide and/or carbon dioxide (CO and/or CO_2), a layer close to the surface would lose their carbon content [76]. As discussed in earlier sections, carbon is one of the most important alloying element affecting the final hardness. Choi and De Cooman studied the effects of decarburization of uncoated 22MnB5 steel. They found that the depth of decarburization layer increases with time, until the oxide layer forms a barrier between the steel and atmosphere. As the carbon is depleted in near-surface regions, the hardness is lowered (Fig. 4.13a) [50]. Decarburization is usually undesirable since it lowers the strength/hardness and may affect fatigue life [77]. However, in the case of 22MnB5, lower carbon layers close to the surface creates a composite with high-strength core and ductile layers, similar to the one explained in previous subsection. As a result, bendability may improve with decarburized layers, as shown in Fig. 4.13 [50].

Belanger [78] estimated that only 38% of hot stamped components in auto-body will be in dry areas. Therefore, high cathodic protection is required in 62% of hot-stamped components. Currently, most coated boron steels sold are AlSi coated, which only offer barrier corrosion protection. Zn-based coatings are favored for their cathodic protection, but may require indirect hot stamping followed by an additional surface cleaning process, such as sandblasting [79]. Table 4.11 is a summary of coatings available in the market and/or proposed for hot stamping.

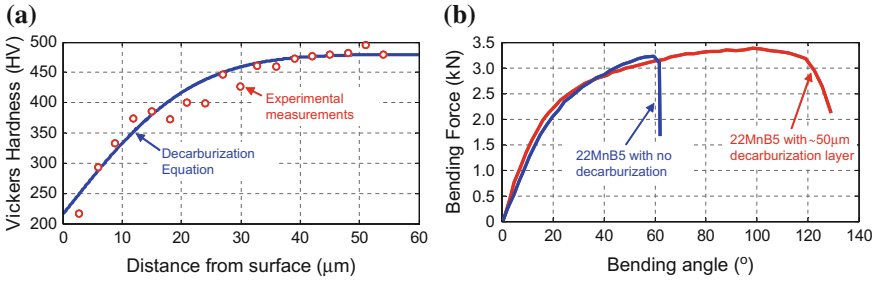

Fig. 4.13 **a** As the surface layers lose carbon (Decarburization), their hardness is lowered, **b** bendability may be improved by decarburized layers (re-created after [50, 75])

Table 4.11 Coatings available for hot stamping blanks [1, 3, 8, 21, 74, 80–85]

Coating type (commercial name)	Thickness and chemistry (before/after quenching)	Advantages	Disadvantages
Uncoated (22MnB5, BTR165)	N/A	• Cost	• No corrosion protection, • Scale formation, • Decarburization
AlSi (ArcelorMittal USIBOR, ThyssenKrupp MBW + AS)	AS 150 (150 g/m^2) 25 μm AlSi / 40 μm AlSiFe	• No scale formation, • Barrier corrosion protection	• No cathodic protection, • Only applicable for direct hot stamping
	AS 80 (80 g/m^2) 13 μm AlSi / 20 μm AlSiFe	• Shorter time in furnace	
Zn (voestalpine phs-ultraform GI)	10 μm Zn / 20 μm ZnFe	• Cathodic protection, • Applicable to both direct and indirect hot stamping.	• Surface conditioning may be required, • Risk of LMAC
ZnNi (ThyssenKrupp GammaProtect)	~10 μm ZnNi / 20–25 μm ZnNiFe	• Fast heating possible, • Low friction coefficient (Fig. 4.14a), • Applicable to both direct and indirect processes	• Risk of LMAC.
Al-Zn (Galvalume)	Not a Standard Coating	• Weldable and has good paint adhesion, • Better corrosion protection than GA	• May require a preheating to 550–730 °C, • May result in microcracks.
Zn-Al-Mg	Not a Standard Coating	• Best corrosion protection, • Can be applied as a postprocess coating.	• Risk of LMAC
(Henkel Bonderite S-FN 7500 PH) Coil Coating	2–3 μm	• Fast heating possible, • Weldable without sandblasting	• Coil Application
Al particles, graphite and wax in inorganic–organic matrix (Nano-X x-tec CO 4020 coil coating)	7 μm Al	• Fast heating possible, • Low friction coefficient (Fig. 4.14b) • Easy to apply (Fig. 4.23) • Room Temp. curing	• Has to be removed before painting/welding, • Coil Application
Al in inorganic matrix (Nano-X Alsi 4001 coil coating)	2–3 μm	• Spot weldable, • Suitable for e-coat	• No cathodic protection, • Coil Application, • High temp. curing

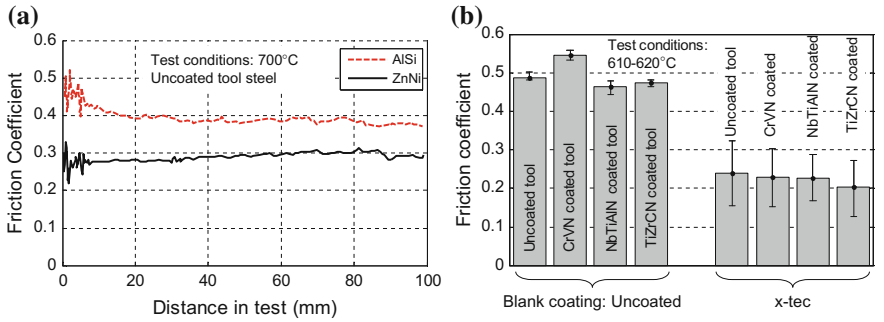

Fig. 4.14 Friction coefficients of: **a** AlSi and ZnNi at 700 °C (~1300 °F), **b** uncoated and x-tec coated blanks versus several tool coatings tested at 620 °C (~1150 °F) (re-created after [86, 87])

Blank coatings and the way they are heat treated have great influence on friction during stamping and the final part quality. Friction coefficient of several coatings and uncoated steels are given in Fig. 4.14 [86, 87]. Other important expectations from the coating are:

(1) weldability,
(2) compatibility with e-coating and paint baking cycles, and
(3) corrosion protection [85].

Although uncoated blanks are still used in automotive applications, there are different coatings available on the market, which could be classified under three main types [82]:

(1) Al-based coatings.
(2) Zn-based coatings.
(3) Varnish coatings.

4.5.1 Aluminum-Based Coatings

Aluminum-based hot stamping coating was first developed by Usinor, a French steel-maker that was later merged to Arcelor, and then to ArcelorMittal. The first pre-coated steel parts were used in Citroën C5 in 2001 [88–90].

The most common coating used in the recent years is 150 g/m^2 AlSi coating. This is equivalent to 25 μm coating thickness before heating. The typical composition is 7–11% Si (nominal 10%) and balance Al. Si is added to form ductile layers in the coating. In the absence of Si, the coating would be very hard but also brittle. Once the pre-coated blank is heated, iron diffusion takes place and forms a 40 μm thick AlSiFe of 5 layers, as shown in Fig. 4.15 [8, 82, 85, 91, 92].

The iron diffusion is a time-dependent process. If the diffusion is not completed (short heating time) the layers would not form as shown in Fig. 4.16a. In a typical process, the blank is kept in the furnace for 5–6 min.s (300–360 s). Layers of coating

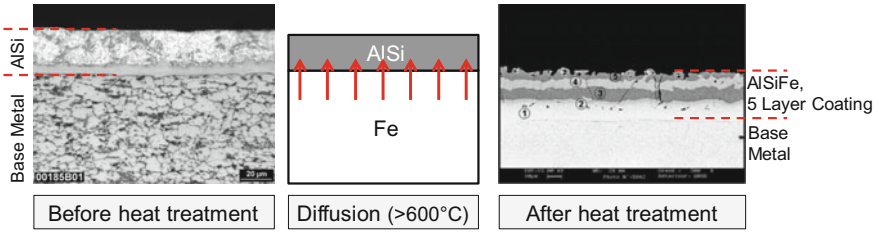

Fig. 4.15 During heat treatment, Fe diffuses from the base steel to the coating and forms AlSiFe coating (re-created after [95])

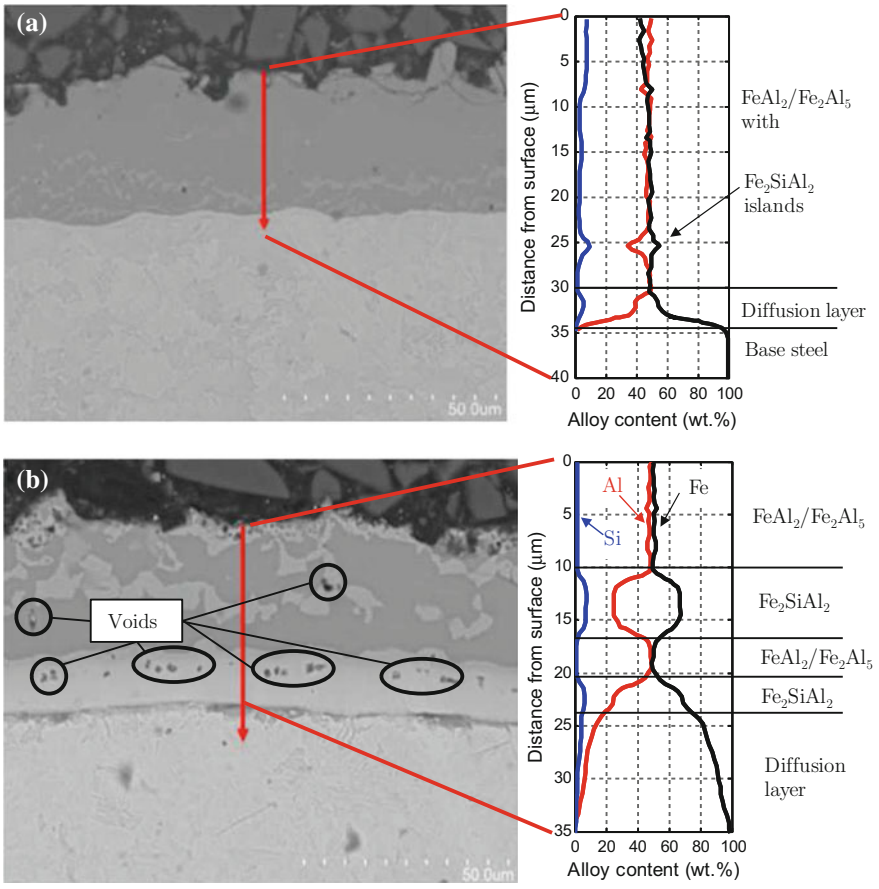

Fig. 4.16 Coating diffusion after: **a** 2 min, and **b** 6 min, in roller hearth furnace set at 930 °C (1700 °F) (re-created after [82, 93, 96])

after 6 min in the furnace can be seen in Fig. 4.16b, for a 1.2 mm thick AS150-coated steel [93]. If the blank is heated for longer durations, (1) more voids may occur which increases the porosity of the coating, (2) the total thickness of the coating increases and (3) Fe_2Al_5, $FeAl_2$, and Fe_2SiAl_2 layers disappear and the coating becomes a single layer of α-iron with Al and Si in solid solution [8, 82, 94]. The coating diffusion is extremely important for most applications as it will affect:

(1) weldability of the final part and
(2) surface properties for painting [91].

AlSi coatings successfully prevent scale formation and decarburization even without an atmosphere controlled furnace. The coating provides barrier corrosion protection. As a disadvantage, these coatings cost more compared to uncoated blanks and require a longer time in the furnace. The total time in furnace is equal to the sum of heating and dwell times, and depends on three variables [21, 95, 97]:

(1) The initial blank thickness: heating time to ensure austenitization.
(2) The type of coating: AlSi coating requires a maximum 12 °C/s, as it will melt over this rate.
(3) The initial coating thickness: dwell time to ensure coating diffusion.

AlSi-coated steels cannot be cold formed (as in indirect hot stamping) as the Fe–Al intermetallic coating is very hard (>600 HV) and brittle during cold deformation. The brittleness of the coating is also critical for the parts produced as their coatings could be damaged in service. Fan and De Cooman showed that the coating could crack easily but the cracks would not propagate to the diffusion layer [82]. For this reason, the thickness of the diffusion layer is critical and has to be controlled. This can be done by controlling the furnace temperature and dwell time [97].

The typical AlSi coating weighs 150 g/m^2. In 2013, ArcelorMittal developed USIBOR 1500 P AS80 with 80 g/m^2 AlSi coating. There were two rationales behind this development [98]:

(1) Lower cost, to be more competitive.
(2) Reduced coating weight would reduce the heating/dwell time in furnace.

Alden [99] has shown that the furnace dwell time could in practice be halved with AS80. Windmann et al. found that the dwell time required to form a single layer coating (which has to be avoided) was 20 min for AS80 and 40 min for AS150 [94]. Both studies prove that the dwell time could be reduced. On the other hand, Fujita [100] has shown that hot-formed steel with AS80 coating had approximately twice the blister width after cyclic corrosion test. Thus, the corrosion resistance is also halved with AS80 coating.

4.5.2 Zinc-Based Coatings

AlSi coating provides limited corrosion protection—"barrier protection"—as AlSi coating forms a barrier between the oxidizing environment and the bare steel. How-

ever, most of the car body components are already zinc coated. Thus, a similar level of corrosion protection may also be required in hot-stamped components [101].

Most Zn-based coatings have problems associated with "Liquid Metal Assisted Cracking (LMAC)". This phenomenon occurs when the coating is in liquid phase (melting point of zinc is around 420 °C ∼ 790 °F which is much lower than the forming temperatures in hot stamping) and stress is applied to the base metal, which cannot be avoided during metal forming. When both conditions are met, the liquid coating may penetrate into the base metal, causing cracks on the surface, as seen in Fig. 4.19.

To avoid LMAC, Zn-based coated steels were typically indirect hot stamped—where Zn is in solid phase. Indirect hot stamping could be through two different methods [1, 101]:

1. Cold deformation (most of the deformation is done in cold state) followed by hot calibration (very little deformation in hot state).
2. 100% of deformation, cutting, and piercing done at cold forming followed by a "form hardening" (where no deformation is done at hot state).

BMW 7 Series (F01, SOP 2008) was the first car to have Zn-coated hot stamped steel in its body-in-white [102]. Figure 4.17 shows the use of uncoated and Zn-coated boron steels in BMW 5 Series GT, (F07, SOP 2009) [103, 104].

For LMAC to happen there are three prerequisites as shown in Fig. 4.18 [79, 105]:

(1) Stress level: during hot stamping stress can be reduced by die design or by improving lubricity (i.e., ZnNi coating has low friction coefficient),

(2) Presence of liquid metal: Pure Zn melts at 420 °C (790 °F), which is far lower than the temperatures in hot stamping process. Therefore, even during heating the blank (i.e., in the furnace) Zn coating on the blank may melt. Thus, liquid

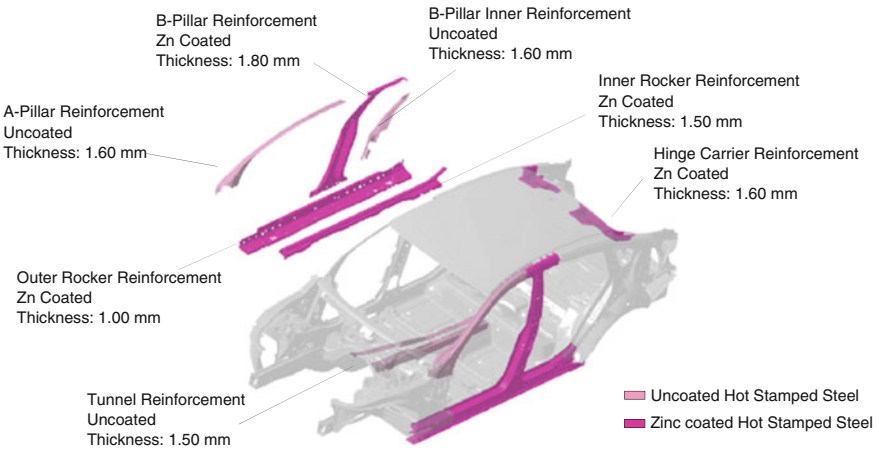

Fig. 4.17 Usage of hot-stamped steels in BMW 5 Gran Turismo (F07, SOP 2009) (re-created after [104])

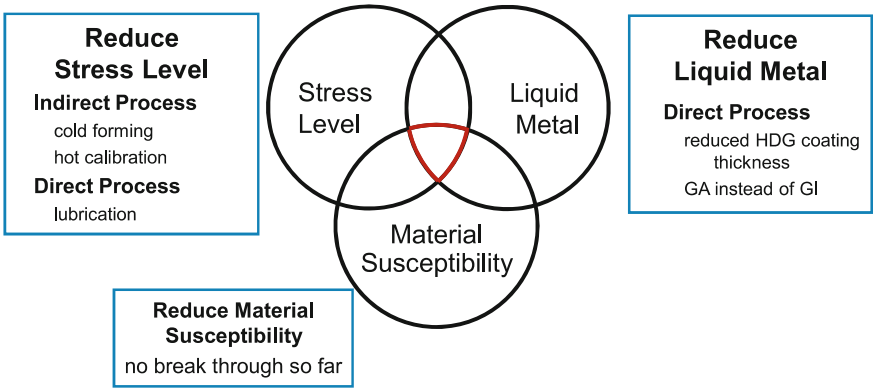

Fig. 4.18 Factors leading to LMAC (Liquid Metal Assisted Cracking) [21]

metal cannot be avoided if the blank is Zn coated. However, the amount of liquid Zn can be adjusted by the weight of coating (typically given by g/m^2) and the coating technology. Reducing coating weight would sacrifice from cathodic protection and decrease the time required in furnace for coating to diffuse [21]. If the coating is galvannealed, iron would diffuse into the coating and increases the melting temperature. Another possibility is to use alloying elements in the coating to increase the melting temperature. One such design was ZnNi coatings [20, 106] (Fig. 4.19).

(3) Reducing material susceptibility: covers a number of properties of the steel, including but not limited to (1) chemical composition and carbon equivalence, (2) yield strength/hardness, and (3) residual stresses [105]. In hot stamping grades, no practical method was found to lower material susceptibility [68].

The presence of microcracks could reduce the fatigue life of the components. Kurz has studied the crack depth and fatigue stress. As seen in Fig. 4.20, microcracks up to 10 μm in the base metal do not affect the fatigue stress. However, if the crack size exceeds 10 μm, fatigue stress reduces drastically [21].

As the coating weight increases, the time in furnace has to be longer. It was also found that as the depth of microcracks is also affected by the coating weight. To avoid microcracks deeper than 10 μm in the base metal, GI coating weight is limited to 70 g/m^2 per side (140 g/m^2 total, abbreviated as Z140) [21].

Hot dip galvanized (GI) steels have an iron diffusion during heating, similar to AlSi coating. In GI coatings, 0.2–2.5 wt.% Al is added to form an Al-enriched layer between the steel and Zn coating [82, 108, 109]. After iron diffusion, there has to be three layers, as shown in Fig. 4.21a [110]. The outermost layer is an oxide layer, consisting of aluminum and zinc oxides. This layer is functional during hot stamping as it suppresses evaporation of Zn but has to be removed before welding/painting by sandblasting [82, 98, 109]. Below the oxide layer, Zn-rich Γ phase is found. This layer plays significant role in the corrosion resistance. For adequate cathodic protection, this layer should have at least 70 wt.% Zn. The Fe-rich α phase determines

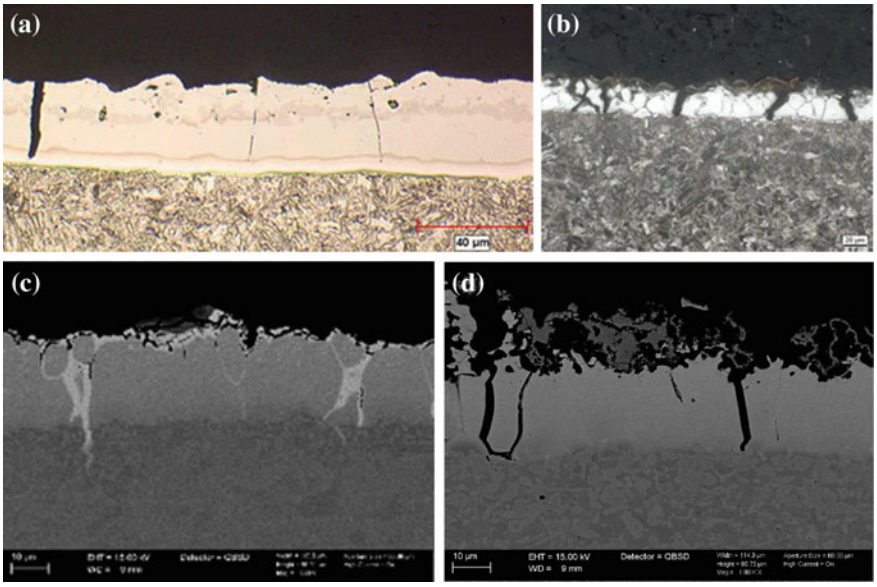

Fig. 4.19 Coatings after hot stamping: **a** microcracks in AlSi coating do not penetrate into steel substrate [8], **b** GI coating melts and Zn may penetrate into base material depending on coating thickness [21]. In **c** GA and **d** ZnAlMg coatings, LMAC problem is reduced but still microcracks may be formed, predominantly not in the base metal [107]

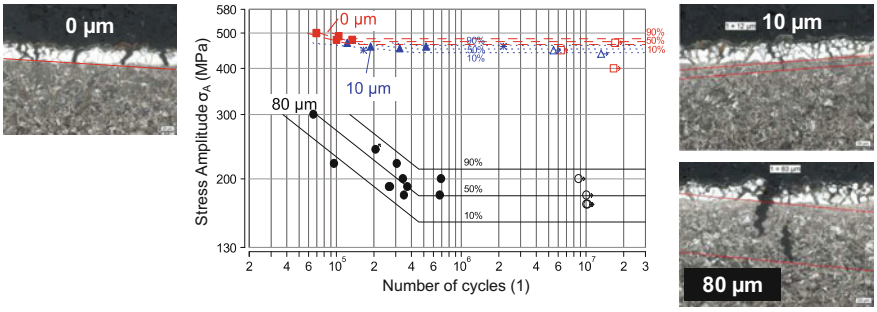

Fig. 4.20 Effect of microcrack depth in base material on fatigue life of Zn-coated 22MnB5 steel. Micrographs showing the cracks are also shown [21]

the adhesion of coating to the base metal. It should contain at least 10 wt.% Zn, preferably in the range of 17–44 wt.% [82, 109].

Zn coating has relatively narrow process window for hot stamping compared to uncoated and/or AlSi-coated blanks. As pure zinc's boiling point (907 °C ≃ 1665 °F) is very close to the austenitization temperature of 22MnB5 (880 °C ≃ 1615 °F). If furnace dwell time is too short, the coating diffusion would not be completed. If the time is too long, deep microcracks may occur in the base metal [21, 111, 112].

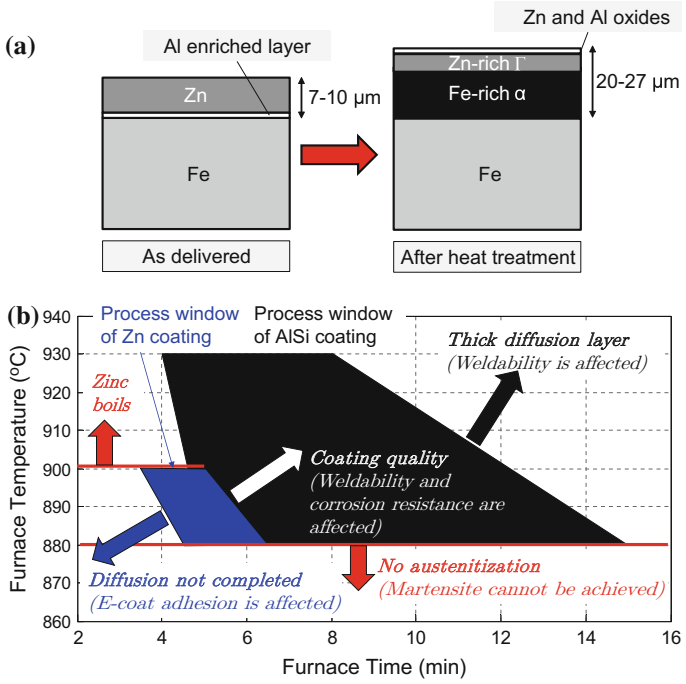

Fig. 4.21 **a** Diffusion of Zn (GI) coating (re-created after [82, 110]), **b** process windows of Zn and AlSi coatings (re-created after [111–114])

To reduce LMAC and/or the need for surface conditioning, alloying elements increasing the melting point of Zn could be added into coating. ZnNi coating was once commercialized by ThyssenKrupp with the name GammaProtect. There were two mass-produced automotive parts using this coating. However, the coating has been discontinued and production was switched to AlSi-coated blanks [20, 111, 115]. Other Zn-alloyed coatings could be ZnFe (Galvannealed coating, abbreviated as GA) and ZnAlMg [92, 108]. Galvannealing (GA) is a process where the galvanized steel is heated to 480–520 °C (~900–970 °F). During this process, iron diffuses into coating and the final coating may have 10–15 wt.% Fe and 85–90 wt.% Zn [116]. GA coatings may be welded and painted without removing the oxide layer [82, 98].

Another recent solution to LMAC is precooling before plastic deformation. Ghanbari [117] found that microcrack formation occurs if forming is done over 782 °C (1440 °F). Kurz et al. [101] developed a precooling stage where the cooling rate is over 50 °C/s (90 °F/s) but the cooling is interrupted before the martensite start temperature, Fig. 4.22a. By this method, forming is still done at austenitic phase [101]. Faderl and Kelsch have shown that if the precooling temperature is lowered, microcrack depth is reduced [118]. At around 550–570 °C (1020–1060 °F), Zn coating is solidified and microcracks are reduced [119, 120]. Typical 22MnB5 could be held at 550 °C (1020 °F) for only 2 s before bainite transformation starts. The newly

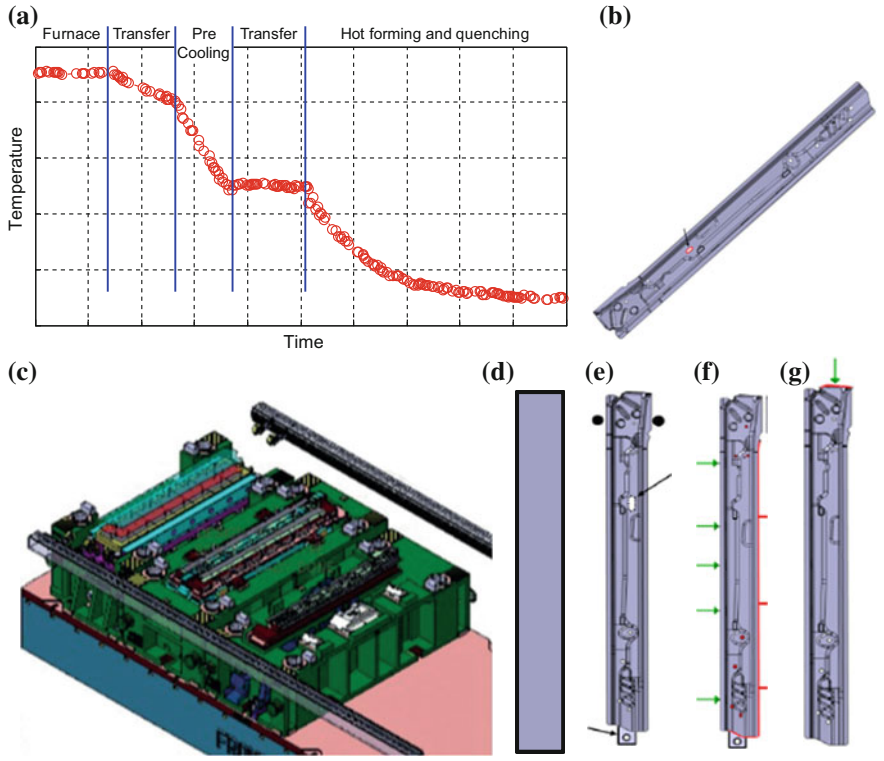

Fig. 4.22 Multistep hot stamping: **a** the temperature-time profile, including the "precooling" stage, **b** The final part geometry, **c** thermal controlled transfer die set, **d** OP10: Precooling, **e** OP20: Forming, **f** OP30: Cutting/Piercing, and **g** OP40: Cam Trimming (re-created after [20, 101, 121])

designed 20MnB8 alloy can be held at this temperature level for more than 20 s before the transformation [68]. By using precooling system 20MnB8 GA 90/90 (ZF180) can be formed in a multistep operation in a transfer press, as shown in Fig. 4.22b–f.

Currently ArcelorMittal, POSCO, and voestalpine offer Zn GI coatings. ArcelorMittal and voestalpine also offer GA coating. Tata Steel is developing MagiZinc (ZnAlMg) coating for press hardening, but this product is currently not in the market [9, 14, 101, 122]. According to Dormegny [123], 76% of the hot stamping steel in EU27+Turkey is AlSi coated. In these markets, 18% of hot stamping steel is uncoated and only 6% is Zn coated.

4.5.3 Varnish Coatings

Another method to avoid scaling and decarburization is to apply varnish coatings. In this method, uncoated blanks are either coil coated or roll coated with the paint-like

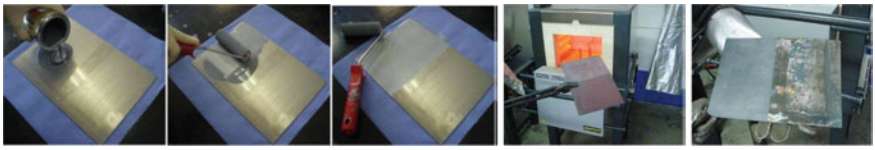

Fig. 4.23 x-tec coating can be applied simply by a paint roll or spray gun [74]

varnish coatings. The first such application for hot stamping process was developed by Nano-X company in 2005. By then, AlSi coating was already in production. However, in several components of the (then) new Passat, part shapes were extremely complex. A two-step forming process was needed where some deformation would be done by cold forming and more in hot forming, as shown in Fig. 1.15, in Chap. 1 [124, 125].

The first-generation x-tec (see CO 4020 in Table 4.11) had Al particles, graphite and wax in inorganic–organic matrix. This coating should be applied 6–7 μm thick on the uncoated base steel. It can be applied simply by paint rollers (Fig. 4.23) or could be coil coated. cures in room temperature. x-tec coating has lower friction compared to uncoated and AlSi-coated blanks, and was on a par with ZnNi coatings, see Fig. 10.7. This coating had to be removed (by sandblasting) before e-coating and/or welding [74].

Second-generation x-tec, AlSi 4001 as shown in Table 4.11, was developed to be weldable without sandblasting. The coating has high heat absorption and since extra time for diffusion is not required, the total furnace time could be lowered significantly. It can also handle inductive, conductive, and near infrared heating and could be applied as thin as 2–3 μm [74].

In 2015, Henkel has introduced a varnish coating for hot stamping, called Bonderite S-FN 7500 PH. The coating is suitable for fast heating and provides barrier corrosion protection. Although its friction coefficient is not published yet, it helps lubricating the blank. The coating is not required to be removed/sandblasted before e-coating or spot welding [85].

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